THE JUDGING
OF THE STABILITY OF SHIPS
AND
THE DETERMINATION OF THE
MINIMUM AMOUNT OF STABILITY
ESPECIALLY CONSIDERING THE VESSELS
NAVIGATING FINNISH WATERS

BY
JAAKKO RAHOLA

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PREFACE

I beg to express my best thanks to the Research Grant Distribution Committee for Young Scientists for the assistance granted me and which has enabled me to accomplish this treatise. It is also my pleasant task to thank all the departments and private persons, who in some manner or other have given me their valued help and advice in preparing this study, first and foremost the Staff of the Naval Forces and the Board of Navigation for their most valuable support. The collection of investigation material for the study of vessel disasters has been greatly facilitated by the kindness shown to me in Germany as well as in England, and I thank most heartily all the persons in those countries, who have offered me their kind assistance.

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THE AUTHOR.
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CHAPTER V. THE JUDGING METHOD FOR THE STABILITY
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Introduction.

The object of the present investigation is to find a procedure by means of which it may be possible to judge with adequate certainty the amount of the stability of a certain vessel which may come to navigate under the conditions prevailing on the lakes and the waters adjacent to our country, and to decide whether it is sufficient or not. The fairways for Finnish vessels can, from the point of view of the present investigation, be subdivided into two great classes, such where action of waves is essential or at any rate an important factor, and such where heavy seas do not appear to any extent. To the former fairways must be counted all the open shores of Finland and Lake Laatokka and the more open waters along the coasts of our country, to the latter belong our lakes, rivers and the inner waters among the islands. Already for the sake of this division the study must be divided into finding two different methods; the fact that these two methods will be so different from one another in principle, is due to the circumstance that the theory of a vessel’s stability has not yet been sufficiently developed. One cannot yet treat with the same certainty the question of the stability of vessels in calm water and on the high seas.

The methods for judging the stability, which are aspired to in this investigation, are intended principally for the use of such persons whose ship-theoretical knowledge is comparatively good. To such persons do not belong, with certain exceptions, officers of vessels, for which reason the parallel problem of the question of judging stability, i.e. a quick and simple method for enabling the officers to estimate the stability, might with good reason be left altogether out of the study. An intermediate main object of the study is to reduce as far as possible the risk of vessels capsizing. The elimination of this risk depends, when all is said and done, upon the officers of the vessel, already for that reason that all such work is done on their responsibility, which in the last instance determines the final amount of the vessel’s stability. It is therefore
impossible to leave the question of a method intended for the use of the
officers of a ship to judge the ship's stability altogether out of this
investigation.

Despite the limitation of the work, quite a number of stability prob-
lems will have to be treated. Before trying to find out any new methods
for judging, we must examine what principles are applied in the general
investigation of stability, and of these principles the most correct and
suitable must be chosen. The subject of the study is acknowledged
throughout the world to be a very important one, which has resulted in
there being already certain methods for judging stability; their adaptability
to our conditions must also be elucidated.

With regard to stability circumstances we must clearly make a
distinction between the determining and the judging of stability. The
well known determination of the stability of a vessel involves the nume-
crical calculation of the different factors of the vessel's initial stability
and its statical and dynamical stability. This problem has been solved
long ago for a vessel sailing on calm water, subject to certain circum-
cstances in connection with rolling. The question of the complete deter-
miming of the stability circumstances for a vessel sailing among waves
is, on the other hand, yet still unsolved, for which reason the numerical
calculation of the measuring of the standard of stability for such a vessel
remains incompletely solved. — When the magnitude of the stability
has been determined — exactly or even inexact — the judging of
the stability can be begun. For performing this work, there are three
methods to be chosen, all differing from one another, which will be
explained in the following:

1. The stability values for the vessel to be studied can be compared
with the corresponding values for similar vessels that have sailed suc-
cessfully for years.

2. As basis for the comparison may be used the stability factors of
vessels that have capsized by reason of bad stability qualities.

3. One can theoretically determine by calculation the magnitude
of those heeling moments to which the vessel may be subjected in the
most unfavourable circumstances, and make the stability qualities of
the vessel such as to allow the vessel to withstand these heeling moments
without risk.

The comparison of the stability qualities for a certain vessel with the
qualities of similar vessels that have sailed successfully is useful and even
sufficient, provided the vessels really are alike, i. e. that the shapes of
their hulls, relation of the main measurements, the relative heights of
their freeboards, the distributions of the weights, etc. are similar, and
provided the courses for the vessels are either similar or the same. If
that be not so, the application of such a method of comparison may lead
to the most fatal mistakes. Besides, the use of this method implies a
large comparative material, which must be of such a nature that a suffi-
cient number of stability factors for the vessels are evident therefrom.
If these conditions are fulfilled, this method is capable of being applied
within fixed limits. For instance, such a master of a vessel may apply it,
who has a sufficient measure of expert knowledge, in judging on the
effect of different cargoes upon the stability of his vessel. — As a scient-
ic procedure this method for judging the stability is however of a
comparatively small value. This is particularly due to the fact that,
although the stability qualities of vessels that have sailed with success,
are clearly obtained, which stability values have been of sufficient magni-
tude for those vessels, they do not however represent the minimum
value sufficient for the stability of all vessels. Thus, it is possible
that in designing a new vessel, if the stability value of a similar vessel
be taken as the basis, that value of stability may be unnecessarily large
for the vessel to be built; it may be unavoidable for obtaining such stabil-
ity qualities to make the beam of the vessel very large, which is of no
advantage to the speed of the vessel, and which may render its rolling
in a high sea uncomfortable for passengers and crew, or it may be neces-
sary to have a lot of ballast, which of course is always uneconomical.
If again the value of the stability, for avoiding these disadvantages, be
reduced on the basis of a summary examination, the consequence may
be, particularly after several such decisions, an excessive reduction of
the stability qualities. Further, as the scope when selecting the qualities
of stability is large and the minimum limit when applying the first men-
tioned method of judging is vague, it may happen that any endeavour on
the part of the vessel's designer or her master to attain a certain object, for
instance to make the vessel's rolling as easy and soft as possible, may in
the end jeopardize the safety of the vessel.

Far more applicable and also more suitable as the basis of a scientific
investigation is to use the second method for judging the stability,
I. e. the one founded on the qualities of stability for capsized vessels.
This method is even considered very favourable, in the opinion of some
the only possible one. Thus, the German Commentz, who has devoted
intense studies to the stability questions of vessels, has declared that
there is only one road to determine the least necessary curve of stability
for a vessel driven by an engine: the practical study of accidents at sea
[C.4].1 This opinion contains a lot of truth, when it is a question of

1) The letters and figures in brackets refer to the alphabetical list of literature
at the end of the work.
determining the standard of stability of actual seagoing vessels. It was already stated above that the stability theory for vessels rolling among waves is not yet sufficiently developed. On the other hand, the force effects of waves acting upon a vessel are so manifold and so difficult to determine by calculation, that there is no sufficient ground for applying a theoretical method, as ERBACH for instance has stated [E 6]. The judging of the stability of seagoing vessels must for that reason so far be done on the basis of such material as is obtained from the stability qualities of capsized vessels and the statements of experts in courts handling such accidents. Formerly, there was very little of such material to be had. Only of late years, at any rate in the great countries, in the first place in England and Germany, one has begun, when studying accidents to vessels, to give more attention to the theoretical stability qualities of the vessels, and the comparing material available has consequently grown in proportion. The numerous remarkable sinkings and capsizeings that have taken place in other countries during last years have finally added to this material so much that it is possible to arrive at a unitary and logically obtained result on that basis. The concentration of accidents just upon those years, during which the author began to study the standard of stability of vessels, is a coincidence; it must therefore also be held as a mere chance that the present study is, as far as known, the first, in which are collected in one single publication the reviews of the stability qualities of twenty to thirty capsized vessels and where an endeavour, founded upon this basis, has been made to establish a new minimum rule for the stability value of seagoing vessels.

The third of the judging methods above referred to, the determining of the heeling moments affecting the vessel and the comparing of the stability with their sum total, is so natural that it might seem unnecessary to give any motive for it. It is the same method that is usually applied in technics in general, for instance when solving theoretical strength problems. The reason why this method of judging stability is used so very seldom would appear to be that it is extremely difficult to determine the actual magnitude of all the heeling moments affecting the vessel, such as rudder pressure, centrifugal force, effect of waves, etc. It is so difficult that a good many, such as even the above mentioned ERBACH, have considered it almost impossible to apply. It is also difficult to determine such a coefficient of safety the use of which would guarantee the sufficiency of the vessel's stability in abnormal conditions, without however bringing about that the vessel be built either uneconomically broad or for instance too stiff in motion. However, the difficulties referred to, are immediately lessened when sailing among waves need not be taken into account. This method is consequently suitable for vessels on our inner waters and lakes when determining the standard of stability. It must also be noted that hardly any other method could come into question when studying these vessels, as there is barely any information from sources in foreign lands on the stability qualities of successful, and still less of capsized, vessels that are similar to those on our inner waters, and we can hardly speak of any earlier studies of stability regarding our own vessels. For all these reasons, the method of calculating has been chosen as the procedure for the present study for judging the standard of stability for vessels on the inner waters.

As stated already, the methods set forth in this study are intended for such persons as have fairly wide knowledge of the theory of stability. When it is the question of the minimum stability of seagoing vessels, their information naturally does not help, as the stability qualities of vessels rolling in waves are not yet finally determined; a method based on practical experience is therefore also of use for them. It might seem to be useless to create a special method for judging the stability of vessels on the inner waters for such a limited application because, if it does not contain anything new and so far unsolved, it might be declared that the users of the method, for instance designers of vessels, know how to calculate the magnitude of the heeling forces by using already known equations at any time. This opinion has been expressed for instance by Hög, where he states that standardizing methods for stability will be of use only in the hands of theoretically educated men, and if this condition is once fulfilled, a standardization is of no use [P 3]. Practical experience however shows that the matter is not so clear. As basis for judgment the use of the heeling forces as such very seldom to be met with and as far as the author knows, there are only published two methods for judging, which will be referred to later on, founded upon this basis. It would appear as if naval architects, for the want of a suitable, speedy and simple method, had no desire or even time to spend on determining the heeling moments, although they are well acquainted even with difficult calculations. For eliminating this want, the second of the methods presented is intended for judging the stability of vessels on inner waters.

In so far as the judging methods, constituting the main objects of this research, prove themselves to serve their purpose in practice, one has use for them in working out two problems in particular: in planning vessels and their grand repairs and in estimating any ballast required for completed ships. In performing such big jobs there is always sufficient time, so that it is possible to use methods requiring such elaborate calculating
work. But despite such solutions having been made, the safety of the vessel is by no means guaranteed thereby. Although the vessel has thus been planned, and any such necessary ballast has been placed in her as to render her stability with a normal cargo adequate in all circumstances coming into question, there is still no certainty that the vessel may not some time capsize. The vessel’s stability depends essentially on the distribution of the weights, i.e. cargo, fuel, passengers, etc., and these distributions may differ greatly from what was assumed by the designer and the man who determined the ballast. Besides, the vessel may be too heavily loaded. Throughout the world the responsibility for loading the vessel and the faulty stowing of cargo devolves upon the vessel’s master. In our country this principle is expressed i.a. in clause 51 of the mercantile marine statute [L 5; page 420]. The vessel’s stability is thus in the end the responsibility of her master and that responsibility appears to be impossible to take away from him. When we take into account that every ship can be made stable or instable by shifting the loads, as Fosterg King once declared quite correctly when discussing the stability circumstances of ships in public [P 3], it is evident that the stability of every ship is not finally or unconditionally secured, unless the vessel’s master is both capable and willing at all times to determine the amount of the vessel’s stability and to judge it correctly. It has therefore been held as unavoidable to treat, in connection with this study, such endeavours also as have been made for facilitating this difficult work of the master, and to examine the difficulties which lie ahead on the road to a future complete solution of the question of minimum stability, also ship service.

A short description of the material used for forming a rule for seagoing vessels’ minimum stability has been held to be unavoidable. This explanation has been added to the end of the work as a special collection of instances, so as to maintain the unity of the ordinary text. Detailed data on stability factors, gathered from investigations of accidents, court resolutions, information given by individuals, etc., have nevertheless been reviewed in the text part of this study, which also includes all the diagrams.

Statistics obtained from of capsizings show that the great majority of vessels that have experienced this kind of accident were all small ones. One of the intermediate objects of this study being to improve as far as possible the stability conditions of our country’s fleet of vessels, especially small vessels have been chosen as type-ships whose stability factors have been determined for this study. Among them are most of the vessels that have sunk or capsized in our waters during the last decades. By comparing these vessels’ stability qualities with the corresponding qualities of vessels capsized in other countries, and with the rules of stability, we obtain on the one hand an explanation of the accidents that have happened, and on the other hand a control of the results of the investigation.

When studying the problem of the minimum stability of vessels there is still one circumstance to observe, which has from time to time been discussed publicly, namely the question whether it is possible to fix any minimum limit for the stability of vessels by statute or rules of classification societies. The demand for making such minimum rules is really a very natural one, and one can quite understand its constant renewal, particularly after some severe accident at sea. When considering the matter more, it seems clear that, once the constructive strength of vessels can be fixed, so as to guarantee their hulls to stand in whatever different circumstances and in whatever cargoes it may be, and considering that it has been possible to prevent an overloading of vessels through the stipulations of the L. W. L., it must also be possible to establish such minimum limits for their stability that capsizing events are eliminated. But the absurd opposition that always meets the proposers of measures in this direction would nevertheless tend to prove that the solving of the question is by no means an easy matter. As often as demands are made for the determination of a minimum value for the stability of vessels, one also finds just as often that such demands cannot be fulfilled. That was even the case, when the Americans prepared their official proposal for the consideration of the international Load Water Line congress in 1929 in London [D 7]; in the proposal, which was the result of four years’ work, certain demands were made concerning the stability of passenger ships, but the proposal was rejected [H 2] [M 7] [A 10]. On this basis it would appear already that the determination of a minimum stability for vessels is of such a nature that it is impossible to expect for a long time anything of the kind in general, and particularly not in our country.

Quite aware of this, the author cannot by any means hope that the methods set forth in this study, or even any of the simplifying modifications of them, can be taken as the basis for some stability statute. When once the establishing of a statute for a standard stability has in the end become absolutely unavoidable, the theory of ships has perhaps advanced so far that the use of altogether new calculating methods for the minimum stability has become possible. The collecting of as extensive material as possible concerning accidents will nevertheless even then be essential, and in that respect the present investigation may be of lasting value.
Notation System Applied.

In the study such marks are mainly used as the German Society of Naval Architects has approved, at the suggestion of the select committee appointed by it [H 8], and which the author has used previously in an article on the rolling of vessels [R 9]. In spite of the decision of the above Society, there still seems to be dissent regarding the mark for the metacentric radius; according to resolution the letter \( a \) should be used as the mark for the metacentric radius, but VON DEN STRICHT has begun to use the letter \( b \) in his writings [S 28] [S 30], for which reason it was also used in the above article on the rolling. However, the motive brought forward by STRICHT does not appear to be sufficient, wherefore the metacentric radius is marked in this study, as well as in certain Finnish publications and quite universally in French and Italian technical literature, with the letter \( r \).

Among the more important notations may be mentioned the following (Figs. 1 and 2):

- \( G \): Centre of gravity of the vessel.
- \( F \): Centre of buoyancy of the vessel.
- \( S \): Centre of flotation.
- \( M_0 \): Initial transverse metacentre, metacentre.
- \( M \): Pro-metacentre.
- \( N \): Shifting metacentre, i.e. the point of intersection between the vertical through the centre of buoyancy at heel with the vertical through the centre of buoyancy in the upright condition.
- \( H \): The point of intersection between the vertical through the centre of buoyancy with the normal drawn to it through \( G \).
- \( L \): The point of intersection between the vertical through the centre of buoyancy with the normal drawn to it through \( F \).
- \( F \): The freeboard amidships.
- \( H = T + F \): Depth.
- \( \alpha \) : Water line coefficient. \( \beta \) : Midship section coefficient.
- \( \delta \) : Block coefficient. \( \psi \) : Longitudinal or prismatic coefficient.
- \( F \) : Surface area mark in general; separate indices show which surface is meant.
- \( J \) : Vessel's polar moment of inertia.
- \( i \) : Vessel's polar radius of inertia.
- \( M \) : Moment of inertia of the water plane.
- \( \psi_a \) : Angle of heel, \( \psi_a \) : Vanishing angle, range of stability, \( \psi_a \) : The angle at which the righting arm attains its maximum.
value, \( \varphi \), the extreme allowed angle of heel, \( \varphi \) amplitude of roll.

\( L \), wave length.

\( T \), wave period.

\( H \), wave height.

\( T \) period of complete double oscillation of vessel.

\( g \) acceleration of gravitation.

\( f \) function mark.

The units of measurement are,

provided nothing else is specifically stated, the following:

unit of length, the metre, \( m \)
unit of area, square metre, \( m^2 \)
unit of cubic measure, cubic metre, \( m^3 \)
unit of weight and force, the metric tonne = 1000 kilograms, \( t \)
unit of work and energy, the metretonne, \( mt \).

Chapter I.

The Phases in the Development of the Problem concerning the Minimum Amount of Stability.

Even the most recent of the fundamental laws that determine the amount of stability for a vessel are already about 200 years old. Consequently, it would seem natural that the estimating of a vessel’s stability and the determining of its minimum amount should have drawn attention very early. However, that is by no means the case. Only about a hundred years after forming the principles for the theory of stability one began to understand, by reason of a certain accident having occurred, the great importance the stability qualities of a vessel have for its seaworthiness and non-sinking qualities. This earlier under-valuation of the stability circumstances appears at first sight difficult to explain, particularly when one compares the fortunes of this question with those of its parallel question, the development of the problem of preventing the overloading of vessels.

It is known that rules existed in Italy for the load water line, in the city-republics, already about the year 1000, if not earlier, and possibly in the municipal laws of Visby about the year 1288 [A 2]. One observes in general that the preventing of a vessel’s overloading was and is held to be a very important matter. It is, of course, true that the load water line was made obligatory in England as late as 1890 and in Germany in 1903, but about 1834 already a certain English committee had recommended the application in practice of the so-called Lloyd’s Rule [A 2] [A 12]. But almost forty years were to pass, before the stability of vessels began to attract more general attention.

The slight interest roused for the amount of a vessel’s stability can in a way be explained very simply. So long as the wind was the propelling force for the ships, one was obliged, without studying the matter theoretically, generally to have a comparatively high freeboard for the hull.
This brought about at the same time that the range of stability became great. The master of a sailing ship was also aware at every moment of the approximate amount of the stability, because when sailing he constantly happened to perform some kind of inclining experiment with his vessel, even if it was primitive. It was therefore easy for the master to avoid imperiling the stability of his ship, and whenever he was tempted to load an excessive deck-cargo or otherwise reduce the stability, he probably did so well aware of the risk he was causing his vessel. The existence of the old regulations for load water line proves the fact that overloading of vessels occurred already in the times of the sailing vessels. Whenever sails were employed long after the taking into use of steam-driven vessels, they acted as a kind of regulator of the amount of stability.

The construction of a diverging type of vessel led to a flagrant violation of the building rules for well tested sailing vessels. The consequence was an accident that happened in 1879, which had a very great significance in bringing the question of minimum stability to the fore. The inventor of the turret Coles designed, on the model of the coastal monitors built in America by Ericsson, a man-of-war called Captain, with a very low freeboard, in spite of the opposition made by Reed, the Chief Designer of the Admiralty. Reed considered the Captain to be far too unseaworthy, by reason of her low freeboard, and recommended that the Monarch type designed by him should continue to be built. The discussion of these different opinions having been carried on just before the completion of the Captain, and as the vessel capsized shortly afterwards, this accident attracted great attention and soon made the use of the statical stability curve known, although by no means general (Ex. 1)).

The accident could also be used as a particularly fine stability-theoretical example, because the Monarch happened to be on the same course as the one where the accident occurred, and weathered the storm without any damage.

In spite of the reasons for this disaster having been made clear by the use of the stability curve and the attention of the experts directed to the stability-theoretical side of the occurrence, its immediate effect seems to have acted only upon one part of this broad question, the understanding of the meaning of the freeboard. The Institution of Naval Architects — abbr. I. N. A. — i. a. refers to this in the lecture held by Barnaby at a meeting the following year, on the influence of the relation between a vessel’s beam and freeboard upon the range of the stability [B 17]. In view of the general demand at the same time to make the load line obligatory for preventing the overloading of merchant vessels, and it appearing that the use of the load water line was actually becoming more universal, the satisfaction brought about by this circumstance simply killed the whole question of demanding a minimum stability. However, there ought not to have been any positive reason for this, because, although the height of the freeboard certainly has a great influence upon the range of the stability, no rules for load water line have place any essential demands for stability upon the scope of the relation between a vessel’s beam and freeboard, nor do they in any way adequately safeguard the vessel’s stability. Besides, as in England almost all references to the stability have been gradually removed from the load water line rules, there is very little now in common between the load water line and the determining of the minimum limit for the stability.

All demands, that are continuously made from time to time, for a separate solution of the question of minimum stability, have again been received in England with very severe criticism, the last time in 1935 [P 3]. Nevertheless, we have come this far, that the Board of Trade requires all shipyards to give to the masters of all passenger liners the complete stability data of the vessels and to take the stability into account when determining the maximum number of passengers [H 2] [B 11].

In addition, inclining experiments are customary for all important vessels, although this is not established by law.

A severe capsizing event was thus the reason why one began in England to pay attention to the question of minimum stability. In Germany as well, the accidents have been the best stimulants for endeavours to solve this difficult problem. When in 1903 a large number of fishing boats had gone down, the Germanischer Lloyd made a study of the stability with the help of curves of stability moments [S 31] [G 4], and arrived at the result that the vessels had capsized (Ex. 4). These disasters as well as the s. s. Narvik lost in 1913 (Ex. 9), the Swedish cargo boats sunk during the War with deck cargoes of wood pulp [S 14] [E 3], the lightship Elbe I capsized (Ex. 27), and many other events, have always given rise to lively discussions how the stability of vessels can be secured. Very few practical proposals have been however made, and very late. The first remarkable endeavour to determine the minimum amount of the stability was made by Benjamin in 1913 [B 8], and subsequently i. a. Förster tried in 1922 to find means by which the masters might judge the stability of their vessels better than before [F 4]. The result of the public conferences and committee work was finally that the See-Berufsgenossenschaft added in 1933 a couple of

1) The reference applies to the collection of instances, on capsizings in foreign countries, at the end of the publication.

2) See also Chapter VI.
points concerning the stability to its Rules for preventing accidents (Unfallverhütungsvorschriften) [S 15], and similar regulations were also added to the statutes concerning passenger and cargo boats [V 1] [V 2]. But any such measures by which the extent of the stability in all circumstances might be judged, and by which it might be seen with full exactitude, whether the sufficiency of stability as assumed in statutes and other regulations really existed, it has not been possible to find, even in Germany. In 1937 the whaler Rau III capsized on her trial trip when performing the turning test, the weather being calm at the time (Ex. 29); on the one hand that circumstance is a proof of what mistakes in judging the stability features one can still make even in Germany; on the other hand it shows how absolutely necessary a practical method for judging the stability is even there.

Shortly after the War one began to work out in the United States a proposal for rules for the stability of liners, and the proposal was approved by the end of 1928, to be given for discussion to the international congress meeting in London the following year [A 10]. This proposal, whose sad fate has already been referred to, happened to be signed just at the same time as expert circles and the minds of all the world were excited by the capsizing of the passenger ship Vestris in the Atlantic (Ex. 19). The solving of the question of minimum stability proved nevertheless as difficult as ever, and the American proposal was filed in the archives.

Of endeavours made in other countries to solve the problem of the minimum stability, those published by Blagovishchensky [W 2] and Pirriottet [P 3] will be treated later on in detail, so I only refer to them in this connection. The fact that these two proposals have been made during the last ten years, proves that interest in this problem continues to be great.

Several capsizing and sinkings have happened in succession in this country, which have made the question of studying the stability of our ships and the correct judging thereof an exceedingly important one. After every disaster the examining authorities have been at a loss to judge whether the reason for the accident was the insufficient stability of the vessel, a mistake made by the master, or some other reason. These accidents have naturally had an effect upon the rules given by the shipping authorities, those rules having been rendered more severe in consequence. Before the capsizing of the passenger steamer Kurin in 1929, comparatively slight attention had been given to the stability qualities in this country. After that accident the Board of Navigation established already in 1930 rules for testing the stability and using ballast. However, these rules were not of any particular usefulness, because there are no regulations for the load water line of vessels sailing within the frontiers of our country, on the inner waters and along the coasts; for that reason one cannot supervise the loading or the burdening of such vessels, nor does one know the amount of cargo when judging the stability. When writing this, the constantly occurring overloading of vessels on our inner waters has also led to the treating of that question. Only after its solving, or in connection therewith, can the question of the measuring of the minimum stability be taken under serious discussion.

After this general review, the following will be devoted to an analysis of the possibilities that exist in the stability theory for endeavouring to determine the minimum stability of a vessel, and to the study, in what manner and with what success these possibilities have been utilized.
Chapter II.

Foundations for Judging the Minimum Stability.

§: 1. General Stability Factors of a Vessel.1)

ARCHIMEDES' law gives the point, through which the buoyancy of a vessel acts, its direction and amount

\[ D = \gamma V. \]  

(Euler's law states that the old and the new water lines for the infinitesimally small \( d\\phi \)-angle on a vessel's inclining intersect along a straight line, which runs through the centre of flotation \( S \).

Finally, BOUGUER's law says that when a vessel heels, the centre of buoyancy runs along a curve whose radius of curvature, the so-called metacentric radius, is at every moment

\[ MF = r = \frac{I}{V} \]  

(Fig. 3)

Thus all the factors required for determining the moment of statical stability

\[ M_u = Dk - f(\varphi) \]  

are known.

The equation (3) is graphically represented by the so-called curve of the statical stability (Fig. 4).

When a vessel heels, its weight remains constant, therefore its supporting force is also constant. Equation (3) can thus be divided by \( D \), when we obtain the correlation of the righting arm of statical stability and the heeling angle

\[ GH = h = f(\varphi). \]  

This arm is hereafter briefly termed stability arm. Fig. 4 also shows its variation with varying heeling angles, when the axis of ordinate in the drawing is provided with a new \( h \)-dimension.

The graphical representatives of the equations (3) and (4) are briefly called with the similar name statical stability curves. Because the stability arm curves of vessels of various size differ far less from one another than the same vessels' moment of stability curves, the former are easier to use, when comparing the stability qualities of the vessels with one another, for which reason the stability arm curves for the vessels are generally given drawn out to a certain determined scale.

From the stability arm curves of a vessel several stability factors are evident, which may be used either singly or jointly with others in judging the stability qualities of a vessel. These stability factors, briefly proved, are given in the following.

1. The inclination coefficient of the tangent to the stability arm curve in an arbitrary point. -- The inclination coefficient is (Fig. 4)

\[ tga = \frac{dh}{d\varphi}. \]

According to Fig. 3, we have

\[ dh = c_\varphi \cdot d\varphi, \]

wherefore

\[ tga = c_\varphi = M_\varphi H_\varphi. \]  

1) In drawing up this paragraph, the following sources mainly have been used: [P 5], [S 5], [L 1], [J 3], [N 3], [P 1].
If therefore to the right from any point of the curve a right-angled triangle be drawn, whose horizontal cathetus is of the same length as the unit of circular measure and whose hypotenuse is a tangent to the stability arm curve, the vertical cathetus of the triangle \( = c_\varphi \) the pro-metacentric height. — We must remember that this length must not be confused with the length \( N_qG \) (Figs. 1 and 2), the so-called shifting metacentric height. Between the latter and the stability arm there is a simple correlation

\[
N_qG = \frac{h_\varphi}{\sin \varphi} \quad (6)
\]

from which the term shifting metacentric height is derived; this length can therefore also be used as the measure for the length of the stability arm, as will be shown later. On the other hand, the lengths \( c_\varphi \) and \( h_\varphi \) have no such simple relation as would enable us to calculate the size of the latter immediately from the former. The pro-metacentric height \( c_\varphi \) at heel therefore does not generally show how long the stability arm of a vessel is.

2. The inclination of the tangent to the stability arm curve at the origin. — Its tangent is

\[
tg \alpha = \frac{dh_\varphi}{d\varphi} \quad \varphi = \varphi_0
\]

According to equation (6) we have in general \( h_\varphi = N_qG \sin \varphi \). When the inclination \( \varphi \) approaches zero the length \( N_qG \) approaches \( c_0 \), and therefore

\[
tg \alpha_0 = c_0 \cos \varphi = c_0 \quad (7)
\]

because \( \cos \varphi_0(\varphi = \varphi_0) = 1 \). The tangent to the stability arm curve at the origin thus intersects a vertical line drawn up at a distance of the unit of circular measure, of the length \( = M_qG = c_0 \) the initial transverse metacentric height. — It must be observed that, when the inclination \( \varphi \) approaches zero, the sizes both of the pro-metacentric height \( c_\varphi \) and the shifting metacentric height \( N_qG \) approach the size of the initial transverse metacentric height.

3. The angle of inclination \( \varphi_\alpha \) at which the stability arm curve reaches its maximum and the maximum value \( h_\varphi \) of the stability arm corresponding thereto. — In this point the tangent of the curve is horizontal and the pro-metacentric height \( M_qH_\varphi = c_\varphi = 0 \).

In spite of that, the shifting metacentric height \( N_qG \) is still positive and has attained such a length that the result \( N_qG \sin \varphi \) is as great as possible.

4. The angle of inclination \( \varphi_0 \) at which the stability arm vanishes, \( h_\varphi = 0 \). — This critical inclination is in this study briefly called capsizing angle or range of stability, as the capsizing of a vessel is in all conditions an unavoidable consequence once this value of the angle is exceeded. The attribute critical is reserved for other purposes.

5. Some particularly remarkable values of the inclination and the corresponding values of the stability arm. — Such values are i. a. the inclinations corresponding to the immersion in water of the edge of the deck, the side of the deck building, the sills of doors that are not waterproof, etc.

6. The figure area bordered by the stability arm curve, the reserve dynamical stability of the vessel. — According to the above, the product of the ordinate of the stability arm curve and the displacement of the vessel gives the amount of the moment of statical stability \( M_\varphi \). The product of the figure area bordered by the arm curve, the \( \varphi \)-axis and the determined ordinate, and the displacement again gives the amount of the work required for heeling the vessel, the so-called moment of dynamical stability

\[
D(a-a_\varphi) = De \quad (8)
\]

(Figs. 1 and 2). This is easily ascertained.

The rate of increase of the moment of dynamical stability corresponding to a small increment of the heeling angle is in general, as the displacement remains constant, \( D \, de \). According to Fig. 5, the increment of the corresponding dynamical lever \( e \) is

\[
de = h \, d\varphi.
\]

Against the heel \( a-a_\varphi \) thus corresponds the dynamical lever

\[
e = \int_0^{\varphi_1} h \, d\varphi. \quad (9)
\]

Thus, when drawing the first integral-curve of the stability arm curve, we obtain the vessel’s dynamical lever curve and, if its ordinates are multiplied by the amount of the displacement, we obtain the corresponding values of the moment of dynamical stability. The dynamical lever curve starts in the origin, touching the \( \varphi \)-axis, its point of inflection lies at the point of the \( \varphi_\alpha \) and its maximum value at point \( \varphi_0 \) (Fig. 6).

The figure area bordered by the stability arm curve and the \( \varphi \)-axis — and therefore the maximum ordinates of the dynamical lever — stand in
The reserve dynamical stability when the vessel is heeled by some external heeling moment. — When the vessel is subjected to some heeling moment's influence and when the co relation of this moment and the angle of inclination \( M_1 - f_1(\phi) \) is known, in the stability curve the moment arm curve of that moment \( M_1/D = f_2(\phi) \) can be drawn. The reserve dynamical stability of the vessel is then proportional to the figure area remaining between the heeling moment arm curve and the stability arm curve (Fig. 6).

8. The statical and dynamical critical heeling angle. — The upper straight line of Fig. 7 represents the constant heeling moment \( M_{1a} \); the steady angle of heel due to this moment is the angle \( \phi_{1a} \). For then the heeling moment equals the moment of stability. The vessel can under no circumstances withstand any larger constant heeling moment. The angle \( \phi_{1a} \) which according to the above is the heeling angle corresponding to the maximum stability arm, is therefore also called the statical critical heeling angle. We observe that the equilibrium of the vessel is at this point unstable, because the very smallest increase of the heeling moment brings the vessel to capsize.

If the vessel is heeled by a sudden constant moment \( M_{2a} < M_{1a} \), it intersects the stability curve at two points \( \phi_2 \) and \( \phi_3 \) (Fig. 7), and if the work done by this heeling moment between \( O \) and \( \phi_3 \) is of the same amount as the corresponding dynamical stability — i.e., if the areas drawn in Fig. 7 are equal — the vessel cannot stand against the sudden action of any greater constant heeling moment without capsizing. The angle \( \phi_4 \) is therefore called the critical dynamical heeling angle. We see that the equilibrium answering to the angle \( \phi_4 \) is stable and that answering to the angle \( \phi_3 \) unstable.

9. Pro-metacentric evolute. — This curve cannot be drawn immediately with the help of the stability arm curve. As the result of calculating the stability arm curve we obtain the course of the centre of buoyancy, the curve \( F_0 \) (Fig. 8). By using either the length \( h \) or \( NG \), which can both be measured or calculated from the stability arm curve, the line of action of the buoyancy answering to every heel can be drawn. By setting off from every centre of buoyancy in the direction of the action line the course \( c_0 \), whose length is obtained by means of the tangent construction (Fig. 4), the corresponding pro-metacentre can be set in its correct place (points \( M_{1a}, M_{1b} \) etc. in Fig. 8). By joining up these points the pro-metacentre evolute is obtained which, according to Bouguer's law, is the course of the curvature centre-points of the \( F \)-curve.

The pro-metacentre evolute is symmetrical on either side of the vessel's middle plane, and the part near its middle plane forms almost,
without exception, a cusp with its end directed either down or up. The
cusp in the evolute implies that the radius of curvature of the centre of
buoyancy curve has in the corresponding point either its maximum or
minimum; its maximum when the cusp is directed upwards, its minimum
when it is directed downwards. The evolute has generally near the
vessel’s middle plane altogether three or five cusps (Figs. 9a & b).

The shape of the pro-metacentre evolute depends only upon the
shape and draught of the vessel, i.e. every vessel has only one pro-meta-
centre evolute corresponding to the draught forward and aft. This curve
can therefore be utilized for investigating the influence of the position
of the vessel’s centre of gravity upon the amount of the vessel’s statical
critical heeling angle and of the range of stability.

§: 2. The Initial Transverse Metacentric Height as a Judging
Principle.

A vessel’s initial transverse metacentric height determines, according
to the above, the inclination which the stability arm curve has to the
φ-line at the origin. If a vessel’s metacentre remains in its place when
the vessel heels, which happens if the sides of the vessel are round and
the common central point of the circles lies on the middle plane of the
vessel, the moment of stability is

\[ M_a = D h = D c_v \sin \phi \]  

(10)

and the stability arm

\[ h = c_v \sin \phi \]  

(11)

and the initial transverse metacentric height then also determines the
magnitude of these stability factors. Then we have

\[ \frac{r}{I} = \text{constant} \]

and the curve for the centre of buoyancy is therefore a circle. Even
though the sides of the vessel should not be circular, the shifting
metacentre N (Fig. 1) does not vary very much, in slight heelings, say
between 5° and 10 degrees, from the \( M_a \)-point. The equations (10) and
(11) can thus generally be used for small angles of heel; the applica-
tion of this method will be called hereunder the metacentric method.

The initial transverse metacentric height thus determines in general
the amount of an upright vessel’s resistance against heeling moments; it
determines the vessel’s initial stiffness.

The greater a vessel’s initial transverse metacentric height, its initial
stiffness, is, the greater heeling moment is required for shifting the
vessel to any extent from its equilibrium position. The greater \( M_a \)
is, the stiffer the vessel is said to be for that reason; the less it is, the
cracker the vessel. When \( M_a = 0 \), even a small heeling moment
brings the vessel to heel considerably, and when \( M_a < 0 \), the vessel
has actually heeled to either side.

The initial metacentric height also determines the length of the vessel’s
period of complete double oscillation — the period of roll — within the
limits of small amplitudes. The period of roll is with great exactitude
inversely proportional to the square root of the metacentric height \( R \).
The greater thus \( M_a \) is, the quicker the vessel rolls.

The initial transverse metacentric height has further a great influence
on the vessel’s rolling among waves. When the initial stiffness of a vessel
is great, its period is small, and the vessel may often meet waves whose
period is the same as that of the vessel. A synchronism arises, which
may increase the vessel’s rolling amplitude dangerously. In a swell
a stiff vessel also strives with great power to keep her momentary
state of equilibrium, in which the vessel is then, when her middle plane
is normal to the wave profile; the vessel thus follows the motion of the
waves with great intensity. For that reason a stiff vessel tosses abruptly
in a heavy sea, whereas a crank ship rolls more easily. This phenomenon
is the reason for the use of the common expression in shipping circles
that a crank vessel is stable and a stiff one unstable, which habit may
easily lead non-experts astray.

The importance of the initial transverse metacentric height for the
phenomena explained above diminishes with an increasing heeling angle,
because then the influence of the other stability factors begins to be con-
siderable. When \( \phi > 5° \) to \( 10° \), the vessel’s stability arm curve no longer
connects with the curve (11); the real \( h \) is greater than \( c_v \cdot \sin \phi \), if the
pro-metacentric evolute is rising in the beginning (Fig. 9a), and smaller
than \( c_v \cdot \sin \phi \), if the evolute is falling (Fig. 9b). The latter case being
very rare, one may say that when using the metacentric method for
small heeling angles the error in general is small and negative, i.e. the
actual stability arm is longer than the one obtained by calculation.
This does not however hold good for the further heeling of the vessel, because
the stability arm curve obtained according to equation (11) very soon
moves over to the upper side of the real curve, so the error becomes
positive. The curve \( h = c_v \cdot \sin \phi \) does not reach its maximum point
until at \( 90° \) inclination, but the true stability arm curve stops from in-
creasing already very soon after the vessel’s deck has been immersed,
in vessels with low freeboards already at angles of about 20° to 30°. When the value of the heeling angle is higher than the actual $\phi_m$ we obtain, when using the metacentric method, absolutely erroneous results. Of errors caused by the method there are three instances given in Table 1.

<table>
<thead>
<tr>
<th>Heel. angle $\phi$</th>
<th>Ship A, $c_1 = 0.375 \text{ m}$</th>
<th>Ship B, $c_1 = 0.387 \text{ m}$</th>
<th>Ship C, $c_1 = 0.606 \text{ m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\phi_{m,1}$ sin $\phi$ m</td>
<td>$h$ m</td>
<td>Error $%$</td>
</tr>
<tr>
<td>2.5°</td>
<td>0.016 0.016</td>
<td>± 0  0</td>
<td>0.017 0.017</td>
</tr>
<tr>
<td>5°</td>
<td>0.033 0.033</td>
<td>± 0  0</td>
<td>0.034 0.034</td>
</tr>
<tr>
<td>7.5°</td>
<td>0.099 0.099</td>
<td>± 0  0</td>
<td>0.100 0.100</td>
</tr>
<tr>
<td>10°</td>
<td>0.165 0.164</td>
<td>± 0  0</td>
<td>0.166 0.166</td>
</tr>
<tr>
<td>12.5°</td>
<td>0.231 0.230</td>
<td>± 0  0</td>
<td>0.232 0.232</td>
</tr>
<tr>
<td>15°</td>
<td>0.297 0.291</td>
<td>± 0  0</td>
<td>0.307 0.306</td>
</tr>
<tr>
<td>20°</td>
<td>0.328 0.326</td>
<td>± 0  0</td>
<td>0.335 0.332</td>
</tr>
<tr>
<td>25°</td>
<td>0.359 0.355</td>
<td>± 0  0</td>
<td>0.366 0.362</td>
</tr>
<tr>
<td>30°</td>
<td>0.388 0.383</td>
<td>± 0  0</td>
<td>0.394 0.389</td>
</tr>
<tr>
<td>35°</td>
<td>0.415 0.410</td>
<td>± 0  0</td>
<td>0.421 0.414</td>
</tr>
<tr>
<td>40°</td>
<td>0.441 0.435</td>
<td>± 0  0</td>
<td>0.445 0.438</td>
</tr>
<tr>
<td>45°</td>
<td>0.465 0.459</td>
<td>± 0  0</td>
<td>0.468 0.462</td>
</tr>
</tbody>
</table>

The heeling angles $\phi_{m,1}$ corresponding to the maximum stability arm of the vessels are in vessel A about 27°, in vessel B appr. 28°, and in vessel C about 57°, the capsizing angles $\phi_{m,2}$ being respectively 52.5°, about 55° and about 105°. From the table it is evident that in using the metacentric method one may commit very remarkable errors already when the heeling angle is 5° only. The percentage of error varies so much and, depending upon the shape of the vessel, so indeterminately that the method cannot be used — at any rate in regard to small vessels — except within the limits of very small angles. The solving of such problems where heeling angles above 10° come into question cannot be done by the metacentric method, in spite of 1. a. HERNER having done so in a couple of instances in his work [H 4; pages 128—129]. ENGSTRÖM has applied the metacentric method in connection with one of his lectures, although the result obtained was a heel exceeding 42° [E 3]. This is of course absolutely erroneous, as was also quite correctly remarked in the discussion following upon the lecture and also later on [S 2]. As a similar error was made in Finland, when examining the case of the fleet tug B 2, by a technical expert, this circumstance must be emphasized.

The period of roll of a vessel also begins at great angles of inclination to become dependent on other stability factors than the initial metacentric height. The period varies to a remarkable extent, particularly depending upon the form of the stability arm curve. If, for instance, the curve for the centre of buoyancy is a parabola and the initial metacentric height is very small, the period can be — with an amplitude of 30° — about 1.45 times larger than when the rolling amplitude is small [R 9].

In spite of the limitations set forth above, the habit of applying the initial metacentric height as the principle for judging a vessel’s minimum stability is not only the oldest one but — even still — the most general one. The value of this method will be best explained by presenting several instances collected from literature, of different proposals whose object is to determine the minimum amount of stability by using the initial metacentric height as factor.

The initial metacentric height having to be smaller or greater depending upon the vessel’s other stability factors, these factors must in some way be taken into account when determining limit values. This may be done either by dividing the vessels into such classes, in which the relation of the vessels’ main dimensions, the height of the freeboard, the relations of fineness, etc., remain within reasonably narrow limits, or by forming equations for the said limit values, in which the other stability factors also appear. If one endeavours to determine some absolute, numerical minimum values for the initial metacentric height, the type of vessel must without fail be mentioned in connection with such numerical value.

A comparatively uniform type of vessel with regard to its relative dimensions, and for that reason a suitable one as an example, is the ocean-going passenger liner. The exchange of opinions, which has been carried on regarding the amount of the initial metacentric height during the last decades in America, England and Germany, illustrates so well the difficulties of determining the minimum value of the initial metacentric height that it is worth the trouble to look into these opinions.

In the beginning of this century rather small values for the initial metacentric height were used in the large passenger liners. According to SCHMIDT, the $M_G$ values for instance in the Cunard liners were 0.5—0.6 m, when the vessels were loaded [S 3], which gave the vessels an easy roll among waves. Most investigators consider 0.35 m (1 Engl. foot) to be a satisfactory minimum for an ocean-going passenger liner in light condition; such opinions have been pronounced for instance by BLAS and WELCH in 1922 [A 8] [R 7] and HØGVAARD [H 11], the latter however proposing that, in the event of the length of the vessel exceeding 150 m, $M_G$ should be at least 0.6 m. The proposed value
particularly in examining accidents that have happened to vessels carrying deck cargoes of timber. The proposals made differ extremely from one another. LEMKE proposes as minimum for ordinary vessels, depending upon the season and the types, 0.08—0.22 m and for turret-deck vessels 0.30—0.37 m [L 2], while other investigators again demand for all vessels 0.2—0.3 m for the $M_G$ [S 19] [S 23]. The freight vessels' abrupt movements not being attended with such inconveniences as in passenger vessels, the principle 'better too stiff than too crank' has been approved rather generally [H 3] [C 3]. For the same reason one has begun to shun a negative initial stability for vessels in light condition.

This is borne upon i. a. in the statutes for passenger vessels of certain countries. The most severe proposal is probably the one made by NIEDERMANN and according to it the distance between the transverse bulkheads of vessels should be determined on such a principle that not even a damaged vessel could have a negative initial stability [N 1]. One does not generally fear an excessive stiffness in freight vessels so much as in the case of passenger ships. An exception in this respect may be vessels carrying heavy cargoes such as ore, whose stability may easily become so great that the construction of the hull may suffer in a heavy sea. RUDICH has drawn attention to this circumstance and proposed that a part of this kind of cargo should be loaded 'ween-deck' [R 6]. There is naturally a limit to an excessive increase of the stability. FOERSTER lays stress upon that a disproportionately great initial stability combined with a low freeboard can, if the vessel is flush-decked, even cause the vessel to capsize [F 4]. The smaller a vessel is, the more uncertain it is to determine the minimum value of its initial metacentric height. The already ignorance of the influence of the main dimensions' diminution adds to this uncertainty. It was indicated above that the initial metacentric height in large passenger liners should be greater than in small ones [H 11] [J 3]. The same is held in view by a linearity-rotation sometimes set forth, according to which $M_G$ might also change linearly with altered main dimensions. It may nevertheless be asserted, as i. a. FOERSTER has done, that it is almost self-evident that, if the displacement is greater, the minimum values for the stability factors may be lower, as the moment of stability is the product of the displacement and the stability arm [F 4]; to these stability factors the height of the initial metacentre also belongs. It is really self-evident that this opinion holds good when the difference between the displacements of the vessels to be compared is very great. For instance, the zero value of $M_G$ not to mention its becoming negative, cannot be allowed for small vessels; this is rendered impossible
already by the fact that small vessels are very susceptible to the influence of wave motion.

It is not to be wondered at, in view of what is mentioned above, that a good many quite different opinions on the minimum limit for the initial stability of small vessels have been expressed. For instance J. H. Fuerstenberg gives as the minimum value of $M_G$ for fishing and smaller vessels approximately 0.7—0.8 m [3, page 462]. Nevertheless the $M_G$ values 0.7—0.9 m obtained in the investigations on the German fishing boats were considered very high [S 31]. On the whaler Rau III having capsized, when performing turning trials in 1937, the authorities did not criticize the height 0.29 m of its sister ship Rau I’s metacentre, and they would probably also have been satisfied with the value of Rau III’s $M_G$, if it had only been of the same size (Ex. 29). The cause of the passenger steamer Negros capsizing was held to be too small a range of stability rather than a low initial metacentric height, although this was only 0.265 m (Ex. 16). This would seem to spring therefrom that it is not desirable to fix the initial metacentric height of small vessels too great, when their other stability qualities are known and when these are sufficient to warrant the safety of the vessel. Actually only when $M_G$ is the sole foundation for judging, and if the vessel’s freeboard is low in proportion, there is a warrant for making the initial stability comparatively great for safety’s sake.

This also applies to such tugs as have to navigate in the open sea. About 0.6—0.9 m for the $M_G$ is held to be suitable for that type, provided the height of the freeboard is normal [R 12] [3]. If the tug works in port only, the initial metacentric height may be lower, about 0.3—0.45 m [R 12; page 61—62]. On account of such accidents as have occurred in our country to a couple of boats of this type, the author has made studies whose results with regard to the $M_G$ values also will be given later on.

In view of the great variation of the initial metacentric height value, and the great difference in the opinions regarding its adequate size, it is natural that the whole method of judging a vessel’s minimum stability on the basis of the $M_G$ has been seriously opposed and considered to be dangerous. Already the capsizing of the Captain in 1879 (Ex. 1) tended to give a beginning to this opposition, and the investigation made in connection with the loss of the German fishing boats in 1902—03 (Ex. 4) gave support to it. On being informed of the results of the investigations regarding the fishing boats, Germanischer Lloyd stated i. a. that the high values of the $M_G$ for these boats give reason for believing that the stability of the boats would fulfill even high demands, and further, that this opinion

has a wide spread, and that it nevertheless does not hold good [S 31]. In conformity with this statement, Germanischer Lloyd has long on declared in its rules for judging the stability of a vessel [G 4] that the initial metacentric height is absolutely insufficient for this purpose. Of value is also the statement made by the commission appointed by the XI German Shipping Meeting in 1924, according to which the knowledge of the $M_G$ value is not sufficient in all instances for judging the stability.

The use of the initial metacentric height as a judging principle may have somewhat better qualifications, if in determining the minimum amount of the $M_G$ other factors influencing the stability are also taken into account. This may be done, as stated above, by working out an equation to suit the purpose.

As far as known, Anderson was the first to propose the use of such an equation, at the conference of the I. N. A. in 1923 [A 8]. The equation he has worked out for big passenger liners is:

$$e_0 = \frac{0.213}{\delta} \frac{F_i}{F_1} \text{ metres.} \quad (12)$$

In the equation $F_i$ is the vessel’s wind surface, $F_1$ is lateral surface, i. e. the surface area of the side projection of its submerged part and $\delta$ is block-coefficient of the vessel. The equation is obviously based upon the wind pressure and the size of the heeling angle caused thereby; in it the form of the ship thus is taken in very small consideration, and the beam not at all. Even Hillhouse referred to the latter circumstance, having also examined into the adaptability of the formula and observed that it has not always led to approvable values of $M_G$. — The equation is obviously not suited for the small passenger ships navigating on our inner waters. The relation $F_i/F_1$ is very great in our ships on the lakes, about 2.5—3.0, and the block coefficient again small, much smaller than in big sea-going liners. By using the equation the minimum $M_G$ would regularly become longer than one metre, up to 1.4 m. Such values are far too great. By changing the coefficient it might be possible to use it even in our conditions.

An equation in which appear both the beam and the depth of a vessel appeared in 1925.\(^1\) Its form is:

$$e_0 = k_B b - k_H d. \quad (13)$$

For the coefficient $k_1$ the value 0.43 is given and for the coefficient $k_2$ values that, depending upon the loading conditions and types of the

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\(^1\) Torgowy Flot 1925, page 485.
vessels, vary between 0.5 and 0.72. These values for the constant coefficients do not suit our conditions. Besides this, the equation has the fault that the freeboard does not appear therein, though that is of far greater importance to the stability than the depth.

An interesting calculating method based mainly on the use of the initial transverse metacentric height has been presented by Holt at the meeting of the I. N. A. in 1925 [H 7]. It is shown in the proposal how one can count the minimum and maximum values for a known vessel's initial stability on the basis that the heeling angle brought about by wind and waves must not become too great. As the result of the calculation a curve table is obtained, in which the said values appear as functions of the vessel's draught, and by its help one can easily judge for instance the influence of different loading conditions on the vessel's stability and seaworthiness. However, as the reckonings are slow and troublesome, this method can hardly become very common. Besides, these calculations also requiring the use of stability curves, the method does not belong to those by means of which one would endeavouer to determine the minimum stability of a vessel, solely on the basis of the initial metacentric height.

A simple form of equation for the minimum stability has been given by Dahlmann [D 1]:

\[ c_v \text{ min.} = c_v (1 + \frac{k}{F}) \]  \hspace{1cm} (14)

In the equation \( c_v \) is such a constant value for the initial transverse metacentric height that suits the type of vessel concerned, and \( k \) a coefficient depending upon the freeboard \( F \) and approaching zero when \( F \) increases and approaches some fixed limit value. The co-relation between \( F \) and \( k \) must be determined by experiment. The equation appears to be theoretically fit for use, provided however that when choosing the constant value \( c_v \) for the \( M_vG \) the beam and other factors acting upon the stability are taken into consideration. This circumstance naturally affects the use of the equation, and also the fact that the law \( k = f(F) \) is not known. Some other method would be required by means of which these difficulties could be removed; as soon as this were done, the equation might be used with benefit.

The method proposed by Blagoveshchensky for judging the vessel's minimum stability on the basis of the initial stability is may be the most complete one published\(^{1}\). The essence of this judging method is the use of a certain safety coefficient \( k \); it is determined by the equation

\[ \frac{D h_m = k \cdot \Sigma M_s}{(15)} \]

where \( \Sigma M_s \) is the sum of the heeling moments calculated on the basis of the constructed vessels and \( h_m \) the maximum stability arm of the vessel. The amount of the coefficient \( k \) depends on the displacement, the course of the stability arm curve, its largest ordinate, capsizing angle, etc., and it must be determined by experience. According to the studies of the inventor of the method the \( k \) of a vessel with good stability must lie between

\[ 3.0 > k > 2.5. \]

A vessel is crank, if

\[ 1.5 > k > 1.0. \]

If the angle answering to the longest stability arm \( h_m \) the statical critical heeling angle \( \varphi_n \) is known, then, according to Figs. 1 & 2 (page 8),

\[ D h_m = D (FPL_m - a_0 \sin \varphi_n), \]

and with the help of the equation (15) \( a_0 \)-value is found, which at the same time is the maximum allowed value of \( a_0 \):

\[ a_0 = \frac{D \cdot FPL_m - k \cdot \Sigma M_s}{D \sin \varphi_n}. \]

The minimum metacentric height is accordingly

\[ c_v \text{ min.} = r_v = \frac{D \cdot FPL_m - k \cdot \Sigma M_s}{D \sin \varphi_n}. \]  \hspace{1cm} (16)

The method seems at the first glance to be very simple and clear, but on studying it more in detail we find that it is rather troublesome to use it. First of all, one must know the vessel's stability curve for an exact determination of the angle \( \varphi_n \) and the length \( FPL_m \). The method is therefore not a pure initial metacentric method, as one might believe on the basis of equation (16). The fact that it is absolutely indispensable to know the stability curve, can be indirectly ascertained by examining those other possibilities that exist in determining the right hand factors of equation (16).

One may think that the said factors might be calculated with the help of the initial metacentric method. Then the heeling angle at which \( h_m \) and \( FPL_m \) attain their maxima, would be \( 90^\circ \); \( FPL_m \) would obtain the value \( r_v \) and the equation (16) be modified to the form

\[ c_v \text{ min.} = \frac{k \cdot \Sigma M_s}{D}. \]
This value would all the same be far too small, if one might wish to use amounts for the above mentioned safety factors. Besides, no regard would have been paid to the different ranges of stability of the various vessels, which in itself alone renders impossible such a wide use of the initial metacentric method.

Even that thought is possible that the angle \( \varphi_{\infty} \) be judged on the basis of the moment when the edge of the deck is pressed to the water, and the other right hand factors of equation (16) be calculated by the initial metacentric method. It would follow that

\[
F_0 L_m = \tau_0 \sin \varphi_{\infty}
\]

according to which

\[
e_0 \min. = \frac{D \tau_0 \sin \varphi_{\infty} - k \Sigma M_5}{D \sin \varphi_{\infty}}
\]

or

\[
e_0 \min. = \frac{k \Sigma M_5}{D \sin \varphi_{\infty}}
\]

This equation could naturally also have been obtained direct from equation (15) by adapting its left hand side according to the metacentric method. The fact that the creator of the method in question has formed equation (16), proves accordingly clearly that he has also thought of using the stability arm curve. This is also indispensable, because the adaptation of the metacentric method to such wide angles as are here concerned is impossible (see table 1).

Thus one observes that this method has only then any significance when both the angle \( \varphi_{\infty} \) and the lengths \( F_0 L_m \) and \( h_5 \) are determined with the help of the stability arm curve and the curve table of the vessel.

Thus we obtain first of all for the length \( a_0 \), its correct value corresponding to the true safety coefficient \( k \).

By writing

\[
e_0 = \tau_0 - a_0
\]

we transfer, by using the value of the initial metacentric radius to be measured from the curve table of the vessel, from length \( GF_0 = a_0 \) to the initial metacentric height, which thus also corresponds to the size of the chosen safety coefficient.

This is explained by Fig. 10, which has been drawn according to the values of vessel A presented above in table 1. Point \( N_{\infty} \), the shifting metacentre, may naturally, depending upon the form of the stability curve, lie either below or above the initial metacentre \( M_c \).

It is easily seen how inconvenient the use of the method in question is. First of all, the stability arm curve for the vessel is to be drawn and its greatest ordinate measured as well as the angle corresponding thereto. Then the sum of the vessel's heeling moments just at this angle has to be determined, a calculating method for the execution of which there are no simplifying means in connection with this method. When these values and the \( e_0 \) corresponding to the stability arm curve used have been inserted in equation (16), we find the size of the safety coefficient \( h_5 \). In case this is not sufficient, we must seek for such values corresponding to one another of \( e_0 \), \( h_5 \), \( F_0 L_m \) and \( \tau_0 \) as increase the safety coefficient sufficiently. If the value of \( \varphi_{\infty} \) also is changed thereby, the sum of the heeling moments must also be calculated anew. — Besides the inconvenient calculating method, a deficiency in the procedure is the purely statical solving of the minimum stability problem. The fact that the dynamical force influences are completely set aside, can naturally be remedied by giving the safety coefficient a sufficient size. Nevertheless it appears that, when once one devotes so much work to judge the stability, one might also take into account the influence of the dynamical phenomena into account.

The draft for the regulations to govern the stability of new passenger vessels, which the Special Committee on Stability and Loading, a sub-committee of the American Marine Standards Committee, made out in 1928, was also based mainly on the determining of the initial metacentric height [D 7] [A 10]. In spite of this proposal having been turned down, as stated above, there is reason to pay attention to it as the official result of four years of study. The points in the proposal that have to do with the determining of the initial stability will be briefly treated here below.

The proposed statute, according to which the stability conditions of new passenger ships were to be regulated, determined the amount of the minimum initial stability so that the following conditions should be complied with:

1. The initial metacentric height of a double-bottomed vessel in the light-ship condition must be at least positive. If the vessel has no double bottom, the \( M_c G \) in the light-ship condition must be at least 6 inches (0.152 m).

2. The initial stability must be so great that the vessel in a steady beam wind does not heel over more than that one half of its specialty
determined so-called reserve freeboard \( F \) is immersed, and not more than \( \gamma \). According to the statute, this condition is fulfilled if the initial metacentric height is at least

\[
e_0 \min = \frac{kF}{kB} D F^2 \tag{17}
\]

where \( F \) is the vessel's wind-surface, \( b \) the vertical distance from the centre of gravity of the wind-surface to one-half of the mean draught, \( B \) the moulded beam measured at the load line, \( D \) the displacement and \( k \) the coefficient indicating the wind-pressure. As the units of measure are here taken, as well as in equations (18) and (19), the English inch, square foot, cubic foot and long ton (=1016 kg). The vessels are divided, for the purpose of determining the wind-pressure, and depending upon the fairways, in the following three groups:

Group I: ocean and coastwise (assumed open fetch 600 miles);

Group II: partially protected waters (assumed open fetch 200 miles);

Group III: smooth and protected waters, such as rivers, ports, etc.

For the speed of the wind have been assumed in the various groups 55, 45 and 37 miles per hour, equalling 24.6, 20.1 and 16.5 m/mr. per second. The wind-pressure is set dependent, besides these speeds, also of the length of the vessel, so that \( k \) has in the different groups the following values:

Group I: \( k = 0.005 + \frac{L^2}{200,000,000} \);

Group II: \( k = 0.0033 + \frac{L^2}{200,000,000} \);

Group III: \( k = 0.0025 + \frac{L^2}{200,000,000} \);

The allowed maximum angle \( \gamma \) is observed by not allowing any higher value for \( F \) in the equation than 0.246. Also, if \( F_e \) is the freeboard measured to the weather deck, \( F \) must not exceed 4 (\( F_e = 1 \)).

3. The initial stability must be so great that the vessel heels when the passengers crowd to one side of the vessel not more than that one half of the reserve freeboard is immersed, and not more than \( \gamma \). According to the statute, this condition is fulfilled, when the initial metacentric height is at least

\[
e_0 \min = 0.005 MB \tag{18}
\]

where \( M \) is the sum of the moments of the centre line of the vessel, in feet\(^3\), of the specially determined net passenger-deck areas on one side of the vessel. The coefficient 0.005 is determined on the basis of the deck surface required by one passenger and the personal weight. Even here certain minimum values have been set for \( F \); so that the healing angle of \( \gamma \) may not be exceeded, \( F \) must not be greater than 0.123 \( B \) and not greater than 2 (\( F_e = 1 \)).

4. The initial stability must be so great that the vessel will heel in the event of flooding two adjacent compartments on one side of the vessel in the most unfavourable position, not more than that one half of the reserve freeboard is immersed, and not more than \( \gamma \). The condition is fulfilled in the event of the initial metacentric height being

\[
e_0 \min = \frac{B \sin \phi + F_{w} m}{F (\mu D + w)} \tag{19}
\]

where \( m \) is the aggregate capacity, in cubic feet, of the compartments to be flooded, \( d \) the distance of the centre of gravity of those compartments from the centre line of the vessel, in feet, \( \mu \) the transverse moment of inertia of the compartments about an axis passing through the centre of gravity of the free surface and parallel to the centre line of the vessel, in feet\(^4\), and \( \mu = 35 \) for salt water, and 35.9 for fresh water. The maximum value allowed for \( F \) is here also 0.123 \( B \) and 2 (\( F_e = 1 \)).

5. The initial stability must be such as will not give the vessel a period of roll which will be liable to synchronize with the period of the waves likely to be met in such waters as are to be sailed by it. It may be mentioned that the minimum complete periods to be recommended are in group I about 10 seconds and in group II about 7 seconds. There is no limit in group III. It being possible that, according to the minimum value equations for \( M, G \), the initial stability becomes too great in view of the rolling of the vessel, a possibility is left for allowances on special request.

If the form of the vessel is such that the actual value of the stability arm at the angle corresponding to that of the required \( M, G \) by the formula is appreciably greater than the product \( e_0 \cdot \sin \phi \), then, according to the proposed statute, a correction may be made in fixing the initial \( M, G \) required, i.e. the initial stability may here be lower than the minimum equations for \( M, G \) indicate.

The greatest imperfection of the proposal is no doubt that it is only restricted to determining the vessel's initial stability limits. This causes all the disadvantages already set forth. The second deficiency is that one has been forced to limit the allowed heeling angle to so small
as \( \gamma \) — the use of the metacentric method for greater heeling angles would also be impossible —; for this reason the \( M_G \) value may easily become so great that the rolling of the vessel will be very abrupt. This possibility has also been observed by the proposers, because the allowing of modifications regarding the minimum value of the initial metacentric height has been mentioned in the proposal. Such allowances also being possible in vessels whose stability arm curve rises very rapidly to begin with, the rightful application of the proposed statute would be very inconvenient and difficult. By this method it should be impossible to obtain such a certainty as would be possible by taking other stability factors, than the initial stability, also into account.

Such possibilities have been explained above, which are offered by the use of the vessel's initial metacentric height in determining the amount of the stability. The author has considered it necessary to treat this matter in particular detail, because in our country it is the custom to use this foundation for judging almost exclusively. From the explanation given, it is first of all evident that it is impossible to form exact conclusions on the sufficiency of the stability solely with the help of the \( M_G \) amount. Most of the proposed minimum value equations for \( M_G \) again contain such constants whose selection demands a lot of comparing material and experience. The more elaborate of the judging methods set forth are very complicated and inconvenient to use and a presupposition for them is also the knowledge of the vessel's stability curve, for which reason they actually are not methods based upon the initial metacentric height at all. The determination of the initial stability according to the American proposed statute is finally, besides insufficient, also difficult to apply.

One may state therefore that the judging of a vessel's stability on the basis of the initial metacentric height is insufficient and can easily lead astray, or, if as a method a complete one be chosen, be so laborious that the extending of the judging principles to comprise other stability factors as well may even be possible without adding to the calculating work.

\[ \text{§ 3. The Main Dimensions of a Vessel as Judging Principles.} \]

The custom of using the main dimensions of a vessel for judging its stability qualities is a very old one, but all the same not so universal and favourable as the one set forth in the above paragraph. The reasons for this will be evident from the following.

The dependence of the vessel's initial stability moment of the main dimensions can be examined by starting from the expression (10) for the stability of a round-sided vessel (page 22) and writing it as follows:

\[ M = D T \gamma \sin \varphi - D a G \sin \varphi. \quad (20) \]

Of the right hand terms of the equation, the first is known as the surface stability moment and the second is called the weight stability moment. In accordance with the laws of Archimedes and Bouguer, the equation can be brought to the following form:

\[ M = L B T \left( a T \right) \gamma \sin \varphi \quad (21) \]

and

\[ M = L B T a G \sin \varphi - L B T a G \delta \gamma \sin \varphi. \quad (22) \]

In the equations, \( i_T \) is the transverse radius of inertia of the water line surface, i.e., a measure belonging to the beam measures of the vessel; it is determined: \( F_{yy} \cdot i_T^2 = I \).

On the basis of equation (21) one can decide that, provided the block and water-line coefficients and the forms of the hull and water line remain the same,

then, with increasing length measurements of the vessel, the initial stability moment grows proportionally to length measures, and that with increasing beam measurements of the vessel, the initial surface stability grows proportionally to the cube of the beam measurements.

From equation (22) we see that

with increasing draught measure the surface stability moment does not change, and that the weight stability moment either grows or is lessened, i.e., the initial stability moment is reduced or increased depending upon the change in the product \( T a_G \).

To the last observation must be added that an increase of the vessel's draught measures naturally lowers the centre of gravity both of the displacement and the vessel. The quantity of the vessel's cargo, its location and size depend upon whether \( G \) falls more or less than \( F \), and further, whether \( a_G \) is reduced as much in proportion as \( T \) grows. As a diminution of \( a_G \), if it appears at all, can seldom be as great in proportion as the growth of \( T \), an addition to the draught measures may be generally said to bring about a reduction of the initial stability moment.

As thus the influences of the beam and the draught upon the initial stability are in general opposed to one another, the relation \( B/T \) is particularly suitable for judging the stability of an upright vessel. For that reason, the effect of this relation upon the stability has been extensively studied. In these studies, such as made by Liddell [L 3],
From the table it is evident the very great importance of the freeboard both for the statical and dynamical stability. The height of the freeboard being at the same time an indication of any possible overloading of the vessel, it is clear that it is of a vessel’s main dimensions the first — and so far the only one — whose minimum value it has been considered indispensable to determine. The minimum value of the freeboard having been determined the relation $B/H = B/T - F$ is a very good foundation for judging the stability, because with its help one obtains an idea both of the vessel’s initial stability and of the other stability factors. Other investigators as well have emphasized the significance of the said relation for a vessel’s stability, i. a. MONTGOMERIE [M 5], SCHRÖDER [S 6], T. B. ARELL [A 1] and WESTCOTT ARELL [A 2], and it has also been admitted, according to FOSTER KING [P 3], in the report of the first loadline committee in England in 1885, that in preparing loadline tables it has been assumed that the relation $B/H$ is such as to ensure safety at sea with the freeboard assigned when the vessel is laden with homogeneous cargo; for vessels of less relative breadth the freeboard shall be so increased as to provide a sufficient range of stability. The proposal contains the idea that, in the event of any value for $B/H$ less than the one assumed, once $F$ is determined, either $B$ must be too small or $T$ too great; either of them brings about that the vessel’s initial stability is less than that assumed, for which reason the range of stability and other stability factors must be increased by adding to the freeboard. The same idea is the principle for the proposal, which the Institution of Naval Architects made in 1870 to the British Parliament, and according to which the freeboard in general should be $1/8$th of the breadth [A 2; page 137].

Neither the use of the main dimensions or of their relations as judging principles for the stability has, however, ever become particularly popular, and i. a. from the loadline rules all references even to the main dimensions have been left out. The judging method in question has even been publicly opposed. When, for instance, SØRENSEN and SCHRÖDER in the journal Hansa discussed the question as to which of a vessel’s main dimensions should be taken into account when judging the sufficiency of the stability in timber-carrying freight vessels [S 6], BENJAMIN took part in the exchange of opinions, opposing in general the adaptation of such a method of judging [B 9]. He referred to the importance of working out the moment calculation and said that every method which is shorter and simpler than it, is unreliable and dangerous. This statement, which at first sight would appear somewhat vague, nevertheless contains a very remarkable truth: when using the vessel’s main dimensions as

<table>
<thead>
<tr>
<th>Main dimensions</th>
<th>Increase of</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L, H, B + 13.8%$</td>
<td>92 % 0 % 89 % 24 %</td>
</tr>
<tr>
<td>$L, B, H + 25.4%$</td>
<td>0 % 125 % 231 % 124 %</td>
</tr>
</tbody>
</table>
principle for judging the vessel's stability, one leaves altogether out of account the position of the vessel's centre of gravity $G$ in relation to the centre of buoyancy $F$, forgetting that in the stability moment equation there appears, besides the main dimensions, a very important factor with them the length $a_0$. The error is the same as one would commit, if one were to judge the vessel's initial stability solely on the basis of the surface stability moment, the first term of the right hand side in equation (20) (page 37). It is clear that this is not enough; the vessel's centre of gravity and its influence must in some way also be taken into account.

It must be assumed that they that made such a proposal, according to which one would guarantee the sufficiency of the vessel's stability by the size-relation of the main dimensions, hold that the distribution of the vessel's cargo in proper places should be left to the master's responsibility. The cargo and passengers may however be located on a vessel in many such manners that cannot actually be called wrong or faulty, and the effect upon the stability of such manners of loading must be possible to judge. Although therefore the main dimensions would fulfill the demands placed upon them, one would nevertheless require some other judging method by which one can determine the effect of placing the weights.

It must also be remembered that as a vessel's main dimensions are not generally altered after the completion of the vessel, the method in question is only suitable for use when designing the ship.

In regard to our conditions, the importance of the method is still less. As we shall see later on, the reason for accidents that have occurred on our waters has often been the overloading of vessels. The prevention of this is, together with the solution of the ballast question, a very important circumstance in the endeavour to limit the number of accidents. The determining of the maximum load and necessary ballast cannot be done with the help of the vessel's main dimensions only, and therefore this method of judging is insufficient for the purpose of the present investigation.


The graphical representative of the equation $GH = h = f(q)$, the vessel's stability arm curve, evidences, as stated in the first paragraph of this chapter, the dependency between the heeling angle and the statical stability moment also, provided a second division be added to the ordinate axis. For that reason, all that has been said in the following treatment of the stability arm curves as judging principles for the stability may be applied to the stability moment curves as well; but in speaking of the length of the ordinates of the curves the amount of the vessel's displacement must even be taken into account. From both curves one can read direct the size of the angle of maximum stability $\varphi_{\max}$, the value of the maximum stability arm — or stability moment — corresponding thereto, and the capsizing angle. Indirectly one can measure from the curves the other stability factors as well, such as the initial metacentric height, moment of dynamical stability, etc.

The use of the stability curves for judging stability was first suggested by Reed at the meeting of the I. N. A. in 1868, in a paper read by him [R 13], but their usefulness was made clearer only two years later in the studying of the Captain's capsizing (Ex. 1). Then, when later on, the stability curves were used in Germany in studying the many losses of fishing vessels in the winter 1902—03 (Ex. 21), one would have thought that the drawing of stability curves when building new ships would subsequently become more general, but that did not happen. First in 1922 did the See-Berufsgenossenschaft in Germany send a circular to the shipyards, using the discussions and resolutions of the shipping meeting of 1919 as their guide, in which the yards were invited to draw out the stability curves for new ships, calculated to correspond to different loading conditions, and to hand the curves to the masters of the vessels; in the circular were enclosed comparing curves for some vessels with good sailing qualities [J 1]. At about the same time Germanischer Lloyd published rules for judging the stability of a vessel with the help of stability arm curves [G 4]. A very great uncertainty, regarding the usefulness of this judging basis and its best manner of application, nevertheless prevailed at the time among experts. This is well illustrated by the discussion which arose in consequence of a lecture held by Johns on the steps taken by See-Berufsgenossenschaft and Germanischer Lloyd [J 1]. The lecturer himself wished to amplify the judging of stability i.a. by instituting inclining experiments, but otherwise considered the method recommended by See-Berufsgenossenschaft good, in the same way as Pagel. The comparing of different vessels with one another was, on the other hand, held to be fateful by Foerster, and he held that the use of such tables and groups of curves would be better, with the help of which one could draw the stability curves corresponding to every displacement and loading condition on the vessel itself. Neither was it sufficient in the opinion of Commentz that the building yard should draw the complete stability curves corresponding to different loading conditions. In spite of these oppositions met by the proposal, a clause
was soon added to the rules for preventing accidents at sea issued by
See-Berufsgenossenschaft [5 15], clause 5 in the present rules, according
to which the shipyards are required to draw the stability curves for
different loading conditions and to hand them to the master. As it is
forbidden in the same rules to load down to the load water line, if the
stability of the vessel is not sufficient, it is natural that the master is
assumed just to use the stability arm curve when judging the stability.
In German law, in the statute on safety appliances for passenger ships
[V 1], there is now also a rule to the effect that data on the stability of
passenger ships must be given to the master, but in the word used in the
statute — "Stabilitätsunterlagen" — it is not expressly stated that the
data must be in the form of stability curves. However, it is probable
—and that is also aimed at by the above rule of Germanischer Lloyd —
that in Germany — and in English also — just the stability arm curve
is used for this purpose. In small countries, however, the drawing of
these curves has as yet not come into regular practice, except for building
more important vessels.

Although the increasing generalizing of the use of the stability curves
is very certain, and although it even represents a remarkable progress
in the endeavour to increase the safety of ships, the question of the
stability of vessels has hereby by no means become solved. The
difficulty lies therein that there has not been available any certain stand-
ard gauge by which one might be able to say unhesitatingly whether the
determined stability curve is sufficient for any vessel navigating in
any known conditions or not. There have, it is true, been presented
various standard gauges, different kinds of minimum curves and points
of such curves, but not one of them has been generally accepted in
practice. The great differences in opinions become evident when com-
paring the suggestions made. The comparison will be made in the
following, first by presenting a group of different typical curves and
then by examining in detail, how scientists, courts et sim. have on
various occasions expressed themselves on the minimum value of the
angle at which the stability arm attains its maximum value, the stability
arms and the capsize angle.

In Germany, the first to suggest the adapting of a determinate
minimum stability curve was Benjamin in 1913 [B 8]. In his opinion
the minimum limits should not depend upon the stability arm, but on the
dynamical lever curve, for which reason the suggestion will be
expounded in detail in § 6 of this chapter; but nevertheless, as the latter
curve is the integral curve of the former, the determining of the
dynamical curve also implies the verification of the statical one; and thus
also the minimum stability curve would indirectly have come into use
through the suggestion made. If Benjamin's curve is differentiated, we
obtain the curve A shown in Fig. 11, which according to its proposer
should be a minimum curve for all vessels.5) In England a certain
standard form of a stability arm curve has been in frequent use
when planning freight vessels, the arm values corresponding to heeling
angles of 30° and 45° degrees being according to Jowh-foerster
0.250 m [J 3], according to Commentz 0.245 [C 4], and the range
of the stability 70° (Fig. 11, curve B). The difference of the curves A
and B not being very great, Benjamin has been of the opinion, in a
discussion following upon a lecture held by Schwarz in 1927, that his
standard curve (curve A) proposed in 1913 has been the model upon
which the English had built when choosing for themselves some kind
of standard curve (curve B) [S 8]. All the same, Benjamin doubts the
generality of curve B, as he has come to the conclusion, on the basis of
material collected by him, that the stability curve of most freighters do
not differ much from the most unfavourable curve C, and yet the vessels
have finished their journeys successfully. All these three curves lie
far below the one presented by Jowh-foerster [J 3] as a kind of
standard curve for cargo vessels (Fig. 11, curve D).

Benjamin's above mentioned assumption does not hold good at all.
England's standard curve is far older than the one proposed by Benjamin
in 1913. In all probability the coming into use of the English curve
rests upon A. Denney's lecture "On the Practical Application of Stability
Calculations" [D 8], which was held at the meeting of the I. N. A. in
1887 already. In his lecture Denney quoted from the "Technical Qualities
Books", which was prepared from the year 1884 onwards for vessels
built in his yard and which contains several curves intended to be used

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5) Benjamin to begin with proposed the adaptation of the minimum value
of two points of the dynamical lever curve, but later he spoke of the whole
minimum curve.
by the officers of vessels. In the book, which to begin with was started under the supervision of the lecturer's brother, William Denny, there are i. a. various diagrams with the help of which one can measure the quantity of a sufficient ballast, provided the cargo is homogeneous, and when changing the space of cargo and quantity of coals. As the basis for all drawings was taken the assumption that a steamer never has less than 0.8 feet (= 0.244 m) metacentric height and 0.8 feet stability arm at a heel of 30 and 45 degrees. For these assumptions, which were mentioned in a couple of points of the lecture, no reasons were given at all.

In the discussion following the lecture, i. a. a certain L. Benjamin took part. If this individual was the same as that L. Benjamin, who in 1913 made the above mentioned proposal for a standard curve, his opinion expressed in 1927 on the birth of the English standard curve comes into a very peculiar light. — When A. Denny (ennobled Sir Archibald Denny) still later (in Rome in 1935) stated regarding the rule taken into use by his late brother, that it was no rule at all, only an idea [P 3], the origin of the English standard curve would seem to be fully explained.

In the rule of Germanischer Lloyd for judging the stability, already mentioned [G 4], it is said that conclusions regarding the amount of the stability are to be drawn by comparing the stability curves of vessels with those of vessels that have navigated the same kinds of water successfully, but no comparing material is annexed to the rules. When speaking of what influence a freight vessel's cargo has upon the shape of the stability curve, a sketch is given in the instruction (Fig. 12) which is presented here. When for instance comparing the curve-pair III with curve B in Fig. 11 — the English standard curve — we find that the English one is far more favourable. Germanischer Lloyd, however, does not want to pronounce any opinion on the curves it gives, which must probably be interpreted so that in the opinion of Germanischer Lloyd the approval of any universal minimum curve is not possible at all, or at any rate as yet.

The same difference in opinion and uncertainty, which one intended to point out here above in regard to the stability curves of cargo vessels, appears still more strikingly in connection with smaller vessels. When See-Berufsgenossenschaft in collaboration with Germanischer Lloyd studied the reasons of the accidents that had occurred to the fishing vessels lost in 1903, they were unable to establish the stability qualities of the vessels, so they had to have recourse to determining the stability factors of other vessels of the same kind. According to the annual report for 1903 [S 31], the stability arm curves for certain examined vessels have been drawn in Fig. 13, and in table 3 the main dimensions and initial metacentric heights of the vessels are given. In the investigations made one arrived at the result that the capsizing of this kind of vessels in unfavourable conditions is not only fully possible, it is actually probable. This opinion is shown to be correct by giving a numerical example, the result of which is that if upon the vessel Oldenburg act simultaneously free water inside the vessel, the water on deck, the pressure of the wind and the action of waves, with a force that corresponds to certainly unfavourable but by no means abnormal conditions, then they capsize the vessels.

Free water in the hold means here only the store of fresh water and such bilge water as cannot be avoided. Of the curves presented, those of the Braunschweig, Breslau and Arthur Friedrich are recommended as the most favourable, because these vessels offer greater security against

<table>
<thead>
<tr>
<th>Name of vessel</th>
<th>$M_o G_{m}$</th>
<th>$G_{H_{m}}$</th>
<th>$\varphi_{m}$</th>
<th>$\varphi_{p}$</th>
<th>Displ. t.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oldenburg</td>
<td>0.762</td>
<td>0.221</td>
<td>27°</td>
<td>61°</td>
<td>267</td>
</tr>
<tr>
<td>August</td>
<td>0.780</td>
<td>0.236</td>
<td>24°</td>
<td>56°</td>
<td>275</td>
</tr>
<tr>
<td>Bremen</td>
<td>0.715</td>
<td>0.167</td>
<td>27°</td>
<td>64°</td>
<td>353</td>
</tr>
<tr>
<td>Arthur Friedrich</td>
<td>0.885</td>
<td>0.404</td>
<td>30°</td>
<td>90°</td>
<td>373</td>
</tr>
<tr>
<td>Breslau</td>
<td>0.660</td>
<td>0.243</td>
<td>34°</td>
<td>90°</td>
<td>440</td>
</tr>
<tr>
<td>Braunschweig</td>
<td>0.750</td>
<td>0.310</td>
<td>55°</td>
<td>&gt; 90°</td>
<td>535</td>
</tr>
</tbody>
</table>
capsize and the other fishing vessels, by reason of their better stability. As the stability factors of the Blexen are stated in the investigation to be low, and as it was proved that the Oldenburg certainly capsized in unfavourable conditions, one may draw the conclusion that stability arm curves of the Blexen, Oldenburg and August — which was rather similar to them in respect of her stability qualities — cannot be held to be sufficient for fishing vessels in the open sea. The same opinion has been stated by Benjamin [B 8] as well. It therefore seems peculiar that in Johow-Foerster's handbook, IV and V edition [J 2] [J 3], among the stability arm curves published, the August's and the Brema's nearly similar curves are included without a single reference to their unfavourableness. This is to be wondered at, particularly for the reason that the said work is very cautious in publishing model curves in general, as is observed already from the curve-examples for cargo vessels mentioned above, and also because in the III edition of the same work a kind of minimum curve was already presented in connection with the same curves [B 8]. This fact may be taken as a new proof of the vacillating opinions, when talking of the approval of some kind of minimum stability arm curve.

Of stability curves for small vessels may be shown a couple of further examples. Fig. 14 shows the stability arm curves [K 4] of a fishing vessel Claus Ebeling intended for working in open sea. The boat's main dimensions are: \( L = 47.0 \, \text{m}, B = 8.3 \, \text{m}, H = 4.65 \, \text{m} \). The draught astern varies from 4.44 to 4.95 m and in the bow from 2.95 to 3.26 m. The boat was built in 1933 and its sister ship has been already proved as an excellent boat in respect of its stability qualities. In spite of that, there is hardly any difference between her curve at the end of the return trip and the Oldenburg's curve, which was judged to be insufficient. As Claus Ebeling's displacement is larger — it varies between 775 and 902 tons — the values of the stability moment for this boat are also greater.

In Fig. 15 the stability arm curves corresponding to two different loading conditions are presented for the Kersten Millers, a two propeller pilot ship working on the Elbe. The main dimensions of the vessel are: \( L = 47.0 \, \text{m}, B = 8.98 \, \text{m}, H = 4.76 \, \text{m} \). The mean draught is 3.65 m.

The vessel's stability is remarkably greater than that of the former boat, which is due to the wider beam and the higher freeboard.

In presenting the comparing material for judging stability arm curves, in the first place must be examined such cases in which a poor stability has evidently or probably been the reason for the accident occurred to the boat. Sometimes this is impossible with regard to the unlucky boat herself, for which reason the quantity of this kind of comparing material is limited. During the last years, however, it has grown so much in Germany in particular — by reason of the obligatory drawing of stability arm curves — that the basing of the judging of a seagoing vessel's stability curves on this basis is possible. It is, besides, the only possible method, until the stability theory of a vessel rolling among waves has been completely established.

In this connection a large number of stability curves for vessels having suffered accidents abroad are given, and their judgings. With their help certain essential conclusions are drawn, which may be used later on for formulating a new minimum rule. The sources used are given in connection with the collected examples.

The stability arm curves for the lost small cargo boats are given in Fig. 16. Stability arm curve A belongs to the cargo boat Galileo, curves B to a spar-deck vessel and curves C to a grain boat.\(^3\) In curve B 1 the deck buildings have been taken completely into account, into curves B 3 and C 2 not at all; in curves B 2 and C 1 the space of the deck buildings has been taken into account while using the same coefficients, that are mentioned in the international rules for determining the freeboard.

Detailed data on the accidents and vessels are added to the collected examples at the end of the investigation (Ex. 12, 13 and 15). According to the resolutions of the courts and their reviewers, one can state regarding the judging of the stability arm curves:

Cargo boat Galileo, curve A. All stability factors, with the exception of the initial metacentric height, are insufficient.

The spar-deck cargo boat, curves B. The changing over from curve B 1 to curve B 2 implies a change over to a critical area, i.e. curve B 2 can still be considered sufficient, but not curve B 2 and still less curve B 3. The initial stability and the range of stability cannot be considered with absolute certainty too small.

\(^3\) Sources: [C 4], [K 24] and [B 10].
Grain vessel, curves C. The stability is in all respects insufficient, especially the amounts of the initial metacentric height and the stability arms at the heeling angles.

In Fig. 16 are also marked the points which correspond to the values for inclinations of 30 and 45 degrees of the stability arms for the above mentioned English standard curve. We see that only the curve of the spar-deck vessel approaches these values, provided the effect of the deck building be taken into account. If Commentz' statement on the stability of the English cargo vessels holds good and, if the stability curve of the majority resembles curve C in Fig. 11 then, according to the above opinion, the stability of most cargo boats lies in the critical area.

Of particular interest to us are the stability arm curves of the passenger ship Negros capsized off the Philippine islands in 1927, because the ship is rather of the same size as most of the passenger and cargo boats navigating along our shores. The accident of the Negros is described in detail as Ex. 16 at the end of this study. The stability arm curves are given in Fig. 17 and the values of the initial metacentric heights, the maximum stability arms, the angles at which the righting arms attain their maximum values and of the capsizing angles are given in Table 4.

Having studied the reasons for the loss Musser states as his opinion of these curves [M 6]:

Curves I and III represent sufficient stability and seaworthiness.

The stability qualities seen from curve II are not of the magnitude required of seaworthy ships.

The stability qualities seen from curve IV lie far below such as are required of seaworthy ships.

<table>
<thead>
<tr>
<th>Curve No.</th>
<th>$M/G$ m</th>
<th>$GH_m$ m</th>
<th>$q_m$</th>
<th>$q_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.670</td>
<td>0.335</td>
<td>35.0°</td>
<td>62.2°</td>
</tr>
<tr>
<td>II</td>
<td>0.427</td>
<td>0.232</td>
<td>33.0°</td>
<td>54.2°</td>
</tr>
<tr>
<td>III</td>
<td>0.646</td>
<td>0.311</td>
<td>34.5°</td>
<td>60.2°</td>
</tr>
<tr>
<td>IV</td>
<td>0.265</td>
<td>0.073</td>
<td>15.0°</td>
<td>27.7°</td>
</tr>
</tbody>
</table>

The judging of the insufficiency of the curve II as stated in the opinion is of special interest. When comparing it with the more inferior curves in Fig. 13 (page 45), of which the curve of the ship August was published in the handbook of Jönow-Foerster without remark [J 3], we see that the difference is not great. An explanation of the severe judging of curve II may be the low initial stability of the Negros, and also the fact that the vessel's deck was not watertight, as was assumed in drawing the curve; consequently water was able to penetrate into the vessel at far smaller heeling angles than the capsizing angles, and the initial stability should therefore have been greater.

The significance has already been mentioned, which the capsizing of the monitor Captain in 1870 had for the study of the stability of vessels, and in the collection of examples the course of this accident has been reviewed (Ex. 1). The stability arm curves of the monitor have been drawn in Fig. 18, next to the curve of the Monarch navigating at the same time. The Captain's curve is far more unfavourable than the Monarch's; the judgment is directed particularly against the low range of stability of the vessel, which in its turn depends on the low freeboard.

Altogether different was the stability arm curve of the Danish torpedo-boat No. 10, which capsized in conducting turning trials in the bay of Copenhagen (Ex. 5) [H 9]; the curve, which is also drawn in Fig. 18, was very long, the range of stability theoretically larger than 90°. The initial metacentric height was however low, only 0.250 m, and the stability arms particularly short, the longest of them about 0.1 m only. For the heeling angles above 60° the values of the stability arms were so insignificant that they had hardly any practical meaning at all.

Formerly, in investigating the capsizings of German vessels, excepting a few cases, the stability curves of the vessels were not drawn, nor were the court resolutions attached. Such being the case, it easily happened

1) In various works somewhat different data have been given on the stability arm curves. The source of Fig. 18 is principally the work [H 10]. Other sources: [H 9], [E 9], [N 5] and [P 1].
that individual experts published opinions differing from the court resolutions, just by using the stability arm curves as proof material. That happened i. a. after the loss of the steamer Margarethe Russ and the s. s. Narvik.

In the juridical investigation the sufficiency of the stability of the steamer Margarethe Russ (Ex. 7) sunk with a timber cargo was held to be highly doubtful, evidently solely upon the basis of the initial metacentric height having been, according to the calculations made in connection with the examination, 0.030 m only. Consequently, L. BENJAMIN wrote an article in the journal Hansa [B 22], a short review of which is given in the example collection (Ex. 7). As in BENJAMIN’s opinion the vessel was not more unfavourably loaded than timber-carrying vessels in general, the resolution of the court implies at the same time that vessels of this type are not suited at all for carrying timber. This conclusion he tries to repeal by presenting the vessel’s stability arm curves (Fig. 19). Their significance and judging are, according to BENJAMIN, briefly as follows:

Curve A: The vessel’s centre of gravity has been assumed to lie at the same level as the court supposed; the carrying capacity of the deck cargo has not been taken into account; the stability is very deficient.

Curve B: The same situation as above, but the carrying capacity of the timber has been taken into account; the stability is quite sufficient.

Curve C: The centre of gravity has been assumed to lie lower down than the above; the stability is quite good.

Curve D: The probable stability curve of the Margarethe Russ at the time of the loss.

Curve E: Vessel without deck cargo; dynamical stability approximately as great as the one corresponding to curve C.

In this judgment by BENJAMIN, attention is drawn to the fact that he considers curve B “quite sufficient”. When comparing it i. a. with the curve of torpedo boat 10 (Fig. 18), it is observed that the values for the stability arms are in both vessels in certain areas equally insignificant, practically zero, as HOVGAARD has declared of the stability arms of torpedo boat 10 at great heeling [H 95, page 92]. Nor does curve B fulfill those two demands which BENJAMIN in 1903 already in his paper placed upon the stability curves of all vessels (cfr. § 6). It is therefore rather probable that, if curve B had not in BENJAMIN’s opinion been based upon too unfavourable an assumption of the position of the centre of gravity, he could not have considered the amount of the vessel’s stability adequate.

When studying the turret-ship Narvik (Ex. 9) capsized in 1913, one also doubted the sufficiency of the vessel’s stability; among other experts heard, BENJAMIN declared that the stability may have been too small. HERNIK, who published the vessel’s stability arm curve (Fig. 20) in the journal Hansa [H 16], in his turn considered the stability fully adequate. The vagueness of opinions is well illustrated by the fact that HERNIK based his opinion upon the very lecture held by BENJAMIN [B 8] the year before. The author cannot say whether the stability curve was already known when performing the official investigation; it would however appear probable that such was not the case.

After the German yards had been instructed, after 1925, to prepare stability arm curves for new and renewed vessels and to hand them to the vessel’s masters, the judging of the stability in examining capsizing cases has also been done with the help of these curves. Consequently it has been possible to obtain valuable comparing material from resolutions
of the courts. In the example collection are given all the capsizing cases in Germany after 1929, except the last one that occurred in the autumn of 1938. The stability curves for the vessels are presented with brief explanations in the following.

The curve corresponding to the fatal moment of the accident of the auxiliary sailing vessel Flottbek (Ex. 24) capsized in 1933 was calculated by Dähmann, who acted as the court’s expert; the curve, which is presented in Fig. 20 (curve II), was held both by the expert and Seeamt Hamburg insufficient both with respect to the range of stability and the ordinates of the curve. On the other hand, the curve (curve I) calculated by the yard that had built the vessel to correspond to other loading conditions was not criticized. Seeamt held the original assumptions applied too unfavourable and considered curve III more correct; according to this curve Flottbek’s stability was sufficient in Seeamt’s opinion.

The curves drawn as the result of the examination into the capsizing of the lightship Elbe I (Bürgermeister O’Swald) (Ex. 27), which attracted so much attention, are shown in Fig. 21. The meaning and judging of the curves are here explained.

Curve A: vessel’s tanks and fuel stores empty. Stability insufficient.
Curve B: vessel at the moment of the accident, assuming that there was no ballast water in the fuel tanks. The stability is insufficient, in the opinion of Dähmann and of Seeamt as well, when taking the circumstances involved into account.
Curve C: vessel at the fatal moment, assuming that 35 tons of ballast water have been filled into the fuel tanks. The stability is in the expert’s opinion still insufficient, maybe, but in Seeamt’s opinion, humanly speaking, sufficient.
Curve D: vessel fully loaded. Stability sufficient.
In the same drawing are given the curves of the lightship Aussenjade, with the ship in light condition — curve E — and with the ship fully loaded — curve F. Aussenjade was in the same gale as Elbe I and would, in the master’s opinion, have capsized, if the anchor had not failed.

In view of this accident it must be remembered that lightships are subjected to far greater heeling moments than vessels in general. For that reason the curves in Fig. 21 and the above mentioned judgings must not be taken as general rules, not even so far as is possible in regard to other accidents.

The capsizing of the whaler Rau III in 1937 during turning trials in fine weather (Ex. 39) was such an accident that its causes were absolutely required to be most exactly explained, already for the honour and good name of German shipping. On the basis of calculations and tests with models, on which considerable sums were spent, it was possible to reconstruct fully the course of the accident; the cause was too slight stability brought on by an unfavourable distribution of the loads. The amount of the stability that had been held — by reason of inexactitudes in the shipyard’s reckonings — to be greater than it actually was. In the investigation attention was limited only to the phases of the accident and to the ideal conditions prevailing at the time. No opinion was pronounced and, to judge by everything, there was no intention to express a definite opinion upon what amount of stability one could consider to be sufficient for the actual conditions prevailing at sea. As it happened in the investigation that the most exact and manifold judging of stability curves was carried out, it would have been desirable from the point of view of other accidents that, for instance, the influence of wind and waves had been added to the results of the calculations. The stability arm curves, which had been calculated by Kemf, who acted as the court expert, as well as the statements made on the vessel’s general build, render it nevertheless possible to obtain some general references to the sufficiency of the stability.

The vessel’s actual stability arm curve was at the time of the accident similar to curve A in Fig. 22. As the vessel capsized in calm water when turning, this curve is absolutely insufficient. The corresponding initial transverse metacentric height was 0.145 m and the displacement 522 tons.

If the amount of the vessel’s stability had been according to the shipyard’s calculations, the vessel would, according to the model trials, not have capsized in a calm water when turning; according to the statical and dynamical calculations a capsizing would have nevertheless been possible. The corresponding stability arm curve (Fig. 22, curve B; $M_G = 0.239$ m, $D = 522$ t) must therefore be held to be either insufficient or at any rate critical.
According to the resolution on the investigation there were no constructional errors in the vessel, and in normal conditions the larger quantities of fuel and ballast water would have increased the stability sufficiently. This would indicate that the court considered a stability arm curve corresponding to a full cargo (Fig. 22, curve C; $M_{G} = 0.577 \text{ m}, D = 722.6 \text{ t}$) adequate. The correctness of this conclusion is however not quite clear, as we shall see later on.

It is remarkable how slight differences in the forms of the stability curves may, according to the investigation on the Rau III, greatly alter the judging of a vessel's stability and the estimating of her seaworthiness. A change over from curve A to curve C makes of a vessel, which capsizes in turning in ideal conditions, a ship against whose seaworthiness no remark can be made.

The motor vessel Monica, which capsized in 1938 in a gust of wind, was loaded so unfavourably that there is very little use for its stability curve, corresponding to the moment of accident, when judging the stability of other ships. The investigation of the accident (Ex. 33) is nevertheless in so far of interest as the vessel's stability curves, made out by the shipyard and previously checked, came to be judged in that connection.

The form of Monica's stability arm curve which, when the vessel was empty (Fig. 23, curve A) and in ballast, was adequate was, when the vessel was fully loaded but without any deck cargo, far more unfavourable (curve B), and when the vessel had full cargo, of which 20 tons on deck, the curve was still worse (curve C). As this curve was drawn in the stability curve-table which had at the time been presented both to See-Berufsgenossenschaft and Germanischer Lloyd — the latter not being the vessel's classification society — various individuals were asked in court to express their opinions on the worst curve of the table. The technical adviser of the shipyard drew attention to the fact that the actual stability of the vessel corresponding to full load and deck cargo was far better than shown in curve C, as the influence of the forecastle and poop had not been taken into account when calculating the curves.

The same was pointed out by the Director of the Germanischer Lloyd, in whose opinion curve C in itself was slightly poor and thin. The representative of See-Berufsgenossenschaft stated that the vessel could be said to be a typical Rhine-Baltic ship, which vessels seldom carry iron on deck. The court expert for his part considered curve C insufficient. The accident by no means proved, however, that this idea was correct, because when capsizing the vessel was so unfavourably loaded that one could not speak of any stability at all; stability arm curve D in Fig. 23 corresponds to the moment of the accident. Although when in drawing the curve, the influence of the deck buildings had been observed — the angle of maximum stability $\phi_{0}$ would then have been $12^\circ$, the corresponding stability arm about 0.01 m and the capsizing angle below $30^\circ$ — the curve would nevertheless have been so low that a gust of wind could easily have managed to capsize the vessel.

The motor vessel Monica's disaster exposed very clearly, the very slight stability-theoretical knowledge the individuals who are responsible for the loading of the vessel may have, and how very little faith they have in the stability curves given to them. At the time of the investigation the vessel's master stated that he doubted very much that the stability curve C held good, as he had successfully carried quite large timber cargoes on deck; he had then not observed that when drawing curve C the carrying capacity of the deck cargo had not been taken into account. As the master, remembering his experience from the timber cargoes, on the fatal trip had taken a large deck cargo of fodder cakes, which were placed very high on top of the hatches, and further left the bottom tank empty, in three different ways he unknowingly impaired the amount of the stability, which the vessel used to have in timber cargo. Thus, the Monica's accident curve belongs to the very worst the author has ever seen.

In the investigation a particularly interesting circumstance was made evident. The expert expressed in his statement the idea that the master could not with his 'feelings' realize the vessel's poor stability, as the initial stability — which is the only one that can be determined with the help of the senses — was comparatively good ($M_{G} = 0.140 \text{ m}$). This fact has already been touched upon in this study. The court, however, did not agree with this correct opinion of the expert, which would appear to be due to the different interpretation of the expression 'feelings'.

Among the accidents overtaking German vessels in these last years, the capsizing of the Kreuzsee deserves to be mentioned. The investigation of the disaster to this motor vessel (Ex. 34) proves in particular the great influence of free fluid surfaces upon the amount of the stability.

The Kreuzsee's stability arm curves are given in Fig. 24. Curve A (corresp. $M_{G} = 0.095 \text{ m}$), in the calculation of which the free fluid
surfaces in the fuel and ballast tanks are not taken into account, proves in the opinions of the technical expert and the court that the vessel’s stability was not very great. However the curve was not condemned outright. In calculating curve B the influence of such of the free liquid surfaces which certainly were in the vessel, is included; the corresponding $M_d G = -0.042$ m. Of the quality of this curve investigators only say that, although a negative initial metacentric height is not always dangerous, one nevertheless must be warned for it in a ship carrying grain. On the other hand, both curve C — the well of the vessel also flooded — and curve D — also a hold full of water — naturally are condemned. The corresponding initial metacentric heights are $-0.155$ and $-0.455$ m only.

The disadvantageous influence of free liquid surfaces mostly acts upon the vessel’s initial stability, and it falls off rapidly when the vessel heels. The exact calculation of this influence at the heeling angles is a comparatively big job. Whether this has been taken into account or not when calculating the curves of the expert’s report, is more than the author knows.

It must be observed that in the expert opinion on the Kreuzsee, instead of the stability arm curves the shifting metacentric height curves were given (see Chapt. II, § 5). According to these curves the stability arm curves in Fig. 24 have been calculated.

Of late one has begun in England as well to use stability arm curves extensively when investigating capsizeings and in explaining such cases, where vessels have been lost without leaving any trace. The acquiring of stability arm curves is not so easy in England as at present in Germany, because the regulation to hand to the ship’s master the stability factors applies there only to passenger vessels; for that reason it has only rarely been possible to base any studies upon stability curves, even during the last years. Although stability curves are presented even in court,

they are not published with the verdict. For that reason it is possible to present the stability arm curves of only one English vessel lost during the last years.

The S.S. Calder was lost in the North Sea in 1931 when carrying a mixed cargo from Hamburg to England. In the investigation instituted, where Mr. Mitchell appeared as expert, one came to the conclusion that the vessel had in all likelihood capsized. The stability arm curve, provided it was calculated with due regard to the bearing capacity of the deck buildings as well, was certainly of a good form (curve A, Fig. 25), but if the calculation of the stability was done only as far as the main deck, the curve became very much worse (curve B). As in the bridge building there were no stern bulkheads above the main deck, one must assume that the waves breaking over the aft deck were able to penetrate into the bridge building. This was possible because the hatches on the aft deck were not fastened. In the same manner, waves may have penetrated into the poop when the vessel was heeling badly. Thus the vessel’s actual stability curve has been very near curve $B$, and the vessel’s stability has in the prevailing circumstances not been sufficient.

The stability arm curve material collected and presented here above is so extensive that it is appropriate to make a study of it, exactly and comparatively. This is useful even for that reason that a unitary comparison of such material has not been published anywhere before.

Before beginning this comparison, there is still reason to examine in general what parts of the stability curve should have the greatest attention in considering the safety of a vessel on the basis of that curve.

The initial slope of the stability arm curve depends solely on the vessel’s initial metacentric height, its significance and the endeavours to determine it have already been treated above in principle, so the slope need not here be touched upon. The initial part of the stability curve as far as to a heel of 5 to 10 degrees also depends mainly on the initial metacentric height, as it does not differ very much from the sinus-curve according to equation (11) (page 22). Therefore, it is
unnecessary in this connection to compare the values of such stability arm ordinates with one another, the heelings of which are smaller than 15 degrees.

The static critical angle of heel, the angle $\varphi_n$, at which the stability curve arm attains its maximum, is a particularly important stability factor, more important than is generally known. This importance is evidenced i.a. thereby that it has been suggested to take the value of this angle as a fundamental measure of the range of stability, and to specify a certain minimum value for it. As far as known, such a suggestion was first made by Achenbach in 1914 (A 4), when he wrote that the angle $\varphi_n$ should henceforth be called the capsizing angle. He confirmed his suggestion by pointing out the following well-known property concerning the states of equilibrium of a vessel. If the vessel is heeled over by some upsetting moment, all states of equilibrium to which the heel $\varphi < \varphi_n$ corresponds to (as an example point A in Fig. 26), are stable states of equilibrium, and those corresponding to the heels $\varphi > \varphi_n$ are unstable (point B). In addition he drew attention to the fact that in the latter state of equilibrium the stability is less than the work which the heeling moment can still do before the capsizing angle (the hatched areas in Fig. 26). The proposal, which Achenbach renewed the following year in connection with a paper read by him [A 13], was not, however, approved as a basis for determining the capsizing angle; in spite of this, its theoretical foundation holds good and emphasizes well the significance of that part of the stability arm curve which lies immediately before the static critical angle of heel.

When comparing the cited stability arm curves with one another, attention must therefore be directed both to the amount of the static critical heeling angle and to the ordinates of the stability arm curve at the points of that angle and of the smaller heeling angles immediately before it.

It is evident from the above that the part of the stability arm curve lying between the static critical heeling angle and the capsizing angle is of less importance than the initial part of the curve. The significance which is nevertheless always given for the amplitude of the capsizing angle, and is still being given, can be easily stated. It is easily seen that

rather generally the ascending part of a vessel's stability arm curve is as long or longer than the descending part, in other words $\varphi_n \geq \frac{1}{2} \varphi_c$, even in such cases where this inequality does not exist, $\varphi_n$ is in general very little less than half the range of stability. Therefore, if some kind of minimum value be given to the capsizing angle, one determines incidentally the minimum limit of the static critical heeling angle at the same time. Just that is the great significance of the capsizing angle.

When beginning to study the stability arm curve material given more in detail, one immediately observes that the quality of the curves varies very much. One can therefore not apply any systematical method of comparison but must be content with the endeavour to determine for certain stability factors such values as have been judged to be sufficient or not in investigations of accidents that have occurred. For that purpose three tables and diagrams of the stability arm curves have been worked out upon which the examining authorities or experts have expressed their opinion. In the first (table 5, Fig. 27) have been entered all the stability arm curves which have been declared wholly or at any rate for the greater part insufficient for the vessels concerned; for the second (table 6, Fig. 28) those have been chosen which have been considered critical, and in the last (table 7, Fig. 29) are given the stability arm curves that have been held to be adequate. At first sight, when looking at the tables and diagrams, one feels as if it would be impossible to find minimum values for the various stability factors out of them. However, on examining the stability factors separately one easily sees that some important conclusions may be drawn with the help of the curves.

Let us begin by concentrating on the values of the static critical heeling angle, so that we may find the limits within which the importance of the stability arms' length is greatest.

We see from the tables collected that the static critical heeling angles of the following values have been called insufficient or at any rate doubtful:

10° 10° 15° 15° 19° 22°;

Against the following values, on the other hand, no remarks have been made:

26° 27° 28° 29° 30° 31° 32° 33° 35° etc.1)

1) In the sources used the judging of the value of $\varphi_n$ has not always been spoken outright. The author has underlined the values of $\varphi_n$ after deliberation i.a. on the principle that, if $\varphi_n$ has been criticized and if $\varphi_n$ has been less than $\frac{1}{2} \varphi_c$—i.e. exceptionally small,—the criticism has been marked as falling upon the value of $\varphi_n$ as well. If again $\varphi_n$ has been many degrees greater than $\frac{1}{2} \varphi_c$ the value of $\varphi_n$ has not been underlined, even if $\varphi_n$ has been deemed too small.
Table 5.
Insufficient stability arm curves.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Year of accid.</th>
<th>Displ. t or length m</th>
<th>$M_{2G}$ m</th>
<th>$\psi_m$</th>
<th>$h_m$ m</th>
<th>$\psi_h$</th>
<th>Stability arms m</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torp. boat no</td>
<td>1912</td>
<td>6540 t</td>
<td>0.039</td>
<td>0.037</td>
<td>18.2°</td>
<td>0.019</td>
<td>0.071, 0.090, 0.034</td>
<td></td>
</tr>
<tr>
<td>Margarethe Russ</td>
<td>1912</td>
<td>6540 t</td>
<td>0.039</td>
<td>0.037</td>
<td>18.2°</td>
<td>0.019</td>
<td>0.071, 0.090, 0.034</td>
<td>Deck cargo does not bear</td>
</tr>
<tr>
<td>Cargo ship</td>
<td>1912</td>
<td>104 m</td>
<td>0.020</td>
<td>0.081</td>
<td>35°</td>
<td>0.019</td>
<td>0.071, 0.090, 0.034</td>
<td>Less deck build.</td>
</tr>
<tr>
<td>840 t cargo ship</td>
<td>1912</td>
<td>104 m</td>
<td>0.020</td>
<td>0.081</td>
<td>35°</td>
<td>0.019</td>
<td>0.071, 0.090, 0.034</td>
<td>Less deck build.</td>
</tr>
<tr>
<td>Negrois</td>
<td>1927</td>
<td>6082 t</td>
<td>0.057</td>
<td>0.065</td>
<td>46°</td>
<td>0.014</td>
<td>0.071, 0.090, 0.034</td>
<td>Accl. curve</td>
</tr>
<tr>
<td>Flottbek</td>
<td>1935</td>
<td>637 t</td>
<td>0.290</td>
<td>0.090</td>
<td>35°</td>
<td>0.026</td>
<td>0.076, 0.089, 0.028</td>
<td>Accid. curve</td>
</tr>
<tr>
<td>Rau III</td>
<td>1937</td>
<td>5221 t</td>
<td>0.145</td>
<td>0.085</td>
<td>41.4°</td>
<td>0.012</td>
<td>0.042, 0.070, 0.016</td>
<td>Accid. curve</td>
</tr>
<tr>
<td>Monica</td>
<td>1938</td>
<td>643 t</td>
<td>0.140</td>
<td>0.008</td>
<td>20°</td>
<td>0.006</td>
<td>0.008, 0.006</td>
<td>Accid. curve</td>
</tr>
<tr>
<td>Kreuzsee</td>
<td>1933</td>
<td>1606 t</td>
<td>-0.042</td>
<td>0.100</td>
<td>35°</td>
<td>-0.002</td>
<td>+0.004, 0.048, 0.088</td>
<td>Free surfaces exist</td>
</tr>
</tbody>
</table>

Fig. 27

Table 6.
Critical stability arm curves.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Year of accid.</th>
<th>Displ. t or length m</th>
<th>$M_{2G}$ m</th>
<th>$\psi_m$</th>
<th>$h_m$ m</th>
<th>$\psi_h$</th>
<th>Stability arms m</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo ship</td>
<td>1925</td>
<td>549 m</td>
<td>0.200</td>
<td>0.220</td>
<td>73°</td>
<td>0.019</td>
<td>0.041, 0.075, 0.110, 0.175, 0.213, 0.210, 0.146, 0.044</td>
<td>Part of deck build. bearing</td>
</tr>
<tr>
<td>Galileo</td>
<td>1925</td>
<td>549 m</td>
<td>0.200</td>
<td>0.220</td>
<td>73°</td>
<td>0.019</td>
<td>0.041, 0.075, 0.110, 0.175, 0.213, 0.210, 0.146, 0.044</td>
<td>Deck build. altered</td>
</tr>
<tr>
<td>Negrois</td>
<td>1927</td>
<td>445-5 t</td>
<td>0.621</td>
<td>0.221</td>
<td>54°</td>
<td>0.039</td>
<td>0.060, 0.101, 0.150, 0.228, 0.162, 0.071</td>
<td>Deck build. altered</td>
</tr>
<tr>
<td>Elbe II</td>
<td>1936</td>
<td>700 t</td>
<td>0.621</td>
<td>0.221</td>
<td>54°</td>
<td>0.039</td>
<td>0.060, 0.101, 0.150, 0.228, 0.162, 0.071</td>
<td>No ballast water</td>
</tr>
<tr>
<td>Rau III</td>
<td>1937</td>
<td>522 t</td>
<td>0.290</td>
<td>0.132</td>
<td>48°</td>
<td>0.058</td>
<td>0.155, 0.195, 0.236, 0.217, 0.137, 0.041</td>
<td>According to shipyard</td>
</tr>
<tr>
<td>Monica</td>
<td>1938</td>
<td>655 t</td>
<td>0.074</td>
<td>0.137</td>
<td>35°</td>
<td>0.059</td>
<td>0.114, 0.137, 0.129, 0.036</td>
<td>From curve table</td>
</tr>
<tr>
<td>Kreuzsee</td>
<td>1933</td>
<td>1606 t</td>
<td>0.095</td>
<td>0.200</td>
<td>61.3°</td>
<td>0.009</td>
<td>0.023, 0.039, 0.061, 0.115, 0.177, 0.197, 0.048</td>
<td>No free surfaces</td>
</tr>
</tbody>
</table>

Fig. 28
We find that opinions have not differed in any of the 25 cases in question; all values below 22° for $\gamma_n$ have been considered at least critical, and none above 26° have been criticized. According to this, a sufficient value for the statical critical heeling angle would be:

$$\gamma_n \geq 26^\circ.$$  

This conclusion cannot however be considered drawn on adequate foundations, because there are too few cases of a direct judgment pronounced on the value of $\gamma_n$. On the other hand, certain other circumstances tend to prove that the said value is not sufficient.

As generally $\gamma_n \geq \frac{1}{6} \gamma_{n'}$, we can at the same time judge the value of the $\gamma_n$ angles on the basis of the minimum values for the capsizing angle. When examining the tables we find that a great unanimity prevails regarding the sufficiency of the capsizing angle values. The following values have been declared inadequate for capsizing angles:

- 18.2° 20° 27.7° 34° 35° 41.4° 43° 48° 54° 56°;

the following values i. a. have not been specially criticized:

- 49° 55.5° 57° 61° 61.5° 62.2° 63° 63.5° etc.

The only value under dispute is the capsizing angle 49° for the 840 ton cargo boat; it must be noted, however, that a private individual has given his judgment on this angle in a very indeterminate form [C.4] (Ex. 13). We may therefore set this value aside with good reason, and say, in examining the stated accidents, that the capsizing angle has been held to be adequate, if it has been

$$\gamma_n \geq 55.5° - 56°.$$

This conclusion also requires a further investigation based upon other sources. For instance, the values of $\gamma_n$, and $\gamma_n$ do not agree with one another, which gives reason to doubt the reliability of the results obtained. This question will be treated later on in this paragraph.

We are able, however, on the basis of the judging of the values already given, to conclude that the limits, within which particular attention must be given the form of the stability curve and the length of the stability arms, lie approximately between 20° and 40°. The lower limit has here been chosen so that $\gamma_n$ would never lie below that value; the top limit has been set at 40°, because, the fate of a vessel heeling over to that extent begun to be determined, as will be proved later on in more detail, by other circumstances already than the vessel's stability qualities.
In estimating the ordinates of the stability arm curves, there is this difficulty, that their form varies so much. For that reason no systematical method can be applied. The best impression of whether the values of the stability arm curves are to be held to be adequate or not, is obtainable by graphical diagram.

When preparing a graphical general survey diagram there is reason for giving attention to a couple of circumstances concerning the course of the curves presented.

First of all, it does not serve the purpose to separate the insufficient and critical values of the stability arm altogether from one another. It is obvious that, if a stability arm wholly or partly runs across the critical area, one cannot consider the stability to be adequate. The use of the word critical may have come to happen only because of the uncertainty which the critics have felt when pronouncing their judgment. On the other hand, and just for this very uncertainty, it is well to preserve these different judgments seen in the diagram, and for that reason the method for representing the stability arms has just been chosen, so that the insufficient and critical values of the stability arms can easily be separated from one another.

Secondly, various curves have been given in the tables, which are not suited as general foundations for judging. Such is i. a. the curve of the lightship Elbe I in table 6. It was judged insufficient particularly because lightships are subjected to work in extremely difficult conditions, differing from the usual ones. If one were to demand of vessels that are able to roll and move freely the stability qualities of lightships, one would be demanding too much. In preparing the diagram, therefore, the curve of Elbe I has been left out. The s.s. Narvik again is a turrett-ship, and in its stability curve there are therefore two maximum points; on the area between the maxima the values of the stability arms may consequently be even very low without being too unfavourable. If we leave the deck building of the vessels out of account when calculating the stability — which is a common and also correct method (see for instance the opinion given by the Board of Trade, quoted in Ex. 21) — two maxima do not generally appear in a stability curve. The Narvik's curve (table 7) is therefore unsuited as a comparing basis. The same must be said of the curve of Margarethe Russ in the same table; her two maxima are due to the deck cargo, which has been deemed to be bearing. These two curves have to be left out when preparing the comparing diagram.

The comparing diagram is presented in Fig. 30. Considering that, on account of what is said above, the area of a vessel's stability lying between the heeling angles 20° and 40° is of particular importance, for such angles at which the lengths of the stability arms have been marked in the diagram 20°, 30° and 40° have been chosen. In addition the length has been shown for a heeling angle of 15 degrees, where the differences between the stability arms are small. The lengths of stability arms that have been deemed too small are given on the columns on the y-axis of the coordinate system, of which the black show stability arms that have been deemed insufficient and the hatched such as have been deemed critical.

The point of the columns is directed upwards and the width of the columns is in a definite point proportional to the number of the stability arm values declared to be insufficient or critical at that level or above. Thus, for instance, the column at the point of 30° shows that there is only one critical value of stability arms greater than 0.2 metres of the examined curves, going from the top downwards we find at the level of 0.175 m one additional value deemed critical, at the level of 0.150 m there is third one, etc. The top of the black column indicates that the longest stability arm deemed insufficient, and corresponding to 30 degrees, is about 0.14 m in the investigated cases, the next longest about 0.1 m, etc.

The stability arm values that have been held to be sufficient are shown drawn as similar columns widening upwards and built on the same principles. In these columns the most interesting is how far down their tops reach. The width of the columns here indicates how many values of a certain amount of stability arm or smaller, have been deemed sufficient in the investigated cases of accidents.
We see from the diagram that at each angle of heel there is only one case of a stability arm having been considered sufficient, which is less than the longest stability arm at the same point deemed to have been critical. Only at the heeling angle of 15 degrees, this does not exactly hold good. If the thin parts of the columns indicating one judged case be left out, then the diagram gives a very clear idea which values of the stability arms have been considered sufficient or not in the examinations in connection with the capsizing concerned. We obtain the result that in the legal examinations such values for the stability arms have not been considered reprehensible as at the different heeling angles they have been of the following sizes:

- at a heeling angle of 20°: 0.140 m,  
- at a heeling angle of 30°: 0.200 m, and  
- at a heeling angle of 40°: 0.200 m.

As the tops of the comparing columns were not considered, there are in the tables 5 to 7 curves, which do not agree with this final conclusion. It is very essential to examine which curves these are.

The vessel whose stability arm values, according to the columns, at the angle of 20 and 30 degrees exceed the minimum amount obtained as comparative results, and whose stability nevertheless is considered critical, is the s. s. Negros (Ex. 16); the stability was judged to be critical by a private individual in his calculating the effect of the altered deck buildings upon the vessel's stability qualities [M 6]. When Negros capsized, her stability was still far worse.—The top of the third column, at the angle of a 40 degree heel, also exceeds the minimum amount; the top applies to a cargo vessel whose stability was held to be critical, even by a private individual in an article written by him in a journal (Ex. 12) [C 4]. That being the case, we find that in the cases investigated no stability arm values for such a vessel exceed the fixed minimum amount that has been deemed, either by court resolutions or in the opinion of persons acting as court experts, to be either insufficient or critical.

We also see in diagram 30 that among the examined vessels there are such as have been deemed sufficiently stable, despite their stability arm values for the heelings in question having been less than the minimum amounts of the comparative results. These ships are the cargo vessel mentioned already, and the whaler Rau III. The court has not pronounced any direct judgment on the stability of the latter when in full-load condition, which corresponds to the curve in table 7, but as it was said that the vessel had no constructional faults, the author has held at any rate the curve representing the full-load condition to have been judged sufficient. Thus these two cases, which are not in full agreement with the minimum demands obtained as results, are neither of any particular importance. The result may consequently be considered rather clear and as uncontested evidence of what has been deemed in investigations, particularly in Germany and also in England, to be a sufficient length for stability arms on the important heeling area between 20 and 40 degrees.

The minimum values for stability arms obtained as results were:

- at a heeling angle of 20 degrees: 0.140 m,  
- at a heeling angle of 30 degrees: 0.200 m, and  
- at a heeling angle of 40 degrees: 0.200 m.

If through these points be drawn such a curve that resembles the ordinary form of a stability arm curve, the value of the statical critical heeling angle would be 35° and the capsizing angle would be almost 60° or slightly greater, thus both angles that would exceed the minimum values, stated above according to court decisions, which are 26° and 55.5 to 56°. We must therefore investigate on the basis of other sources which of these angles can be held to be actually sufficient for seagoing vessels.

Despite the acknowledged importance of the statical critical heeling angle, no investigations regarding the determination of its minimum value have been made, at any rate such as have come to the knowledge of the author. It is remarkable that it is very seldom that any opinion has even been pronounced on the sufficiency or insufficiency of the values of a determined $\psi_m$-angle. For that reason one can only indirectly see what values one expects it to obtain in general. For instance, according to the English standard curve, which on the basis of what has been held forth above might better be called Denny's curve, the value of $\psi_m$ would come to lie between 30 and 45 degrees. We also obtain good references to the amount of $\psi_m$ on the basis of the capsizing angle values, wherefore we have reason first to check the development of its minimum value.

The capsizing angle is a stability factor for whose value the size of the ship has no particular importance. We can therefore expect that the different opinions regarding its minimum amplitude do not vary very much, which is also the case.

The capsizing in 1870 of the monitor Captain already repeatedly referred to gave rise to the first known judging of the amount of the capsizing angle of war vessels. The vessel's range of stability was 55°, but that was not held to be sufficient at all. Barnaby read a paper in 1871 at the meeting of the I. N. A. [B 17], in which he declared his
opinion to be that the capsizing angle for sailing monitors ought to be at least 90°. This severe demand depended naturally upon that sailing monitors especially were treated in the paper; a proof of this is that in the same year the Admiralty Committee of Design stated that it considered 50 degrees sufficient for the capsizing angle of non-sailing monitors [H 9; page 92] [H 10]. This minimum value for warships was soon however increased; in 1920 Høngaard no longer considers a capsizing angle of 70 degrees excessive [H 9; page 93]. According to information gathered by the author from various sources, the minimum value for the range of stability of warships is held in Germany to be 60 degrees, and in Sweden one endeavours to establish that the capsizing angle shall not fall below 70°.

Such severe demands depend upon the special circumstances in which warships have to work, such as dangers from mines, torpedoes and aerial bombs, and they cannot therefore be taken as standards when judging the range of stability of merchantmen. Nevertheless, endeavours have been made to improve the capsizing angles, also in connection with the safety of merchantmen. Already in 1886, Merrifield declared in a discussion following upon a paper read [M 9] that a vessel, whose stability extent is only 50 degrees, may be capsized by a small quantity of water on deck or a shifting of cargo [S 8]. Although the first British Load Line Committee in 1885, when discussing the sufficient range of stability, did not establish what value of the angle should be considered to be actually sufficient [P 3], it all the same proved by its declaration that it appreciated the great significance of the capsizing angle. Most declarations, both by individuals and courts, appear to prove that the above mentioned angle of 50 degrees is very generally held to be inadequate. Thus Pierrotet by choosing, in his proposal of 1935, for a limit angle of heel at which the inclining of a vessel must be stopped even in the very most unfavourable circumstances, for passenger and cargo ships the angle of 40° to 50°, made the demand that the capsizing angle must be considerably more than 50° [P 3].

A capsizing angle of 60° value is begun to be held sufficient in literature at any rate for some vessels. Germanischer Lloyd recommends a range of stability of this size or even greater, in stating that the capsizing angle must normally be greater than 50° to 60° [G 4]. This is also very usual at present. For instance, θ, of the English standard curve is 70° [J 3] [S 8] and the German trawlers' range of stability, which in the beginning of the present century could even lie below 60° [S 31], has been increased, so that it is now 75° to 90° [H 2], for instance that of Claus Ebeling (Fig. 14, page 46) generally 70° to 80°, and 60° only at the end of the return voyage, with a more unfavourable loading [K 4]. The present strict judgment scale for the capsizing angles is i.a. evidenced by the fact that Erbach uses in an article regarding the range of stability of a pleasure yacht — calculated without forecastle — the words not particularly great, although it varies, depending upon the load, between 60 and 75 degrees [E 5].

The minimum value for the capsizing angle may thus be said to establish itself — without any regulations or statutes — at about 60°, but in any case even greater ranges of stability, about 70° and above, are considered necessary. These values, however, apply to genuine seagoing vessels only, such ships as will have to navigate in heavy seas. If the fairways for the vessels are protected, the demands upon the range of stability may be reduced.

This final conclusion, drawn regarding the adequate minimum value of the capsizing angle, confirms the result arrived at in investigating the various minimum values for the stability arms. A couple of cases still remain before the court, which are in opposition to this conclusion: the values 55.5° (Rau III, table 7) and 57° (Kreuzsee, table 5) for the capsizing angle have not been criticized. It must nevertheless be observed that these values have neither been declared to be sufficient in court, wherefore their contrariety to the conclusion drawn would appear to be only apparent. These values may be left out when determining the minimum amount of the capsizing angle.

When comparing the range of stability of 60° to the minimum value of 35° of the statical critical heeling angle, obtained with the help of the minima of the stability arms, we observe that they are in good agreement with one another, the value of θm being 5° more than the half of θr. Thus, we can consider as the more correct minimum amount of θm, the value obtained on the basis of the stability arm values, than the one we arrived at by direct examination of the tables.

That being the case, we are able to state that, if the value of the statical critical heeling angle of a small seagoing vessel is

θr ≥ 35°,

and the value of the capsizing angle

θm ≥ 60°,

the values of these stability factors are in all probability sufficient, provided it is not a question of special types of vessels, or exceptionally difficult conditions.
values for these angles and minimum stability arms a combined rule, which the stability qualities of each seagoing vessel must comply with, the same kind of rule that has been used in England and which Benjamin in his days has formulated [B 8] [S 8]. It is useful to form such a rule, although the author will make certain reservations later on. The rule would be in all its brevity as follows:

1. The values of a vessel's stability arms must be at the angle of 20° at least 0.140 m, and at the angle of 30° at least 0.200 m.

2. A vessel's static critical heeling angle must be at least 35°:

\[ \varphi_m \geq 35°. \]

The determining of the minimum stability arm at a heel of 40° is also futile, because once the conditions of the rule are complied with the value of the said stability arm is also sufficient. The establishing of a minimum value for the capsizing angle is also unnecessary, because its principal object, the ensuring of the sufficiency of the \( \varphi_m \) value, is already accomplished by other means.

The established rule, which is hereunder called the minimum rule for the statical stability, the author does not however wish to propose for general use. A few words will suffice to explain this unwillingness.

First of all may be mentioned the unsuitability of the same standard stability arm curve both for large and small vessels. The lost vessels examined above and used as the foundation for the minimum rule are, with a few exceptions, small ones. The initial metacentric height of small vessels can never without danger be so small — for instance negative — as that of large vessels, a fact which has already been mentioned. For that reason, the first part of a small vessel's stability curve, upon whose course the initial metacentric height has still an influence, generally ascends more abruptly than that of the larger vessels.

It is therefore possible that the value for the stability arm, corresponding to the 20° heel of the proposed minimum rule, is difficult to apply to large vessels.

Secondly, if we are to compromise regarding this first minimum value, a remedy must be obtained by means of greater stability arms at the larger heeling angles. This is quite possible with large vessels with a high freeboard, because the values of their statical critical heeling angle and also of the corresponding stability arms are generally far greater than those of the investigated vessels. For that reason, the minimum demands placed on their stability factors at larger heeling angles should also be raised, which would bring about at the same time greater freedom in the choice of the initial metacentric height.

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The capsizing angle being generally so great, the question arises how capsizing accidents are at all possible, for it is well known that the normal heeling angles of vessels even in bad weather lie far below these values. It is also true that of the disasters upon which the vessel's stability circumstances have had an effect, only a part have been true capsizings, i.e. such accidents where the vessel has suddenly heeled over, either capsizing altogether or else as far as the broadside, and then rapidly sinking. Most often the accident has happened so that upsetting moments first bring the vessel to heel over quickly so as to have a list, in which position the vessel has remained for some reason so long that water has penetrated, through open or leaking hatches, doors or any other ports on the ship, into her inner parts, and impaired her stability, or brought her to sink without capsizing. There are instances among the collected examples in which the vessel's first heel has been only 24 to 32 degrees, and in that position the vessel has remained for some time. Before her final capsizing the passenger boat Kurru also remained for a moment at an inclination of about 35° to 45°, and on the s.s. Louhi water began to pour in through the open side-scuttles while the ship was heeling only at about 17°. Similarly, the steamers B 2 and B 6 heeled over to begin with so much that water managed to pour into them, sinking them rapidly. If a vessel has heeled over so much that her deck is immersed, and comes into a moantory state of stable equilibrium, for instance due to wind pressure, water on deck or through leakage, her risk of sinking is exceedingly great. An instance is the saving of the fishing boat Neck, when she had been heeling over for 15 minutes, so that her gunwale was submerged; Germanischer Lloyd has stated that the saving stands wholly to the credit of the clever handling of her by her master and to a happy chance [G 4].

The above confirms what has been stated above regarding the importance of the capsizing angle to a vessel's safety, compared with the statical critical heeling angle. The range of stability cannot have any noticeable immediate value when it is a question of a vessel's non-capsizing. It is far more important that the angle of heel of the vessel does not become greater than the angle of maximum stability even in the most unfavourable cases; always assuming that the heeling angle has not become greater than \( \varphi_m \), that the cargo has not shifted, or that no other disaster has occurred, the vessel will certainly right herself again.

After all this investigation, and on the basis of its results, it occurs to us, whether it might not be possible to form out of these minimum

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\[ ^{2)} \text{Record of the police court examination of the accident.} \]

\[ ^{3)} \text{Records from the investigation proceedings.} \]
A choice of a standard form for the statical stability curve, so that it would suit both all sizes and types of vessels, thus proves to be an insurmountable difficulty. The minimum rule for the statical stability at which we arrived with the help of the studies of the above accidents, may nevertheless be applied with caution as the basis for judging the stability of small seagoing vessels as well. To this kind of ships belong i. a. our coastal vessels and Baltic traders, but not our lake vessels. Although the author considers theoretically more correct and better applicable in practice that developed form of the minimum rule, which is set forth in chapter IV, there is reason in this connection already to emphasize a couple of essential circumstances, for the eventuality of it being desired to use the rule in its above mentioned fundamental form.

As will be shown later on, the dynamical stability of a vessel is of greater importance than the statical stability; we must for that reason see that the surface area between the stability arm curve and the $\gamma$-axis remains of sufficient size. The values of the stability arms and the $\varphi_m$ angle of the formulated minimum rule may therefore be changed without danger, provided the value of the dynamical stability calculated to that limit angle to which the vessel is allowed to heel, does not decrease. Accordingly, one might thus also reduce the $\varphi_m$ angle, provided one enlarges the lengths of the stability arms presumed for it. The author is nevertheless of the opinion that a 35° statical critical heeling angle is not too great in any way for our coastal waters and the Baltic, nor may its minimum value be reduced.

It is interesting to examine to what extent the earlier proposed standard curves comply with the demands of the new minimum rule. Of the curves in Fig. 11 (page 43), both the English (curve B) and Benjamin’s curve (curve A) are more strict than the minimum rule, partly considerably stricter. That being so, the question arises whether the minimum rule is not too easily fulfilled. This is however not the case. For instance, the curve published by Benjamin [88] and which in his opinion does not differ very much from the curves applied at present in England (curve C in Fig. 11), does not fulfill the requirements of the minimum rule. It must also be noted that, among the stability curves for the German fishing boats investigated in 1903 there were three which were held to be insufficient (Blexen, Oldenburg and August, Fig. 13, page 45), and that no one of these curves complies with all of the conditions made. On the other hand the stability of the vessels, which were held to be irreproachable, is also adequate according to the new rule.

On the basis of the comparison we may say that, according to the investigation regarding statistics of marine accidents, the standard forms for stability arm curves proposed formerly are too severe. This must be noted particularly in preparing later on a rule based upon the dynamical stability.

Above we have been able to come, by the second investigation procedure mentioned in the introduction, to a minimum rule for the statical stability, which may be used in investigating the stability of such a vessel whose stability arm curve is known. As the use of this rule nevertheless is impracticable and allows only a very few possibilities, for instance in choosing the initial stability, the result will be used in this investigation only as an assistance in changing over to a more elastic determination of the minimum stability, based upon the dynamical stability.

Although we cannot use any standard form for the minimum stability arm curve, as is sufficiently evident from the above, as a minimum curve in common for vessels of all sizes and kinds, the importance of this curve in working out the minimum stability problem is most essential. This depends in the first place thereupon that, when the calculating of stability curves is a general custom or when it is obligatory, every vessel while being constructed or repaired must have her stability qualities fundamentally examined and at any rate the most flagrant constructional errors rectified. In addition one obtains — and this is quite as essential — a collection of such material, concerning both successful and capsized vessels, the comparative examination of which renders it possible to approach the solution of the minimum stability problem.


At various times some proposals have been made according to which the stability arm curve should be replaced by some other stability factor as a function of the heeling angle. Considering that a method intended for judging the stability value of a heeling vessel has only then a meaning, when by it in some way or other one can either directly see, or at any rate indirectly measure, the amount of the statical or dynamical stability, all substitutes for the stability curve must be mathematically derived from it. That being the case, such substitutes can be, in comparison with the stability arm curve, advantageous only in so far as with their help some particularly important stability factors become more accentuated than with the help of the stability arm curve.
As a rule, the variation of the stability arm curve is a stability moment curve. The difference in the curves lies, as stated in the preceding paragraph, only in the scale of the ordinate axis, so a more complete analysis of the stability moment curve may be substituted by referring to what has been held forth above about the stability arm curve. The stability moment-scale is often not marked on the ordinate axis of the stability arm curve; it is evident that it is required if one examines the influence of some known heeling moment upon the inclining of a vessel.

A variation of the stability arm curve, which emphasizes a certain stability factor, is the shifting metacentric height curve proposed as a judging basis in 1919 by WROBBEL and COMMENTZ [W 11] [C 13] [S 5]. The shifting metacentric height, the distance of a vessel’s centre of gravity from the point of intersection between the vertical through the centre of buoyancy at heel with the vessel’s middle line, is according to Fig. 1 and equation (6)

\[ N_y G = \frac{h_y}{\sin \psi} \]

The qualities of this stability factor will be examined below.

When the heeling angle is zero the expression for the shifting metacentric height has an indefinite form; it is still easy to observe, although the function \( h_y = f(\psi) \) is not known, that when the heeling angle approaches zero, \( N_y G \) approaches the value of the initial metacentric height.

The curve in question therefore begins at point \( (\psi = 0; N_y G = c_0) \). So long as the stability arm curve joins curve \( c_0 \sin \psi \), the shifting metacentric height is a constant and its graphical representative thus a horizontal line. If a vessel’s metacentric evolve ascends in the beginning (Fig. 9a, page 21), the \( N_y G \) curve ascends tangentially above the said straight line, and if the evolve descends in the beginning (Fig. 9b), the beginning part of the curve falls. The \( N_y G \) curve reaches its maximum generally in some other place than the stability arm curve, although the maximum points may lie very near one another. The correctness of this assertion may be ascertained by the following checking.

In the maximum point of the \( N_y G \) curve, the condition is fulfilled:

\[ \frac{dN_y G}{d\psi} = 0. \]

By differentiating the expression for the shifting metacentric height we obtain:

\[ dN_y G = \frac{dh_y}{\sin \psi} - h_y \frac{\cos \psi}{\sin^2 \psi} d\psi. \]

At the maximum point of the shifting metacentric curve, the equation applies:

\[ \frac{dN_y G}{d\psi} = \frac{dh_y}{d\psi} - h_y \frac{\cos \psi}{\sin^2 \psi} = 0, \]

from which we obtain the following:

\[ \tan \psi = \frac{h_y}{dh_y}. \]

The right hand side of this equation always obtains at the maximum point of the stability arm curve the value \( \infty \), because then applies:

\[ \frac{dh_y}{d\psi} = 0, \frac{h_y}{\psi \neq 0}. \]

Therefore, only then when the stability arm curve’s maximum point is at \( 90^\circ \), the maxima of this curve and the \( N_y G \) curve coincide, because only in this point — within the limits in question — the tangent of the heeling angle is of infinite value.

After its maximum point the \( N_y G \) curve falls, intersecting the \( \psi \) axis at the capsizing angle.

Fig. 31 presents the \( N_y G \) curves of three vessels. The ship A is a small auxiliary vessel, with an \( M_y G \) of 0.348 m and a capsizing angle of 57°; ship B a small Danish torpedo boat No. 10, the same whose stability arm curve is given in Fig. 18 (page 50), and vessel C a medium-sized freight and passenger ship without cargo and fuel, \( M_y G = -0.21 \) m.

The use of the shifting metacentric height curve seems to have been proposed for the reason that one obtains from it at the first glance an idea of the amount of the initial metacentric height, nor need one use any tangent construction for its measuring. The desire seems also natural to use the shifting metacentric height of a heeling vessel for judging the vessel’s stability, just as a measure of the initial stability the initial metacentric height has been used from the earliest times, the determin-
nation of both lengths being similar. As a further advantage of the curve in question may be taken the circumstance that the differences between the initial stability of such vessels whose \( M_r G \) values lie very near one another, and whose stability arm curves have a course of the same nature for small heelings, appear very distinctly, more distinctly than by using stability arm curves.

The use of the \( N_r G \) curves has, however, certain disadvantages. It must be observed first of all that, when judging the stability by means of them, conclusions are drawn solely with the help of the statical stability, because it is difficult to measure the dynamical stability value from the graph. This disadvantage is especially great, as one can note from the next paragraph. Another great deficiency is that one cannot see from this curve the amount of the angle of maximum stability, \( \phi_{max} \), the importance of which has been explained already. In this respect the \( N_r G \) curve may lead direct astray. From the \( N_r G \) curve of the torpedo boat, given as an instance in Fig. 31, we obtain the idea that the vessel's statical critical heeling angle is very small, although it is actually perfectly normal, about 35° (Fig. 18).

On the basis of these circumstances, we may say that the use of the \( N_r G \) curve for judging the stability is generally of no such very great profit as would compensate for the imperfections of the procedure, and for that reason the use of it cannot be recommended, nor has the curve come into general use. Still, DAHLMANN's assertion, that the proposal has not been repeated since its publishing [D 1], does not hold good. For instance, SCHMIDT seems as late as 1922 to consider the use of the \( N_r G \) curve very beneficial [S 5]. One can concur in this opinion only on condition that the judging is to be made on such a vessel for which the amount of the initial stability will have a decisive importance compared with the dynamical stability, range of stability and other stability factors.

In paragraph 1 of this chapter it has been shown that the direction coefficient of a tangent line drawn at any point to the stability arm curve is equal to the vessel's pro-metacentric height:

\[
\tan \alpha = \frac{dh}{dp} = c_p = M_q h_q.
\]

The graphical representative of the direction coefficient is therefore the differential curve of the stability arm curve (Fig. 32). This curve will in the following be called briefly the \( c_p \) curve.

The \( c_p \) curve, the pro-metacentric height curve, has also been proposed to be used in judging the stability. Such a possibility is referred to i. a. by CASSONE [C 10] and it is also mentioned by DAHLMANN [D 1]. We have reason therefore to examine the qualities of this curve, which might be utilized when judging the stability.

The stability arm curve of a round-sided vessel is a sine curve

\[
h_q' = \psi \sin \psi,
\]

and the \( c_p \) curve of such a vessel is therefore a co-sine curve

\[
c_p' = c_p \cos \psi.
\]

The initial ordinate of this curve is equal to the vessel's initial metacentric height. As the direction coefficient of the tangent drawn to the stability arm curve at the origin for all vessels = \( c_p \), the \( c_p' \) curve of all vessels begins in point \( (\psi = 0, c_p' = c_p) \). The more a vessel's stability arm curve differs from the \( h_q' \) curve of a round-sided vessel, the more the \( c_p' \) curve of the vessel differs from the \( c_p' \) curve of the round-sided vessel. At small heelings angles the \( c_p' \) curve remains above or below the \( c_p' \) curve, depending upon whether the vessel's pro-metacentric evolute ascends or descends in the beginning. In other respects as well the \( c_p' \) curve and the pro-metacentric evolute depend upon each other: the \( c_p' \) curve attains its maximum at the angle at which the evolute has its upward cusps, whereas the minimum of the \( c_p' \) curve and the downward cusps of the evolute correspond to one another. At those points the inflection points of the stability arm curve lie. How the said curves are allied, is seen in Fig. 33, where the points corresponding to the points in Fig. 32 are marked with the same angle symbols. The \( c_p' \) curve intersects the \( \psi \) axis at those points, where the maximum and minimum points of the stability arm curve lie.
In Fig. 34 are shown the $C_p$ curves of the same vessels whose $N_p G$ curves are drawn in Fig. 31.

It is evident from this explanation that by the $C_p$ curve one may fairly well visualize the amount of a vessel's initial stability and accentuate those heeling angles at which the greatest steepness of the stability arm curve, the point of inflection, and the maximum and minimum points lie. As a particularly important quality of the curve has been considered the fact that it attains its zero value already at the point of the statical critical heeling angle $[D_{1}]$, wherefore the significance of that point becomes sufficiently accentuated.

The curve has nevertheless many faulty qualities. The greatest is that one cannot measure the amount of the vessel's dynamical stability with its help. It is also difficult to compare the curves with one another, because in their initial parts there may be several maximum and minimum points depending upon the number of cusps of the pro-metacentric evolute, and the nature of the curves may thus be very variable. The worst is nevertheless the circumstance that the length of a determined ordinate to the curve does not as such indicate the amount of the vessel's stability; it only shows in which direction the stability arm curve runs at this point. One must integrate the whole of the $C_p$ curve, before even arriving at any lucidity regarding the amount of the statical stability.

On account of these qualities, the $C_p$ curve, the pro-metacentric height curve, can hardly come into universal use, at any rate not as the sole principle for judging the stability.

In a public discussion on the stability question, Bruhn has repeatedly recommended an idea, a vessel's 'stiffness', as a foundation for judging its stability. Although a vessel's stiffness is, as we shall see in the following, before all dependent on the vessel's initial metacentric height and therefore indicates the amount of the initial stability, there is reason to mention this idea in connection with the variations of the stability arm curve, because Bruhn in his studies has used the stability moment curve as a help.

Already in 1925 Bruhn had, in the discussion following a lecture by Holt [H 7], stated that he considered the geometrical and dynamical method for examining unsuitable for a vessel's master. In 1927 he then declared in connection with a paper read by him [B 12] that the idea of the stiffness may be taken as a basis for judging; he determined, as did also Pollard and Dedebout already in 1890 [P 5], this stiffness to be the heeling moment, which is capable of heeling the vessel one degree. As the tangent drawn to the stability moment curve at the origin intersects the ordinate at the end of the absolute angle unit (57.3 degr.), whose length is $D \cdot C_i$ (see $\frac{C_i}{C_0}$), and as the stability moment curve may be still said to unite with its tangent at 1 degree, we obtain the expression for the stiffness:

$$\text{stiffness} = \frac{D \cdot C_i}{57.3}$$ (23)

The advantages which this idea has, compared with the initial metacentric height, are briefly determined on the basis of Bruhn's lecture, as follows:

first of all, the stability problem is a question of moment, and the moment is also such a quantity whose use a practical man can understand; secondly, it is far easier for a vessel's master to determine the amount of the stiffness than of the metacentric height.

The determination of the stiffness is so done that the vessel is slightly heeled by using a known moment, and the heeling moment is divided by the measure in degrees of the accomplished slight heel.

The idea of the stiffness has, according to Bruhn, been taken into use in the Norwegian school of navigation for judging a vessel's stability, and good experience has been obtained of its suitability for the purpose.

As in the expression for the stiffness both the vessel's displacement and initial metacentric height appear, its amount depends very much on both the size and the form of the vessel. Bruhn was of the opinion that one can only by experience obtain data on the amount of the minimum stiffness, nor did he therefore try to give any numerical values for the same. He also said that he hardly expected that one would be able to work out any simple equation for calculating the minimum stability. This opinion he emphasized by reminding, how the first International Conference for the Safety of Life at Sea in 1914, or rather one of its
select committees — Committee on Safety of Construction — refused to support any addition to the rules for the stability question of steamers, as it is impossible to determine the amount of stability a ship must have, so that it be safe under all conditions. — The theoretical maximum value of the stiffness was held by Brunn to be 710 foot-tons (≈ 220 mt).

Bruhn defended the method again in 1935 in the discussion following Pierrot’s lecture [P 3]. He then stated that an ordinary vessel would have an approximate normal stiffness of \( L^2 B^2 \) foot-tons, when \( L \) and \( B \) are expressed in English feet (the expression equals about \( \frac{L B^2}{560} \) mt, when \( L \) and \( B \) are given in metres). In thus making the normal stiffness dependent upon the length and beam of the vessel, one proceeds exactly as when writing the initial metacentric height as a function of the ratio \( B/L \). This is easily seen. In virtue of equation (23) we obtain

\[
D_c = \frac{L B^2}{57.3} \frac{L B^2}{560} \approx \frac{1}{9.8} \frac{B}{T}.
\]

and therefore

\[
c = \frac{57.3 L B^2}{560 L B T} = \frac{1}{9.8} \frac{B}{T}.
\]

In the same manner as the use of the stiffness-expression in judging the stability is to be coordinated to the use of the initial metacentric height, in the same manner the making of the normal stiffness dependent on the expression \( L B^2 \) is the same as determining the value of \( M_y \) with the help of the ratio \( B/T \). To the similarity are also due the same inconveniences and limitations. In the stiffness the other stability factors are generally not taken into account, not even then when its normal value is calculated by means of the above expression; the most important of the discarded factors are the statical critical heeling angle and the capsizing angle, as well as the amount of the stability corresponding to the former. The insufficiency of the method is evident already from Brunn’s own words: when the stiffness is sufficient, the dynamical stability is also generally sufficient, provided the freeboard is high enough [P 3]. The use of the word ‘provided’ unmask the weakness of the whole judging method. The method is nothing but a substitute for the initial metacentric height method, and besides such a substitute whose application to certain vessels is very troublesome. Its importance is therefore of no value in connection with the present investigation. In spite of this, it is not said that the idea of the stiffness might not be useful as some kind

of observation means in learning, for instance the changes of the ratios of a vessel’s main dimensions and the moving of the position of the centre of gravity on the stability of vessels.

§ 6. The Dynamical Lever Curve as a Judging Principle.

About half a century after Atwood [A 11] had published in 1798 his known fundamental equation for the statical stability, Morely [M 8] formulated an equation of a corresponding kind, which gives the value of the dynamical stability for a heeling vessel. When Barnes [B 18] in 1891 showed a method, by which these equations can be applied in practice, there were possibilities at hand for the use both of the statical and the dynamical stability in judging a vessel’s seaworthiness. Although the importance of a vessel’s dynamical stability among the other stability qualities of a ship was subsequently universally recognized [R 13] — a proof is already the frequency of the expression ‘reserve stability’ — suggestions for using it as a measure of the minimum value of stability have met with far more severe opposition that such proposals as are based on the use of the statical stability. This is seen when looking into the fortunes of the couple of proposals that have been made with this in view, and which have become subjects for public discussion.

The first of this kind of proposals was made, for a wonder, in Germany and not in England. This is remarkable for the reason that in England in particular the stability problem had been treated publicly quite a lot already, whereas in Germany, Benjamin’s paper read in 1913 [B 8], which contained the said proposal, was only the second of the proposals made concerning the stability of vessels at the meetings of the Schiffbautechnische Gesellschaft. Benjamin based his measuring of the minimum stability on the establishing of minimum values for the two ordinates of the dynamical lever curve. Ulffers [U 11] had already used the dynamical lever curve some years earlier, basing himself on Hoek’s theoretical evolutions [H 14], as an intermediate result in calculating stability arm curves, but the novelty in Benjamin’s proposal was the direct judging of the stability with the help of this curve.

Benjamin performed the choice of the minimum values for the dynamical lever by applying the first of the methods mentioned in the introduction to this study. He had, in other words, collected a large comparing material of vessels, small and large, that had performed their work successfully already for a long time. On the basis of the dynamical
lever curves for the investigated vessels, he proposed that as the minimum dynamical lever corresponding to a heel of 60 degrees 200 mm be approved, and 90 mm to correspond to an inclination of 30 degrees; provided the vessel's capsizing angle be less than 60°, the dynamical lever corresponding to the capsizing angle should be at least 200 mm. The determining of the largest dynamical lever required of a vessel was in the opinion of the lecturer comparatively easy, as they vary only very little from one another for vessels of different sizes, but in the selection of the lever corresponding to a slighter heel the difficulty arises that small vessels' dynamical levers at the heel angle of 30 degrees are generally longer than those of larger vessels. On the other hand, it was difficult in practice to obtain experience of the adequacy of the greater dynamical lever, because vessels that had heeled to 60° had mostly sunk. The choice of the limit angles 30° and 60° BENJAMIN based upon the fact that no vessel as a rule may be allowed to heel more than 30 degrees, because heels above that are already dangerous; an inclination of 60 degrees is already so dangerous that the dynamical lever must be sufficient to prevent any such inclination even in the worst conditions that can appear.

This suggestion, which thus was based altogether on another foundation than those previously published, was met with great coldness. It was criticized, because the displacement as a stability factor had been left out of account, because old stability factors were considered more favourable, because the importance of the period of roll was not accentuated, etc., briefly: the suggestion was not understood at all or was wrongly understood, as the lecturer was forced to admit in his concluding words. During the discussion LEIDELL alone showed some understanding for the method, and COMMENTZ agreed with him in his own paper read at the same meeting; the latter even wished to extend the method, so that the minimum value of the dynamical lever should be fixed, corresponding to a heel angle of 5 degrees, and that also the critical values of certain ordinates of the stability arm curve should be determined [C 6].

BENJAMIN again defended his method in 1927 in connection with one of his public speeches [B 6] asserting that his suggestion was very suitable in practice. As it was necessary for a vessel's master to know before all his vessel's heeling resistance, the amount of the dynamical stability of the ship, the dynamical lever curve is better as a means of judging than the stability arm curve. Moreover, the course of the former curves varies less than that of the latter.

Again in 1928 BENJAMIN's proposal came under treatment in connection with a discussion following upon a paper read by SCHWARZ.

[S 8]. Although the original proposal applied only to the determination of the minimum values of the two ordinates of the dynamical lever curve, its proposer spoke in the discussion of determining the normal form of the whole curve. According to that, the curve was said to have the form of the A-curve in Fig. 35. The difference between these two methods for determining the minimum stability is essential. When one only knows the minima of the two ordinates of the dynamical lever curve, there remain several possibilities for changing the form of the dynamical lever curve, the initial stability of a vessel, etc. If one instead knows the normal dynamical lever curve in its entirety, its differential curve, the stability arm curve, cannot be drawn in more than one manner, assuming of course that one does not wish to exceed any ordinates of the normal lever curve. Thus, the stability arm curve A in Fig. 11 (page 43) has been obtained by differentiating the A curve of Fig. 35. Such being the case, it would be fairly immaterial whether the normal form be determined for the dynamical lever curve or that of the stability arm curve. From this it does not seem likely that BENJAMIN, when speaking of the normal curve, had in mind the exact determination of the form of the whole dynamical lever curve. It is probable that he has drawn his normal curve approximately through the terminal points of the two above named ordinates, only to indicate that the English may possibly have used as a model, when drawing their normal stability arm curve, the stability values determined by him. This indication of BENJAMIN does not however hold good (see page 43). The integral curve of the English normal curve is shown in Fig. 35, curve B. In the same discussion, after the paper read by SCHWARZ, BENJAMIN presented a dynamical lever curve (curve C, Fig. 35), drawn by him on the basis of the stability arm curves of several cargo boats in service, and for that reason he stated as his opinion that his demand in 1913 may have been too severe. The stability arm curves corresponding to the dynamical lever curves of Fig. 35 are given in Fig. 11 (page 43).

In trying with
the help of what is said above, to form an independent opinion on
Benjamin's proposal, attention is drawn first to the theoretical
foundation for the method. The whole matter is of such essential
importance to the present investigation that there is every reason to pay
the greatest attention to it.

For trying to prevent a vessel from heeling in normal conditions
suddenly beyond some determined angle, it is the desire of the proposer,
both the stability moment and the stability arm curve are insufficient
as foundations for the calculation. The same is the case, if the desire
is to limit the increase of the heel in the most unfavourable circumstances
to some such amount that the vessel is not yet in danger. The limit
angle of a suddenly heeling vessel is not determined by the stability
moment, but by the amount of work done by that moment. Above
has been explained how in such cases of accidents a vessel may often fall
into a dangerous situation, if she for a short time heels over sufficiently
to allow the sill of an open door or some open hatch or porthole to
come immersed. Such a momentary heel cannot be prevented by
other means than by seeing that the dynamical stability of the vessel is
adequate. In this investigation the danger has also been referred to, to
which a vessel is subjected when the heel becomes greater than the statical
critical heeling angle. This danger can only be evaded by making the
vessel's dynamical lever curve such that the moment of dynamical stability
at the maximum allowed heeling angle is able to overcome the work done
by even the greatest heeling moments. It is quite correct what Dahl-
mann wrote in 1937 about the proposal under debate, when he said:
'The whole capsizing event is a dynamical event, because statical states
of equilibrium do not arise among waves, and a pure statical capsizing is
possible only in calm water by a gradual filling of the side compartments.
It is a question of the amount of heeling angles, and that amount is
determined by the dynamical work due to the wind and waves [D 1].
Byles had also in 1924 already accentuated the same thing at a meeting of
the I. N. A., and stated that one gets to know the normal stability of a
vessel by comparing the moment of dynamical stability with the capsizing
influences of the wind and waves [B 10].

One may therefore find oneself of the opinion that Benjamin's
starting point, to choose the dynamical lever curve as the basis for
measuring the minimum stability, was quite correct. The fact that this
was not yet fully understood in Germany in 1913, is may be for the
greater part due to ignorance of the subject, due to the strange idea of
the dynamical stability and dynamical lever as compared with the meta-
centric height and the stability arm, which were known to all, and further
perhaps due to the feeling of the very theoretical integral nature of the
dynamical lever curve. No blame could be attached to the principle of
the proposal on positive grounds, nor is that possible even now. The
proposal has, however, not been adapted even later on; the reasons
therefore must be sought elsewhere.

In discussing the proposal in 1913 Probst, although he opposed
it principally for using wrong premises, nevertheless brought forward
the correct point of view that, when judging a vessel's amount of stability,
the job has to be done individually. That opinion, with which later on
Flamm concurred [B 8], is correct for examining the stability of small
vessels in particular and especially in choosing the angles at which the
dynamical lever is to be measured. Instinct already says that the choice
of the angles 30° and 60° as limit angles for all vessels, irrespectively of
types, heights of freeboards, hatches, openings and the like, cannot be
correct, in view of how dissimilar vessels can be. For instance, on small
lake steamers it may occur that their hatches, which may not be water-
tight, are immersed at so slight an angle as about 30 degrees, which on
large passenger liners never can come to pass.

The first limit angle proposed by Benjamin — 30° — lies on the
area where the statical critical heeling angle \( \gamma_{c} \) of most vessels also lies
(see § 4). The second of the limit angles — 60° — lies again approxi-
ately in the place where the capsizing angle \( \gamma_{c} \) for normal vessels lies.
On the basis of what has been said above, partly regarding the importance
the reaching and passing of the \( \gamma_{c} \) may have for the fortunes of a vessel,
and partly regarding the slighter direct significance of the capsizing angle,
one may draw the conclusion that the value of the dynamical lever at the
heeling angle of 30 degrees is far more decisive than the value of the
dynamical lever corresponding to a heel of 60°, when a vessel's capsizing
or non-capsizing is concerned. Even Benjamin admits that a passing
beyond 30 degrees is already dangerous for a vessel [B 8]. Once the
dynamical lever corresponding to that angle is so large that the vessel
cannot heel any further at all, it is fairly immaterial what amount the
dynamical lever has at the heeling angle of 60 degrees. When comparing
the different curves in Fig. 35 with each other, we observe that their
ordinates begin to differ from one another remarkably only at heeling
angles above 30 degrees, in an area where the inflection point of the curves
and thus also \( \gamma_{c} \) begins to be passed, and where accidental circumstances,
such as the watertightness of hatches and doors, the number and size of
freeing ports, etc., begin to be of great importance for the vessel's fate.
In addition, we see from Fig. 35 that the ordinate even of the worst C
curve at the 30 degree point is approximately of the same size as the
proposed minimum. This explains that the dynamical levers happen to be at large angles as small as the ordinates of the C curve indicate, and the vessels have nevertheless performed their voyages safely and well [S 8].

According to the above mentioned it is essential that the dynamical lever corresponding to the first limit angle is correctly chosen and that the size of the limit angle itself is suitable. These questions will be treated later on in this investigation.

In Benjamin's proposal the choice of the values of the limit angles had not been a happy one, which is one of the main reasons why the proposal, in spite of its correct theoretical principle, cannot count on support. The other reason is the uncertainty regarding the suitability of the selected minimum values for the dynamical lever, which appeared from the later statements of the proposer himself and which is partly due to the manner in which these values have been determined. The proposal has nevertheless been of great importance, because it has led the investigators of the minimum stability problem on the road along which the final solution of the question is doubtless to be found.

Of such methods of judging the minimum stability as are based on the use of the dynamical stability curves, there is, in addition to those treated above, only one that has been presented publicly, the standardization of the stability proposed by the Indian Pierrottet [P 3]. A careful study of it is necessary also in connection with the present investigation.

Pierrottet's proposal, which was presented at the meeting of the I. N. A. in Rome in 1935, and which has been referred to repeatedly, is remarkable therein that it includes, in addition to a method for judging the stability, a complete draft for statutes by which the minimum value of stability of all seagoing vessels should be determined. The proposal comprised two main principles:

1. A vessel is not allowed, in the most unfavourable circumstances, with all possible upsetting force moments acting at the same time and in the same direction, to heel beyond some determined limit angle \( \varphi \); as the value of this angle should be fixed, with due account paid to the shifting of the cargo, in general 50\(^\circ\); for ferries however 25\(^\circ\).

2. The said condition is complied with so that the moment of dynamical stability \( E_{\varphi} \) corresponding to a vessel's \( \varphi \), must be equal to or greater than the sum total of the amounts of work due to the wind, waves, the centrifugal force and the movements of people on board, acting between the angles \( a - \varphi \):

\[
E_{\varphi} \geq A_1 + A_2 + A_3 + A_4,
\]

(24)

The force values are generally calculated according to known expressions, of which in the following a short summary is given with necessary explanations.

The moment of dynamical stability. We generally have:

\[
E_{\varphi} = D \cdot \varphi_v.
\]

According to Fig. 2 (page 8), we have:

\[
\varphi_v = \frac{F_{\varphi} L - a_1 (1 - \cos \varphi)}{D},
\]

(25)

wherefore

\[
E_{\varphi} = D \left[ F_{\varphi} L - a_1 (1 - \cos \varphi) \right].
\]

(26)

According to Fig. 36, with a heeling angle of 50\(^\circ\), the equation (26) can be written in the form:

\[
E_{\varphi} = D \left( CF_{\varphi} - 0.64 BF_{\varphi} - 0.36 a_{\varphi} \right),
\]

(27)

in which form it is proposed to be entered in the statute. The unit of energy is the metre-tonne.

The heeling work done by the wind. We assume the velocity of the wind to be 40 m/sec, as wind-surface the wind-surface \( F_{\varphi} \) of an upright vessel, centre of pressure the centre of gravity of this surface, and as moment arm of the wind moment the vertical distance \( b \) between this centre of pressure and the half of the draught. As none of the wind moment factors is thus marked as a function of the heeling angle, and as the pressure of the wind is 0.0001 \( F_{\varphi} \cdot 40^2 \) tonnes, the work done by the wind between the angles \( a - \varphi \), is

\[
A_1 = 0.0001 \int_{a}^{\varphi} \frac{F_{\varphi} b \cdot 40^2 \, d\varphi}{b} = 0.16 F_{\varphi} b \varphi.
\]

(28)

The heeling work done by the waves. The vessels are divided, on the basis of the initial stability into two classes:
\[ a) \quad \frac{c_0}{2 \tau_0 + a_0} \geq \frac{5}{6} \overline{\psi}_w^2 \quad \text{and} \quad b) \quad \frac{c_0}{2 \tau_0 + a_0} \leq \frac{5}{6} \overline{\psi}_w^2. \] (29) (30)

The angle \( \overline{\psi}_w \) is the attainable maximum amplitude of synchronous rolling among waves. For calculating this angle, we assume that the vessel's period of complete double oscillation is:

\[ T = 0.68 \frac{B}{\overline{\psi}_w}. \] (31)

Using this value of the period, we obtain \( \overline{\psi}_w \) by interpolation from table 8.

| Table 8. |
|-----------------|---|---|---|---|---|
| \( T \) sec. .... | 10 | 15 | 20 | 25 | 30 |
| \( \overline{\psi}_w \) rad. .... | 0.53 | 0.39 | 0.33 | 0.30 | 0.27 |

The heeling work done by the waves is thus finally in instance a:

\[ A_2 = \int_{\psi_0}^{\psi_v} D \psi \psi \, d\psi = \frac{1}{2} D \left( \psi_v + \overline{\psi}_w \right)_v. \] (32)

in instance b:

\[ A_2 = \frac{1}{2} D \left[ c_0 + \frac{1}{12} (2 \tau_0 + a_0) \overline{\psi}_w^2 \right]. \] (33)

The heeling work done by the centrifugal force. The moment of the centrifugal force is assumed to be constant during the whole of the heeling, the moment arm is assumed to be the distance \( d \) between the vessel's centre of gravity and the half of the draught, \( t \) the vessel's speed in m/sec., and the vessel's turning radius \( nL \) in metres. The work done is then:

\[ A_3 = \frac{D \psi^2 \, d}{nL} \int_0^{\psi_v} \psi \, d\psi = \frac{D \psi^2 \, d}{n \overline{\psi}_w L} = \frac{D \psi^2 \, d}{kL}. \] (34)

The coefficient \( k \) obtains for different types of vessels, depending on the ratio between the vessel's length and turning radius, the following values, when \( \psi_v \) is 50°:

- Men-of-war: \( k = 44 \); passenger ships: \( k = 88 \); cargo vessels: \( k = 110 \).

Heeling work brought about by movements of people on board. We assume that the whole crew and all the passengers — aggregate weight

\( p \) tonnes — suddenly moves a distance of \( 3/8 \)ths of the vessel's beam in the vessel's transverse direction. With the vessel heeling \( \psi_v \), the work done by the upsetting moment, thus arising, is:

\[ A_4 = \frac{3}{8} B \int_0^{\psi_v} \cos \psi \, d\psi = \frac{3}{8} p B \sin \psi_v. \] (35)

To the allowed limit angle of 50° thus corresponds the work

\[ A_4 = 0.287 \, p \, B. \] (36)

In addition to the relation (24) concerning the sum total of the amounts of work shown, a minimum value should also be set for the vessel's initial stability, according to Pierrot's proposal. If the vessel does not belong to such as are subordinate under the bulkhead regulations, \( M_G \) should be \( \geq 0.1 \) m. If pursuant to the prevailing statutes, the vessel must be able to float with one or two compartments flooded, \( M_G \) must even then be \( \geq 0 \), when we assume that the height of the centre of gravity from the keel \( KG \) and the initial metacentric radius \( r_0 \) diminish to the size of the following equations:

\[ KG = \frac{K_G \cdot D - 0.257 \, h \, v}{D - 0.257 \, v}; \] (37)

\[ r_0 = \frac{I_n - 0.8 \, I_n}{D - 0.257 \, v}. \] (38)

In the equations: \( K_G \) is the height of the centre of gravity from the keel when the vessel is fully loaded and tight, \( D \) the corresponding displacement, \( v \) the volume of the flooded compartments, \( h \) the height of the same compartments' centre of gravity above the keel, and \( t_v \) the sum total of moments of inertia of free water-surfaces of the compartments.

The value of \( M_G \) obtained on the basis of equations (37) and (38) must also be used in equations (30) to (33) and the \( c_0 \)-length appearing in equation (27) is also to be determined accordingly.

The discussion following upon the paper was particularly interesting and illuminative in that respect that it well illustrated the practical difficulties for solving the minimum stability problem and disclosed the unwillingness felt in England for the statutory solving of this question. On the other hand, hardly any attention at all was given in the discussion to the theoretical side of Pierrot's proposal. Criticism was only directed towards the value of the limit angle used; Archibald Denny
supposed that at a heeling angle of 50 degrees nothing would remain in its place on a vessel, and Hogg agreed with him and wanted to reduce the minimum angle to 35 degrees. In addition, Bruhn considered the geometrical and dynamical method of checking to be unsuitable for masters of vessels, although it is a natural one from a shipbuilder's point of view.

It is surprising that no supporters of the draft statute in question have appeared in public even later on, with the exception of the declaration by Dahlmann [D 1], in which he states that he considers the method theoretically correct but the chosen value for the limit angle too great (see note at the bottom of page 86). It is surprising, therefore, that the critical examination of Pierrottet's proposal is of exceedingly great usefulness for the solving of the minimum stability problem.

One can at once say of the proposal in general that it is based, in the same manner as Benjamin's judging method, on a perfectly sound foundation, the determining of a vessel's moment of dynamical stability. The novelty is that the comparison of the stability qualities with the corresponding qualities of successful vessels has been abandoned, and a bold endeavour has been made, in spite of it having been declared previously to be almost impossible [E 6], to determine the work quantities by calculation. Thus, it has been possible — in theory — to remove the first of the deficiencies of Benjamin's method, and one has come one step nearer the individual method of solving the problem. Setting aside for the moment the question of how far this removal has succeeded, let us first concentrate upon the selection of the limit angle used by Pierrottet. The maximum limit angle has been determined to be the same for all vessels, 50 degrees, and the use of two separate limit angles has been abandoned. There is no great difference herein, because whether there be one angle or two, whether its value be smaller or greater, it can never be adapted to all vessels.

This standard measure for the limit angle is the first remarkable deficiency of Pierrottet's proposal, which is the easiest for the opponents of the draft statute to criticize. The weakness of this point is illustrated by the interesting observation that, in the same way as Benjamin, a few years after reading his paper, was prepared to reduce the second of the minima proposed by him for the dynamical lever to half the amount, Pierrottet already stated in the concluding words of his paper that he was willing to diminish the limit angle.

In forming the equations for the heeling work in the proposal a number of assumptions have been made, with respect to which there might be reason to make certain reservations. As the exact examination of the equations would lead too far in this connection, and as the same matters will appear later on, it may suffice to mention a few main circumstances in the following.

The equation (28) for the work done by the wind moment is only approximately correct. Assuming that the wind pressure remains constant, that the moment arm is independent of the heeling angle and the amount of the pressure independent of the level of measuring, the equation for the work done by the wind has been brought to a very simple form. These assumptions must be considered, however, to be rather crude. The changes in the wind surface and the moment arm are considerable in a vessel's heeling, as we will see later on; and, on the other hand, there was nothing to prevent one from allowing the equation to be slightly more complicated, as it nevertheless becomes simpler when using the constant value of the limit angle. It is also very severe to choose 40 m/sec. for the velocity of the wind, as we will see in Chapter V of this investigation.

Regarding the method for calculating the maximum work done by waves, it must be observed that, when a vessel is assumed to roll on synchronous waves, which bring her greatest heeling to vary according to table 5 between approximately 15 and 30 degrees for different ships, the force influences of other heeling moments may occur simultaneously with these swingings, wherefore these amounts of work ought to be calculated with the use of limit angle values increased accordingly. This might perhaps be too unfavourable and severe, but it would in any case be logical when complying with the principles of the proposer.

These remarks on the equations used for the work done by the heeling moments do not signify very much compared to what must be said on the calculating method for the moment of dynamical stability of the vessel. The amount of that stability factor has been calculated according to the simple equation (26), which is certainly applicable in still water, but in that only. The application of this equation upon a vessel which rolls among waves up to a heeling angle of 50°, and the comparing of the sum total of upsetting work obtained by other equations to the value of the moment of dynamical stability obtained by this equation, must of necessity bring about so great errors that one can hardly say that the method is even approximate. At present, a lot of industrious work is being devoted in the world to the solving of the stability problem of the vessel navigating among waves — for instance in Germany under the leadership of Von den Steinen; — until this kind of studies have led to a satisfactory result, one can hardly speak of a solution of the stability problem of the seagoing vessel by purely theoretical calculation methods.
3. From the dynamical lever curve are also evident, either directly or indirectly, all other stability factors. The curve shows directly if an other ordinate scale be added, i.e., the amount of the moment of dynamical stability. Every capsizeing accident of a vessel is a dynamical occurrence. The dynamical lever curve is therefore a particularly suitable foundation for judging the stability.

4. Assuming that the limit heeling angle of a vessel is known, to which the vessel may heel without danger, as well as the sum total of the work done by the upsetting moments corresponding to this limit angle and the worst possible conditions, one single point of the dynamical lever curve, corresponding to this allowed angle, is theoretically and generally a sufficient foundation for judging the stability. If one wishes to ascertain the rolling qualities of the vessel, one must also know the other points of the dynamical lever curve.

5. Both the greatest allowed heeling angle — the limit angle — and the minimum amount of the dynamical lever, corresponding to that angle, must be determined as far as possible, individually for every vessel separately. The amount of the limit heeling angle is to be chosen with due attention paid to the nature of the vessel's stability curve, the vessel's build, form, hatches, cargo, and other circumstances. The determination of the minimum value for the dynamical lever must be done before all on the basis of the vessel's build and exterior circumstances.

6. The minimum value of the dynamical lever, corresponding to the individually chosen limit heeling angle, can be determined either by calculation or by comparing the vessel with capsize ized ships and similar vessels that have navigated successfully. The former method cannot be used, however, in examining such vessels as have to navigate in open water. In the second method it is essential to compare the vessel to be judged particularly with capsize ized vessels and with such whose stability has proved to be unsafe; one cannot establish an actual minimum value for the stability, on the basis of ships that have sailed with success. Even although a comparison with capsize ized vessels should not lead to any theoretically certain results, it is as yet the only possible method in regard to seagoing ships.

In accordance with these conclusions, as the basis for new methods to be worked out is chosen that point of the dynamical lever curve which corresponds to the greatest allowed heeling angle, the so-called limit heeling angle of the vessel. The minimum amount of the dynamical lever is chosen for seagoing vessels by basing upon material published in this study concerning examinations of capsize ized vessels; for vessels on inner waters it is determined by calculating.
Chapter III.

Main Principles of the Methods for Judging the Stability of our Seagoing Vessels and those on our Inner Waters.

§ 1. Practical Demands to be Made upon the Judging Methods.

In the introduction to this investigation it has already been mentioned briefly, in what connection in practice the applying of the judging methods for the stability can come into question. Before trying to find out methods that are suited for our seagoing vessels, and for vessels on our inner waters, there is reason to examine in detail the practical difficulties arising for application of the judging methods.

The tasks for which the methods here in question are needed, are the following:

a. the designing of a vessel, i.e. the determination of the vessel's main dimensions, form, freeboard, distribution of weights, etc.;

b. the performing of examinations, surveys, etc. as established by law and statutes, the determination of the maximum number of passengers, maximum cargo, any ballast required, load water line, etc.;

c. stowing and placing of cargo in the vessel's holds and on deck.

It has already also been mentioned that careful attention must be given to the theoretical knowledge of such persons as will have to use this kind of judging methods. It must be established at this point already that judging methods as such, that comply with all demands, can be applied only when designing a vessel and may be when surveying, because it is only such persons who have to do this kind of work who can be capable of it. The practical application of the methods places certain demands on the quality of the same, and the solving of these demands must therefore be investigated more intimately.

Both when determining the amount of the stability and in judging it, the height for the vessel's centre of gravity, i.e. the distribution of the vessel's cargo and other weights, must be carefully noted. Therefore, in designing a vessel and in inspecting it, the amount of the stability factors must be calculated to correspond to several different loading conditions, and the stability must be judged in each case separately. The location of the centre of gravity is preferably determined when the vessel is light, by making the inclining experiment, and the effect of different loading conditions on the height for the centre of gravity is worked out by calculation. As a result one obtains a number of parallel values for the stability factors, which correspond to certain draughts and loading conditions of the ship. The greater the number of the assumed loading conditions is, the more probable it is that all loading conditions that will come into question in actual practice have been examined. But as the variation of the various cargoes' specific gravity is very great and the manners of stowing the cargo are practically unlimited in number, and, on the other hand, as it is for practical reasons possible to take only a limited number of these conditions under examination, it is quite possible that the vessel may often have to sail so loaded that the sufficiency of the corresponding stability has not been established.

That is the reason why of the tasks above mentioned, the first and second, which are performed by the vessel's designer and surveyor, even when applying good methods, are most frequently left very imperfectly accomplished. For instance, the method which is now being applied in Germany, and which was explained by HEBERLING in a paper [H 2], certainly guarantees that all common loading conditions are examined, such as are generally agreed upon between the owners and the master of the vessel. The number of the determined parallel values for the stability factors is, however, generally limited to four only, may be to six, wherefore there is a very small certainty that safety has been established, although the judging of the stability should prove to have been performed correctly.

The sufficiency of a vessel's stability thus depends upon the performing of the above mentioned third task, the stowing and placing of cargo on board. This is a task that, as remarked in the introduction already, devolves exclusively on the vessel's master, nor can the final responsibility of the master be taken from him or transferred to someone else. One can, of course, exact to give to the master data of the vessel's stability qualities, and his task may also be otherwise made easier. Whether the application of these data be easy or difficult for the master in practice, whether the result of the method for securing the vessel's stability be good or bad, depends very largely just upon the form in which these data have been given to him.
In Germany, pursuant to the demands of the See-Berufsgenossenschaft, a number of the vessel’s stability arm curves are given to the master of new or thoroughly refitted vessels [§ 15]. If the master is unable to load the vessel in a manner assumed, when working out the calculations, he does not forthwith know the form of the stability arm curve. He must then in one way or another determine the vessel’s metacentric height and find out the height of the centre of gravity above the keel; then he must take into account the extent of the vessel’s draught and, by interpolation, estimate the true kind of curve. This interpolation is an extremely difficult task. We must remember that the form of the curve depends both on the draught and the place for the centre of gravity, and that complete curves have been calculated only to correspond to certain pair values of T and the height of G. Even if, for instance, the vessel’s draught were the same and the T value which calculating some of the curves given to the vessel, the height of G may differ greatly from the height of the centre of gravity corresponding to the curve. The vessel’s master would have to be very well acquainted with the stability theory, to be able even then to estimate the course of the stability arm curve. And in addition, the master would have to try to draw conclusions regarding the sufficiency of the stability on the basis of the interpolation result obtained by the help of this inexact method and on the basis of several stability arm curves of other vessels. We see what a hopelessly difficult task is presumed to be solved by the master, and for which he is responsible. That must also be held to be the reason why the method being applied in Germany has been subjected to such severe criticism and been considered risky (see § 4).

The determination of the true form of the stability arm curve would be to some extent easier, if the vessel’s master were to have at his disposal a group of curves worked out systematically. The application of such a system has been proposed by Commentz [§ 2]. According to his suggestion, there should be calculated and drawn for every vessel ten groups of stability arm curves corresponding to ten separate draughts of the vessel. Each of the groups should contain ten stability arm curves, which should correspond to the values of the initial metacentric height varying within the limits that come into question. The vessel’s master would be able to draw a correct curve on the basis of these hundred stability arm curves by using a two-fold interpolation. Doubtless this procedure would be better than the one at present in use in Germany; the drawing of a hundred curves, however, would be very laborious, and it might be confusing to the master to use so many curves. Besides this, the master would not even then have clear performing rules for his main task, the judging of the sufficiency of the stability.

The matter would not be improved to any extent, even if the master were to receive, instead of the stability arm curves, dynamical lever curves, if one could not at the same time show him how long the ordinates of these curves must be. It is easily understood that, for instance, the determining of the aggregate work done by the heeling moments would be too much of a task for him.

We thus arrive at the conclusion that the safety question of ships cannot be solved finally, as long as the judging of the stability curves is left to be done by the master. The responsibility for the stability in the last instance cannot be taken away from the master, but it can be limited and made clear. This is possible, always assuming that there is a method fit for use for judging the stability, so that the highest allowed position of the centre of gravity, i.e. the lowest allowed initial metacentric height corresponding to each draught of the vessel concerned is already determined on land, if possible already in designing her, and data on these, perhaps checked by the inspecting authorities, are given to the vessel’s master. His task would then be only to see that the vessel’s centre of gravity, when loading the vessel or otherwise, is never permitted to go higher than the allowed limit; he would not be required to form any other judgment on the stability. Such a distribution of the responsibility, which Pierrottet already [P 3], and Dahlmann [D 1] still clearer, have proposed, would be unavoidable at any rate until the stability-theoretical instruction of the masters of vessels has been improved considerably.

On the principle of what has been said above, it is unnecessary to try to make the methods for judging the stability too simple, as has been done often before. The methods will be applied, provided the responsibility is distributed as explained above, exclusively on land and mostly in the drawing offices of the shipyards; their users are all persons with good theoretical knowledge and with good mechanical instruments at hand. Care must only be given to the methods being sufficiently simple, so that they come into general use. They must also be quick, so that the dependence of the highest allowed position of the centre of gravity

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2) To avoid any misunderstanding it must be remarked that, although we now arrive in determining the vessel’s initial metacentric height, it is not a question of using the $M_G$ as an ordinary basis for judging the stability; we use its value only for applying the amount of the stability determined in other ways.
the minimum value of the initial metacentric height — of the vessel's draught may be quickly found. The information on this law of dependence, either in the form of a curve or a table, will be the final result of the methods.

We must still, before leaving the question of the practical application of the judging of stability, study means and possibilities at the disposal of a vessel's master for determining the height of his vessel's centre of gravity. Upon the proper performing of this task depends whether the division of labour outlined above is of actual value.

When looking upon the matter from a theoretical point of view, it may be said that there are two methods for determining the vessel's centre of gravity: either first of all to find out the value of the initial metacentric height, and then to calculate the position of the centre of gravity by means of a curve table, or to work out the moment calculation for the vessel's different weight groups in the vertical direction, using as the moment arm of the weight groups their distance from the vessel's keel.

The initial metacentric height is generally determined by means of the inclining experiment. Several suggestions have been made for rendering this work easier. Thus, Taylor in 1884 already proposed that fixed heating tanks should be built in the vessels, and for all ships a so-called stability indicator should be made, by means of which the initial metacentric height be found without any calculating [T 1]. Förster again has recommended heating tanks and curve groups [F 4]. One can always get to know the initial metacentric height approximately by the rolling experiment as well, Hovgaard has also proposed its use [H 11]. For making this method more exact, it has been suggested that the inclining and rolling experiments be combined, the latter being generally used and the results of the inclining experiments being only the theoretical basis [H 15]. It is, however, futile to begin to point out the good and bad points of these experiments and the difficulties appearing in applying them, because, although for instance the inclining experiment is necessary for determining the initial height of the centre of gravity in judging the stability, not even that is suited for the everyday use of the vessel's master. If the ship's master would wish by such means to be aware of the height of his ship's centre of gravity, he would be obliged to apply the method of inclining his vessel after every loading and unloading, and even on the voyage at sea. During the time of the experiment there would of necessity often prevail such conditions as would make the result anything but exact. The worst is, however, that by the time the ship's master knows the position of the centre of gravity, the vessel would as a rule otherwise be ready for sailing. The temptation to leave a stability, which may have been found to be too small, as it is, would then be very great, and it would also be difficult may be to demand that the master on his own initiative should start rectifying the whole cargo every time he found the centre of gravity at a slightly too high position. On the other hand, it would be impossible to have recourse to official inspection in such cases.

The determining of the centre of gravity by means of the moment calculation appears at the first glance to be very theoretical and too laborious, but it is by no means so. Weights can be distributed in such large groups that the number of the aggregate moments is not very large. Besides this, as the proposer of the method Dahlmann suggests [D 1], one can, by cooperation between the building yard and the officers of the ship, make such good instruments for assisting in the calculating work, tables, drawings of the spaces in the holds and of the positions of the centre of gravity, etc., that the calculation of the moments would become very simple. On submarines, where this kind of weight and moment books are constantly kept, it has been proved that the task is not too difficult for men who have even the least theoretical education.

The use of the moment calculation for determining the centre of gravity would bring about an exceedingly great advantage: the master of the vessel would be able, already before taking his cargo on board, to form his conclusions on the position of the centre of gravity, and during the whole time of loading he would know what effect each quantity of weight will have upon the stability. It is naturally often difficult for a master to stow his cargo in a particular, determined manner, nor can one demand this of him; but, if he were to use the moment calculation to help him, it would be far easier to keep the centre of gravity below some highest allowed position, than when following some formal loading scheme.

This working programme thus outlined, the determining of the stability on land, and applying the results, the limit-positions of the centre of gravity, on board, by using the moment calculation, would be an ideal practical solution of the stability question. It can unfortunately be applied only on large ocean liners. Even in them it may be doubtful, whether the master's responsibility can be limited in the manner suggested. If that cannot be done, the unravelling of the limit positions for the centre of gravity on land, by applying the judging method for the stability, will only become a kind of guidance to be given to the master, and its application will always depend on the master himself. In small
coasters and vessels on the inner waters, that touch here and there to load from piers and discharge onto them, it is naturally impossible to keep a continuous moment-book of the boat's centre of gravity positions. In such vessels one can of course limit the quantity of cargo, but cannot demand too much regarding its stowing. For boats of this type the object of the method for judging the stability will have to be, to decide which is the value of the minimum stability — on the basis of the final conclusions presented: — what is the minimum value of the dynamical lever corresponding to the determined limit heeling angle, which the vessel must have, when it is loaded in the most unfavourable manner and sails in the most unfavourable outside conditions. The most unfavourable quantity and stowage of the cargo can only be estimated for there are no other means. Whenever such estimating seems uncertain, the value of the stability must be increased accordingly. The minimum stability which one obtains by the method of judging can be obtained in existing vessels either by ballast or by limiting the quantity of cargo.

§ 2. The Presentation of the Problem.

In accordance with the above, as the basis of judging the stability of both coastal vessels and those navigating on the inner waters, is chosen the point of the dynamical lever curve which corresponds to the greatest heeling angle allowed. The first task will therefore be in both methods to find the abscissa-value of this limit point, i.e.: 

to select the greatest heeling angle allowed, the so-called limit angle $\gamma$, which is to be determined separately for every vessel, and to make clear the principles to be followed in that selection.

For the coastal boats, i.e. those vessels that navigate along the Finnish coasts and on Lake Laatokka as well as on the more open waters adjacent — these will be called in the following seagoing vessels — the following object applies:

to determine the minimum amount of the sufficient dynamical lever corresponding to the limit angle, on the basis of the stability curves of capsize vessels.

For the vessels on the inner waters the minimum amount of the dynamical lever corresponding to the limit angle can be determined by calculation. The result of the calculation will be the sum total of the work done by the heeling moments; the amounts of work to be added, i.e. that done by the heeling moments of the rudder pressure and centri-

fugal force, the wind pressure, etc., is calculated separately for each. As all these kinds of work depend i.a. on the value of the limit angle, and as this may be dissimilar in different vessels, it is most simple to calculate for each work quantity a curve group, so the work corresponding to an arbitrary limit angle is easy to measure. The demand for rapid calculating is thus complied with.

In the terms of the sum total of the work, certain factors depending on the vessel's size will appear, such as the vessel's displacement, wind surface, etc. As the work curves for vessels of unequal size would thus have to be distributed over a fairly wide area, and using them would be troublesome, the work curves are changed into work lever curves, so the vessel's displacement is taken as the force doing work even in such cases, where the quantity of work is directly independent of the displacement.

The result of the calculation will thus be the sum total of the work-lever of the heeling moments. Its presentation is divided into the following sub-tasks:

-the drawing of the work-lever curves due to the rudder pressure and centrifugal force;
-the drawing of the work-lever curve due to the wind pressure;
-the drawing of the work-lever curve due to the movements of people on board.

There still remain to be taken into account the heeling force effects and their work-values due to the waves and water breaking on deck. These factors are not determinative for our vessels on inner waters. As it is besides difficult to calculate exactly the amount of these kinds of work, this question is taken up for general investigation, and this sub-task is stated as follows:

taking into consideration the effects of the waves and water breaking on deck.

After this there only remains the last task,

-the determination of the amount of the vessel's sufficient dynamical lever on the basis of the sum total of the work-levers due to the heeling moments.
Chapter IV.


§ 1. The Determining of the Seagoing Vessels’ Limit Angle.

In the foregoing, those suggestions have often been mentioned which have been made for establishing the value of the greatest allowed heeling angle $\varphi$, for seagoing vessels. As a summary of the opinions of various individuals the table below is given, as well as the sources used:

- **Benjamin:** general limit angle $\varphi' = 30^\circ$ [B 8]
- **absolute maximum limit angle $\varphi' = 60^\circ$ [B 8]
- **Pierrotet:** general $\varphi_r = 40^\circ - 50^\circ$ [P 3]
- in draft statute $\varphi_r = 50^\circ$ [P 3]
- **Sir Archibald Denny:** $\varphi_r < 50^\circ$ [P 3]
- **Hogg:** $\varphi_r = 35^\circ$ [P 3]
- **Dahlmann:** $\varphi_r < 40^\circ$ [J 1]
- **Holt:** $\varphi_r = 40^\circ$ [H 7]

The last named limit angle determination is found in a paper read by Holt [H 7], where an instance is calculated, assuming that the greatest allowed heeling angle is $40^\circ$.

All the enumerated proposals have been left, at any rate in the above sources, without stating exact reasons for their bases. By the wording used in formulating the proposals, the conclusion can be drawn that most of them are not the results of close investigation. The proposed limit angles also deviating very much from one another, it is impossible to take them as the foundation in this investigation for determining the limit angle of our seagoing vessels. At the utmost the said values may be used as some kind of comparing material.

Endeavours must therefore be made to solve the question of the choice of a suitable limit angle by a detailed study of the reasons why the safety of a heeling vessel is endangered. In this investigation must be assumed that the angular velocity of the heeling vessel is of a comparatively high value, which is the most usual case in practice.

The most important circumstances that endanger the safety of a heeling vessel are:

a. the passing beyond the statical critical heeling angle;

b. the immersion of non-watertight openings;

c. the shifting of cargoes.

In the following, each of the said circumstances will be investigated separately.

a. The passing beyond the statical critical heeling angle must be considered the most dangerous on the principle held forth in this investigation already. Without repeating what has been stated before, we refer to how the said angle divides the whole range of stability so to say into two parts, the stable and the unstable one, and how on this basis the $\varphi_m$ angle has been proposed to be used as capsizing angle. One has wished to accentuate the importance of the statical critical heeling angle in a way, even in the proposals according to which the $\varphi_m$ curve should be used as the foundation for judging the stability. To these theoretical circumstances may be added a couple of practical remarks.

One may hold as a proof of the danger of greater angles than $\varphi_m$ as Achenbach has remarked [A 13], the fact that vessels have capsized, whose range of stability has been 70 to 90 degrees and above. To this kind of vessels belongs also the Danish torpedo boat mentioned in the collection of examples (Ex. 5). Such kinds of accidents can easily be explained in the manner indicated in Fig. 26 (page 58), i.e. upsetting moments have heeled the vessel beyond the $\varphi_m$ angle, the vessel has come into an unstable state of equilibrium and capsized. But heeling angles between $\varphi_m$ and $\varphi_h$ are dangerous for other reasons as well. When the vessel’s heel goes beyond the $\varphi_h$ angle, the edge of the deck is already immersed to quite an extent. It has now become far more difficult for the vessel to reach an upright position, by reason of the water accumulated on deck. Hatches and the sills in the doors of deck buildings on the upper watertight deck are perhaps already partly immersed, or at any rate they touch the water, so the penetration of water into the vessel’s inner parts depends entirely on the build and condition of the doors and other closing arrangements on deck.

On the basis of this, a vessel’s heeling beyond the angle $\varphi_m$ must be prevented by all possible means, and as the absolute maximum limit
angle of the vessel must be chosen the vessel's static critical heeling angle:

\[ \varphi_c \leq \varphi_w. \]

In order to avoid all misunderstandings, it must be mentioned at once that a vessel's capsizing is by no means an absolute certainty, even though the \( \varphi_w \) angle must happen to be exceeded by any amount. This property of the \( \varphi_w \) angle must be held to be only an advantage, because the limit angle may not be such an angle whose slight exceeding would bring about the certain loss of the vessel. Thus a certain reserve stability is preserved, the existence whereof is useful and necessary.

b. One should naturally never allow a vessel's non-watertight openings to be immersed. Even on board of seagoing vessels there are several closing arrangements, whose watertightness is only conditional: wooden skylights, sounding pipes, tonnage openings, non-watertight hatches, etc., that lead into the inner parts of the vessel. These possible roads for water to penetrate into the ship must be carefully separated from such openings as lead for instance only into the deck buildings, without opening up any roads to parts in the interior. Of such nature are i. a. uncaulked doors of deck buildings; they have no influence whatever upon the judging of the stability, always suppose the volume of the deck buildings, to which such openings lead, have not been taken into account when calculating the stability factors (see Ex. 21). But, if the opening belongs to the former group, i.e., if it leads directly into the vessel's interior, one must examine when determining the limit angle, whether such an opening will be immersed on the vessel's heeling, after angle \( \varphi_w \) or before it already. In the first case, the value selected as the basis for angle \( \varphi_w \) need not be altered, in the second case the limit angle must be reduced accordingly.

In working out a minimum rule for the stability of seagoing vessels, which is based upon the collected material of capsized ships, it is difficult to take into account the possible reduction of the limit angle, which is due to the immersion of non-watertight openings at angles below \( \varphi_w \). The author has not had sufficient material at his disposal, to be able to make the influence of that circumstance quite clear. In the reports of the capsizings and sinkings it has only been stated in a couple of instances at what heeling angle the openings have been immersed. According to these instances, this occurred generally not till then when the heeling angle was very near the \( \varphi_w \) angle or even beyond it.

In treating the material collected in the home country the immersion of non-watertight hatches and openings are mentioned separately and it is observed in judging the stability of the vessels.

c. A shifting of cargoes has been the cause for many a vessel's loss. Among the instances quoted in the examples collected, in four cases, i.e., about 12 %, a shifting of cargoes has certainly, or at any rate as presumed by the investigator, been one or the only cause of the sinking. In the cases of accidents decided by court resolutions, and which the Board of Trade has given to the author for his use, the said percentage is about 48 % [B 25 to B 38]. It is for that reason necessary to examine this question with particular care and its influence on the selecting of the limit angle.

To shifting of cargoes belong in the first instance fluids and bulk cargoes. Due to the liquid cargoes carried in tanks the stability of the vessel is virtually reduced and the amount of this reduction can be and also should be calculated already in drawing the stability curves for the vessel. As the judging of the stability in this investigation is done just with the help of those curves, attention need not be given to liquid cargoes nor to their effect on the determining of the limit angle. On the other hand, the dangers involved in carrying freely moving granulous bulk cargoes — such as for instance grain, salt and fine coals — must be investigated separately.

The danger of bulk cargoes lies therein that in the case of heavy rolling there will be a tendency to shift cargo which causes shifting of the centre of gravity of the ship, and the vessel obtains a remaining hecl. A heel thus arising may be very great, for instance in an English vessel in grain cargo 25° [B 28], another 30° [B 38], and a third, together with the action of free water entering into the vessel, as much as 35° [B 34]. It is easily understood without further explanation, what a great influence upon the stability and qualities of seaworthiness such a great heel must have. For preventing a shifting of cargo, the extreme heeling angle that exterior moments bring about ought to be kept remaining sufficiently slight, so slight that not a single part of the cargo can shift. The exact determining of this angle is laborious, and its amount depends upon many of the vessel's qualities.

The angle at which a bulk cargo still manages to withstand without shifting, when a vessel heels slowly over, is called here the statical angle of repose of cargo \( \varphi_r \). Jenkins has already shown in 1887 that, if the free surface of the cargo lies above the vessel's rolling axis — the axis through the centre of gravity —, the angle at which the cargo begins to move with the heel of the vessel, the so-called dynamical angle of repose \( \varphi_d \) is very much smaller than the statical angle of repose. 1)

is due to the acceleration of the rolling motion. According to Scribanti [S 13], the vessel’s dynamical angle of repose is

\[ \varphi_d = \frac{\varphi_s}{1 + \frac{4}{\pi^2} \cos (\pi - \varphi_s)} \]  

(39)

where \( y \) is the distance in metres of the part of the cargo starting to move from the rolling axis, \( \alpha \) is the angle between the plane through the moving part and the rolling axis and the vessel’s centre plane, and \( T \) the vessel’s period of complete double oscillation, in seconds (Fig. 37). In spite of the equation being only approximate, one can nevertheless form an idea of the magnitude to which the angle of repose is reduced.

The natural statical angles of repose of different granulous cargoes are, according to Johow-Foerster [J 3; page 457], as follows:

- grain: 25° to 35°
- coal and coke: 30° to 50°
- sand, limestone, etc.: 30° to 45°
- ore: 30° to 50°
- rock salt: 35° to 50°

The greater of these values appear according to other sources to be rather liberal; even according to Scribanti [S 13], the statical angle of repose of all kinds of grain averages 25°, and in certain Reports of the Court in England the statical angles of repose for a couple of qualities of coal were found to be 32° and 36.5° [B 26]. Holt gives the statical angle of repose for a certain kind of coal as 35° and for a certain kind of grain at 21.5° [H 7]. We may estimate on this basis that the amounts of the statical angles of repose of the unfavourable bulk cargoes are approximately:

- for grain 25° and for fine coal 35°.

Below is calculated, on the basis of these values and with the use of equation (39), what the values of the dynamical angles of repose will be with varying factors of the equation (table 9).

<table>
<thead>
<tr>
<th>( y )</th>
<th>( T )</th>
<th>( \varphi_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m</td>
<td>8 sec</td>
<td>20.4°</td>
</tr>
<tr>
<td>12 sec</td>
<td>22.7°</td>
<td></td>
</tr>
<tr>
<td>16 sec</td>
<td>23.7°</td>
<td></td>
</tr>
<tr>
<td>6 m</td>
<td>8 sec</td>
<td>18.7°</td>
</tr>
<tr>
<td>12 sec</td>
<td>21.7°</td>
<td></td>
</tr>
<tr>
<td>16 sec</td>
<td>23.0°</td>
<td></td>
</tr>
</tbody>
</table>

Values of \( \varphi_d \)

<table>
<thead>
<tr>
<th>( \varphi_d )</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°</td>
<td>28.3°</td>
<td>23.8°</td>
<td>21.2°</td>
</tr>
<tr>
<td>30°</td>
<td>21.7°</td>
<td>19.0°</td>
<td>17.3°</td>
</tr>
<tr>
<td>35°</td>
<td>32.4°</td>
<td>27.8°</td>
<td>25.9°</td>
</tr>
</tbody>
</table>

We find that the dynamical rolling angle of bulk cargoes can be very small. If the vessel’s period is small and if the upper surface of the cargo lies high up, i.e. if \( y \) is great and \( \alpha \) small, it might happen according to the table that \( \varphi_d \) would be only about 73% of \( \varphi_s \). Such a great reduction of the angle of repose will, however, hardly be met with in practice, i.a. because for arriving at the most unfavourable pairs of values, the moving cargo would have to be carried on the ‘tween deck, which does not generally happen.

The great variation in the values of the angle of repose brings about that, in formulating a general minimum rule for seagoing vessels’ amount of stability, the influence of any special movable cargo cannot be taken into account. It must be left, in the same manner as the immersion of hatches, to the detailed study of each individual vessel. This cannot be avoided, particularly as on different ships dissimilar methods may be applied for preventing a shifting of cargo. Already the regulations for the division of the holds into longitudinal compartments, the covering of grain in bulk with grain in sacks, etc., may be different in various countries.

A certain kind of final conclusion may, however, be drawn from what has been stated above. One can estimate approximately the value of such a heeling angle which must never be exceeded, at the risk of the cargo shifting, be the cargo of whatever kind it may. As uncovered fine coal does not even begin to shift statically before a 35° heel, and dynamically perhaps at 30° already, the value of this angle must be more than 30° to 35°. For a cargo having a statical angle of repose of 50° — coke, ore and rock salt —, the dynamical angle may be about 40°. The extreme general limit angle can hardly be determined higher than this latter value of dynamical angle of repose. One must remember that it has been already said of an angle of 50 degrees that at such an angle nothing on deck can
remain in its place, and that already an angle of 35° has been considered sufficient as the limit one [P 3].

The absolute maximum heeling angle permitted for all vessels would thus be about 35° to 40°. Assuming that, in judging the stability of a certain vessel, attention is given to the special conditions prevailing on it, holds, longitudinal bulkheads, way of supporting the cargo, and other circumstances, the general absolute limit angle must of course be as great as possible. We thus arrive at the conclusion that, for preventing the cargo from shifting, on all vessels, irrespectively of the nature of the cargo, the build of the vessel, or other circumstances, the maximum allowed heeling angle must not be greater than 40°, i.e.

\[ \varphi_r \leq 40°. \]

On the basis of the principles set forth in this paragraph, the conditions that must be complied with by the maximum allowed heeling angle for all vessels, the limit angle \( \varphi_m \), are:

1. The limit angle must at the utmost be of the same amount as the vessel’s static critical heeling angle:

\[ \varphi_r \leq \varphi_m. \]

2. The limit angle must not exceed the value 40°:

\[ \varphi_r \leq 40°. \]

3. The heeling angle must be limited so that the vessel’s non-watertight hatches are not immersed.

4. When estimating the limit angle for a vessel carrying an uncovered and unsecured cargo, the dynamical angle of repose of the cargo must be determined. This angle is obtained approximately, if the statical angle of repose of the cargo is known, by equation (39), by inserting in it the value for the period \( T \) and the actual term pair \( y \) and \( a \) leading to the most unfavourable result possible.

Before leaving the question of determining the limit angle for seagoing ships, it is interesting to compare the results obtained and the definitions of the extreme allowed heeling angle previously proposed.

It can be said first of all that this method for determining the limit angle has one great advantage compared with the other proposals: that is the individual judging of each vessel. The area within which the limit angle may lie is fairly large. In chapter II paragraph 4 of this investigation is mentioned that even so small a value for the \( \varphi_m \) as 26° has not been criticized in court enquiries as too small. The limit angle might therefore vary between 26° and 40°, although the said lower limit is too small in the author’s opinion. When determining the limit angle individually, the significance of the statical critical heeling angle becomes accentuated as it should be. The amount of stability of a vessel, calculated on the basis of that heeling angle, is thus actually fit for use. Benjamin’s first limit angle was 30°. If we, applying his method, compare with one another two vessels whose \( \varphi_m \) values are for instance 26° and 40°, the amounts of stability of the vessels corresponding to the heeling angle of 30° may be the same, although the security of the vessels against capsizing differs altogether. The vessel whose \( \varphi_m \) angle is less than the limit angle will by this method be judged too mildly, the other one too severely. Piaf et al. limit angle again was so great that, if the vessel’s \( \varphi_m \) was small, one came to reckon into the value of the moment of dynamical stability also such a part of the stability as has no complete importance for judging the risk of capsizing, i.e., one obtained too favourable an impression of the stability qualities of the vessel.

It has been possible to eliminate these two disadvantages by the new method of determining the limit angle. It is certain that the amount of stability which comes to be the basis for judging the stability according to the new method, is never erroneously large. On the contrary, the determining of the limit angle leads thereto that in the calculated magnitude of the dynamical stability may perhaps not be included the whole of such an amount of stability by which the vessel actually resists the capsizing influence of upsetting moments. The reserve stability which one thus does not come to take into account, is however not so great that it can be considered excessive.

§ 2. The Determination of the Minimum Rule for Seagoing Vessels’ Dynamical Stability.

The minimum value of the adequate dynamical lever for seagoing vessels, corresponding to the limit angle, will be determined here below on the basis of the stability arm curves of the capsized and lost vessels, which the author has collected for this purpose, published and explained in chapter II of this investigation (tables 5, 6, and 7; Figs. 27, 28 and 29). The division of the curves into irreproachable, critical and insufficient curves will be retained, and this division is considered the foundation for determining the minimum dynamical lever. Besides the said curves will be used as material of the same value the stability curves of those fishing vessels, which were published and judged by See-Berufsgenossen-
### Table 10.
Stability arm curves of German fishing boats.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Displ. t</th>
<th>$M_G$ m</th>
<th>$\varphi_n$ m</th>
<th>$h_n$ m</th>
<th>$\varphi_k$</th>
<th>Stability arms m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bremer</td>
<td>355</td>
<td>0.750</td>
<td>55°</td>
<td>0.310</td>
<td>&gt;90°</td>
<td>0.068</td>
</tr>
<tr>
<td>Oldenburg</td>
<td>267</td>
<td>0.762</td>
<td>27°</td>
<td>0.221</td>
<td>61°</td>
<td>0.068</td>
</tr>
<tr>
<td>August</td>
<td>275</td>
<td>0.780</td>
<td>24°</td>
<td>0.236</td>
<td>50°</td>
<td>0.087</td>
</tr>
<tr>
<td>Finnin</td>
<td>295</td>
<td>0.860</td>
<td>26°</td>
<td>0.236</td>
<td>71°</td>
<td>0.082</td>
</tr>
<tr>
<td>Hannover</td>
<td>285</td>
<td>0.833</td>
<td>29°</td>
<td>0.271</td>
<td>69°</td>
<td>0.077</td>
</tr>
<tr>
<td>Breunschiwig</td>
<td>355</td>
<td>0.750</td>
<td>55°</td>
<td>0.404</td>
<td>90°</td>
<td>0.082</td>
</tr>
<tr>
<td>Arthur Friedrich</td>
<td>373</td>
<td>0.885</td>
<td>35°</td>
<td>0.243</td>
<td>90°</td>
<td>0.090</td>
</tr>
<tr>
<td>Brodau</td>
<td>440</td>
<td>0.760</td>
<td>34°</td>
<td>0.243</td>
<td>90°</td>
<td>0.090</td>
</tr>
</tbody>
</table>

### Table 11.
Insufficient dynamical lever curves.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Displ. t</th>
<th>$M_G$ m</th>
<th>$\varphi_n$ m</th>
<th>$e_n$ m</th>
<th>$\varphi_k$</th>
<th>$e_k$ m</th>
<th>Dynamical levers m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torp. boat no 10</td>
<td>17 t</td>
<td>0.234</td>
<td>35°</td>
<td>0.042</td>
<td>&gt;90°</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Margarethe Russ.</td>
<td>650 t</td>
<td>0.030</td>
<td>10°</td>
<td>0.003</td>
<td>19°</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>Cargo ship</td>
<td>104 m</td>
<td>0.200</td>
<td>19°</td>
<td>0.013</td>
<td>35°</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>84 t cargo ship</td>
<td>-</td>
<td>0.075</td>
<td>27°</td>
<td>0.027</td>
<td>45°</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Negros</td>
<td>608.2 t</td>
<td>0.263</td>
<td>15°</td>
<td>0.011</td>
<td>27.7°</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>Flottbek</td>
<td>637 t</td>
<td>0.290</td>
<td>22°</td>
<td>0.022</td>
<td>45°</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td>Rau III</td>
<td>522 t</td>
<td>0.145</td>
<td>28°</td>
<td>0.018</td>
<td>41.4°</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>Monica</td>
<td>643 t</td>
<td>0.140</td>
<td>10°</td>
<td>0.001</td>
<td>20°</td>
<td>0.082</td>
<td></td>
</tr>
<tr>
<td>Kreuzsze</td>
<td>1006 t</td>
<td>-0.042</td>
<td>46°</td>
<td>0.028</td>
<td>57°</td>
<td>0.042</td>
<td></td>
</tr>
</tbody>
</table>
### Table 12.
Critical dynamical lever curves.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Displ. t or length m</th>
<th>$M_G$ m</th>
<th>$\phi$ m</th>
<th>$\psi$ m</th>
<th>$\varphi$ m</th>
<th>$\psi$ m</th>
<th>Dynamical levers m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10°</td>
</tr>
<tr>
<td>Cargo ship</td>
<td>104 m</td>
<td>0.200</td>
<td>46°</td>
<td>0.050</td>
<td>73°</td>
<td>0.163</td>
<td>0.163</td>
</tr>
<tr>
<td>Galilee</td>
<td>54.9 m</td>
<td>0.390</td>
<td>30°</td>
<td>0.051</td>
<td>50°</td>
<td>0.098</td>
<td>0.098</td>
</tr>
<tr>
<td>Negros</td>
<td>444.5 t</td>
<td>0.427</td>
<td>33°</td>
<td>0.070</td>
<td>54°</td>
<td>0.121</td>
<td>0.121</td>
</tr>
<tr>
<td>Rau III</td>
<td>522 t</td>
<td>0.239</td>
<td>20°</td>
<td>0.037</td>
<td>48°</td>
<td>0.067</td>
<td>0.067</td>
</tr>
<tr>
<td>Monica</td>
<td>655 t</td>
<td>0.704</td>
<td>18°</td>
<td>0.022</td>
<td>34°</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>Kreuzsee</td>
<td>1666 t</td>
<td>0.005</td>
<td>49°</td>
<td>0.083</td>
<td>61°</td>
<td>0.113</td>
<td>0.113</td>
</tr>
<tr>
<td>Blomen</td>
<td>333 t</td>
<td>0.713</td>
<td>27°</td>
<td>0.039</td>
<td>64°</td>
<td>0.116</td>
<td>0.116</td>
</tr>
<tr>
<td>Oldenburg</td>
<td>267 t</td>
<td>0.762</td>
<td>27°</td>
<td>0.066</td>
<td>61°</td>
<td>0.145</td>
<td>0.145</td>
</tr>
<tr>
<td>August</td>
<td>275 t</td>
<td>0.780</td>
<td>24°</td>
<td>0.061</td>
<td>50°</td>
<td>0.142</td>
<td>0.142</td>
</tr>
<tr>
<td>Emsy</td>
<td>255 t</td>
<td>0.860</td>
<td>25°</td>
<td>0.073</td>
<td>71°</td>
<td>0.359</td>
<td>0.359</td>
</tr>
<tr>
<td>Hanover</td>
<td>285 t</td>
<td>0.833</td>
<td>29°</td>
<td>0.087</td>
<td>69°</td>
<td>0.204</td>
<td>0.204</td>
</tr>
</tbody>
</table>

### Table 13.
Adequate dynamical lever curves.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Displ. t or length m</th>
<th>$M_G$ m</th>
<th>$\phi$ m</th>
<th>$\psi$ m</th>
<th>$\varphi$ m</th>
<th>$\psi$ m</th>
<th>Dynamical levers m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10°</td>
</tr>
<tr>
<td>Cargo ship</td>
<td>104 m</td>
<td>0.200</td>
<td>46°</td>
<td>0.050</td>
<td>73°</td>
<td>0.208</td>
<td>0.003</td>
</tr>
<tr>
<td>Negros</td>
<td>426.7 t</td>
<td>0.610</td>
<td>35°</td>
<td>0.110</td>
<td>62.2°</td>
<td>0.210</td>
<td>0.008</td>
</tr>
<tr>
<td>Calder</td>
<td>73.3 m</td>
<td>0.235</td>
<td>30°</td>
<td>0.164</td>
<td>84°</td>
<td>0.254</td>
<td>0.004</td>
</tr>
<tr>
<td>Flottbek</td>
<td>601 t</td>
<td>0.082</td>
<td>33°</td>
<td>0.117</td>
<td>61°</td>
<td>0.156</td>
<td>0.009</td>
</tr>
<tr>
<td>Elbe I</td>
<td>~ 700 t</td>
<td>33.3°</td>
<td>0.110</td>
<td>75.5°</td>
<td>0.244</td>
<td>0.013</td>
<td>0.027</td>
</tr>
<tr>
<td>Rau III</td>
<td>722.6 t</td>
<td>0.577</td>
<td>26°</td>
<td>0.0447</td>
<td>55.5°</td>
<td>0.074</td>
<td>0.009</td>
</tr>
<tr>
<td>Braunschweig</td>
<td>555 t</td>
<td>0.750</td>
<td>53°</td>
<td>0.216</td>
<td>50°</td>
<td>&gt; 382</td>
<td>0.012</td>
</tr>
<tr>
<td>Arthur Friedrich</td>
<td>373 t</td>
<td>0.885</td>
<td>39°</td>
<td>0.179</td>
<td>90°</td>
<td>0.298</td>
<td>0.024</td>
</tr>
<tr>
<td>Breslau</td>
<td>440 t</td>
<td>0.760</td>
<td>34°</td>
<td>0.099</td>
<td>90.5°</td>
<td>~ 250</td>
<td>0.011</td>
</tr>
</tbody>
</table>
The ordinate values of the vessels, stability arm curves and their other stability factors are collected in table 10 and some of the curves have already been published in Fig. 13. Of the curves in the table, See-Berufsverband has considered only the last three to be sufficient for seagoing vessels, those of the Braunschweig, Arthur Friedrich and Breslau, and only these curves also comply with the minimum rule for the static stability formulated at the end of chapter II, § 4 (page 71). Accordingly, of the curves of the fishing vessels, only the said three are grouped among the irreproachable curves; the others belong to the group of critical ones.

The first integral curves of the collected stability arm curves, the dynamical lever ones, have been drawn with the help of the integrator, the ordinate values of these curves have been measured exactly and given in tables 11, 12 and 13. The values of the dynamical lever $e_0$ corresponding to the static critical heeling angle $\varphi_m$ and the dynamical lever $e_0$ corresponding to the capsizing angle $\psi_1$ have been calculated separately and given in the same tables.

When beginning to study, on the basis of the tables, whether it be possible to find a reliable minimum rule for the dynamical lever corresponding to the limit angle, a presumption must be made. Considering that the building in detail of the capsized and lost vessels is not known, we must assume that no non-watertight hatches, doors, etc. of the vessels are immersed before the static critical heeling angle, or, as far as $\varphi_n > 40^\circ$, not before a $40^\circ$ heel. Such an assumption may to begin with seem rather far-reaching; but we must remember that all the vessels concerned were designed as seagoing ships, and that only one vessel — Negros — has been stated in the sources used to have had a deck that was not watertight. It must also be added that the curves are divided into groups according to the judging they have been subjected to as curves, for pure theoretical consideration. The assumption formed therefore does not give rise to a wrong impression of the amount of the stability of the vessels. The same must be said of the fact that a possible shifting of the cargo and its effect on the choosing of the limit angle cannot be taken into account in the following investigation.

As the greatest heeling angle allowed for vessels, that limit angle at which the suitable dynamical lever must be measured, is thus held to be the static critical heeling angle of the vessels, or, if $\varphi_m > 40^\circ$, a heel of 40 degrees. On this principle, in the diagrams below (Figs. 38, 39 and 40) have been shown, of the curves according to the tables, only the parts before the limit angle, and the value of the dynamical lever corresponding to the limit angle is marked with a black dot. Thus, one may obtain the best idea of such an amount of the dynamical stability of the vessels which is actually fit for use.

Having applied for each vessel a separately determined idea for the limit angle, one can compare the values of the dynamical levers — the measures of the available dynamical stability of the vessels — corresponding to this angle, with one another, without paying attention to the value of the limit angle. This brings about an exceedingly great advantage, which will be seen when making the comparisons.

With the help of the tables and diagrams, the following combination may be made. The dynamical levers arranged in number of value here below, which correspond to the limit angle of each ship, are insufficient for seagoing vessels:

0.001 0.003 0.011 0.013 0.018 0.022
0.027 0.028 0.042 0.062 m.
The values for the critical dynamical lever are:

0.022 0.037 0.050 0.051 0.053 0.061 0.066 0.070 0.073 0.073 0.087 m.

Irreproachable, sufficient dynamical lever values would be, according to the investigations, the following:

0.044 0.062 0.085 0.099 0.104 0.110 0.110 0.138 0.179 m.

To obtain a precise picture of this combination, the instances judged are shown graphically on the same principle as has been used above for comparing the values of the stability arms with one another. The insufficient and critical dynamical levers are shown in black and hatched columns, so that the thickness of the columns at any height is proportional to the number of dynamical levers judged to be insufficient or critical on that level or above (Fig. 41). The number of sufficient dynamical levers is shown by a column widening upwards, whose thickness on each level is proportional to the number of those dynamical levers that have been judged as sufficient and are as long or smaller than the dynamical lever corresponding to this level. The breadth of the thin tops of all the columns mark one judged instance.

The diagram shows that a dispute about the judging of the various instances will hardly occur. Only one dynamical lever, that was said to be sufficient, is at the limit angle smaller than some of the greater critical, and still less than even the greatest insufficient dynamical lever. The vessel whose small dynamical lever — although it was judged to be sufficient — the hatched top of the column applies to, is the whaler Rau III, when the vessel was in fully loaded condition but without any ballast. In judging this sole vessel to be sufficiently stable in opposition to the other vessels judged, a couple of circumstances are worth attention. The stability curves of the boat are placed in the irreproachable group, on the basis that in the investigation of the accident it was not stated that the boat had any constructional fault (see §4 of chapter II). Already when comparing the stability arms of the different vessels one came to observe that the Rau III's stability was not, when the ship was in fully loaded condition but without ballast, as good as that of certain other vessels that had been deemed critical. On the basis of the dynamical lever we now see that it is not even as good as the best of those ships that have been called insufficiently stable. This raises strong doubts as to whether the court judging holds good. These doubts are enhanced by the fact that the technical expert of the court had calculated, to what extent the vessel's stability would improve, if it took fixed ballast should be taken into the vessel, and had stated that the initial metacentric height would be increased by 26 %. (Ex. 29).

From the court records, it is further evident that this quantity of ballast had been added to the Rau vessels later on [R 18]. One has the impression therefore that the amount of the "sufficient" stability of the Rau, which appears in certain tables and diagrams of this investigation, was, in spite of this not being considered to be really sufficient, although it was not the intention to say so right out in the records of the court. On that principle, the stability arm curves and the dynamical lever curves of Rau III, appearing in the tables 7 and 13 and in diagrams 29, 30, 40 and 41, may be left out of account when judging the stability of the other vessels.
The setting aside of this disputable curve explains decisively the final result. Fig. 41 shows, when we imagine the thin top part of the hatched column to be removed, that a dynamical lever corresponding to the limit angle of the vessel must be held to be sufficient, provided its length is

\[ e \geq 0.080 \text{ m.} \]

That is the new minimum rule for the dynamical stability of seagoing ships.

Both this minimum rule for the dynamical stability and the minimum rule for the corresponding statical stability, as set forth in chapter II, have been worked out with the use of the same investigation material concerning accidents of vessels. It is therefore necessary to examine whether the said rules agree with one another.

If we wish with any kind of approximate exactitude to draw a typical sort of curve for stability arm curves with the use of the minimum rule for the statical stability, we must determine in advance the amount of the initial metacentric height, i.e., the direction coefficient of the tangent drawn to the curve at the origin. For this purpose, it is assumed in the following for comparison that the initial metacentric heights of three vessels are

0.350 m, 0.450 m and 0.550 m,

the stability arm curves of the vessels have been assumed just to comply with the minimum rule for the statical stability:

\[ h_{90} \geq 0.140 \text{ m, } h_{00} = 0.200 \text{ m and } \varphi_m = 35^\circ, \]

and on the basis of the stability curves the dynamical levers corresponding to the limit angle 35° of the vessels have been calculated. The values for these, depending upon the initial metacentric height, are

0.070 m, 0.077 m and 0.083 m.

Thus, we see that the minimum rule for the statical stability is in agreement with the new dynamical stability's rule, always presuming that the vessel's initial stability is of a determined value. As the minimum value of the initial stability should never be limited by any general regulations, but its amount be left to the free consideration of the designer of the vessel, the new minimum rule for the dynamical stability is more favourable than the rule for the statical stability.
Chapter V.


§ 1. The Determining of the Limit Angle for our Vessels on the Inner Waters.

All that has been stated about the determining of the extreme heeling angle allowed for the seagoing vessels in the preceding chapter of this investigation applies in principle as a guidance for judging the stability of the lake vessels as well. Without repeating the principles set forth, one may say that the limit angle of the lake vessels must also comply with the following conditions:

- the limit angle must not be greater than the vessel’s statical critical heeling angle;
- the limit angle may not be so great that non-watertight hatches, doors, etc. are immersed;
- the limit angle may not be so great that the vessel’s cargo begins to shift before it is reached.

Of the said conditions, the statical critical heeling angle was given a particularly great significance. According to the minimum rule for the statical stability, the value of this angle must be at least 35°, and in the minimum rule for the dynamical stability we came to determine the value of the limit angle in the first place on the basis of the angle $\varphi_n$. In judging the stability of the lake vessels we cannot put up anything near the same severe demands upon the $\varphi_n$ angle, nor is its significance in the individual determination of the limit angle of each vessel even particularly important. This is due to certain circumstances concerning the form and construction of the lake boats.

The vessels upon the basis of which the above mentioned minimum demand of the statical critical heeling angle was made, were practically without exception vessels that had an official load line. The International Loadline Convention [K 2] is to be applied in Finland only to vessels making international voyages, to which the lake and coast vessels do not belong. Neither the height of the freeboard nor the level of the load water line of these vessels being either specified in other statutes, the height of the freeboard of these vessels is absolutely devoid of any regulations and therefore very variable, in most vessels very low. This leads to that the angle at which the deck becomes immersed, as well as the statical critical heeling angle, which is intimately dependent on the height of the freeboard (see § 3 of chapter II), also vary very much. It is thus difficult to try to determine any absolute sufficient minimum value for the $\varphi_n$ angle, because, if it be not very small, it would be very rarely that a lake vessel would be able to comply with the demand in that respect.

On the other hand, the determining of the minimum value of the statical critical heeling angle is futile for our lake vessels as well, because a determining of the limit angle for any vessel to be of the value $\varphi_n$, even if that were small, will hardly ever come to pass. This is due to certain circumstances of constructive detail.

The directions in the International Loadline Convention [K 2] also concern the nature of the closing arrangements on the decks of vessels, the coamings round the hatches and the heights of the sills and other circumstances. The danger from water pouring in through the openings on deck at heeling angles below $\varphi_n$ is consequently small on seagoing vessels, although a factor to be noticed. But there is no statute in force in our country regarding closing arrangements on deck nor about the heights of sills, which leads to the fact that non-watertight openings on the decks of these vessels may be immersed very shortly after the edge of the deck has been dipped, thus very much before reaching the angle $\varphi_n$. This naturally reduces the importance of that angle for the selection of the limit angle, and one may say even that the immersion of non-watertight openings will probably in most cases limit the greatest heeling angle allowed for our lake vessels to a value below that of the $\varphi_n$ angle.

The above also implies that a shifting cargo cannot be a very important factor for determining the limit angle of our lake vessels. Attention having been drawn to this circumstance also in connection with certain accidents to vessels in our country, the shifting of the cargo cannot altogether be passed by in this connection. A special examination must here be made of any shifting general cargo, because such cargoes are very frequently carried on our inner waters.

Finland’s old maritime law, § 82, as well as § 51 in the statute of 1924 for merchant vessels, require that the vessel’s master shall stow
and secure his cargo. In addition, good seamanship requires that all such cargo, general cargo or whatever it may be, which on a heeling vessel may shift, should be properly stowed and secured. In spite of this, so many violations of these demands are committed in our country, that in a theoretical study it must be assumed that vessels on our inner waters carry deck cargoes that are not secured.

The angle of repose of the deck cargo depends upon so many circumstances that a determination of its lowest appearing value is an unsurmountable task. The cargo may be bags, cases, iron goods, barrels, and all these begin to move at different degrees of heeling. If the only force holding the goods in position is the friction and if they cannot roll, one may, however, obtain some approximate idea of the value of the dangerous heelings with the help of the frictional coefficient. On the basis of the general table of coefficients of friction published by Förster,\(^1\) one can conclude that the statical coefficient of friction between the uneven deck and an object lying thereon (case, iron, etc.) cannot well be less than 0.60 to 0.75, which corresponds to a frictional angle of 30° to 37°. The heel at which a general cargo on the deck of a slowly heeling vessel starts moving, would thus be hardly less than 30°. If the vessel heels over suddenly, the dynamical angle of repose may be about 23° to 25° (see table 9, page 107). An angle of that degree already would be an absolute limit angle for such a vessel as carries on deck unsecured general cargo, cases, etc. The value of the angle obtained, as the result of this approximate conclusion, is so high that the deck of most of our lake vessels have then already been immersed.

The above suffices as a guidance for the selection of a limit angle for such vessels as do not carry passengers. The determining of the greatest heeling angle allowed for passenger-carrying vessels on inner waters leads to the study of a new problem. The heel of a vessel may cause a sudden terror among the passengers, a panic, and they may press in dense groups towards the rail, bringing the vessel into the most extreme danger. Such a terror must be prevented from arising by limiting the heel of the vessel to so low an inclination that a panic is not apt to arise.

\(^1\) How very frequently deck cargoes are left unsecured in our country, is evident from the resolution of the district court, in session at the intermediate assizes for the parishes of Kuopio et al. in 1935, made in the case concerning the capsizing of the passenger vessel Louhi. It is said in the resolution i. a.: nor — could it be demanded in reason, that the cargo carried on the vessel must be fastened or secured by means of special arrangements, such having not been generally used, at any rate before this occurrence, on passenger ships belonging to this port — i. (Abstract from records of district court).


Albrecht has given some information [A 6] about the size of this panic angle. According to him, passengers begin to be troubled at a heel of 8°, at 10° frightened, and at a heel of 12° they are seized with panic. An assumption for this is probably, although it is not expressly stated, that the vessel heels over fairly slowly and also remains at a heel. In studying the stability question dynamically the vessel must, however, be assumed to incline suddenly, and immediately after heeling return to the upright position and perhaps heel over to the opposite side. In a vessel so moving it would be impossible to determine a certain panic angle in common for all vessels, because the reaction of the passengers in such a case must depend very much upon the local conditions, the nearness of the water surface, the nature of the gunwale, and other circumstances. It should nevertheless be possible to establish some kind of limit angle in regard to the rolling of the vessel. In any case, the water must be prevented from pouring down to the lower deck where the passengers are. The expression lower passenger deck must be arbitrary, as it depends naturally on the build of the vessel and the location of the decks. This condition may be held as an additional direction, when determining the limit angle for passenger vessels on inner waters.

The determination of the greatest heeling angle allowed for vessels on inner waters must thus be left completely depending on the build, form, stability qualities etc. of each vessel to be judged. It is nevertheless natural that the absolute maximum angle —40° — which was determined in formulating the minimum stability rule for seagoing vessels, applies for the examination of vessels on inner waters as well. It is probable that the circumstances taken into account in selecting the limit angle referred to above will always limit the value of the angle to considerably below 40°.

§ 2. The Drawing of the Work Lever Curves due to the Rudder Pressure and the Centrifugal Force.

When studying the effect of the heeling moments arising when the vessel turns, from a minimum stability point of view, the first task is to choose from the moments those that, by reason of their amounts or suddenness, are more dangerous than others. When the rudder of a vessel going straight ahead is suddenly put over, in the centre $S_r$ of area of rudder a pressure arises, whose component perpendicular to the vessel's middle plane forms, together with the force of inertia acting upon the vessel's centre of gravity $G$, a heeling moment.
The vessel heels under the action of this moment to begin with onto the same side to which the rudder was shifted, as $S_g$ almost without exception lies lower down than $G$ in all vessels. The heel reaches its highest extent, when the work done by this moment equals the work done by the stability moment of the vessel. Two additional forces arise: in $G$ the centrifugal force acting outwards from the turning centre and a pressure acting upon the centre $S_g$ of the lateral plane — the submerged middle line plane — which prevents the vessel from drifting outwards, thus neutralizing the action of the rudder pressure and the centrifugal force. It now depends upon the difference in height of these three forces' points of action and of the amounts of the forces, whether the vessel heels outwards or inwards in relation to its turning centre.

Our lake vessels have generally always the point $G$ above the point $S_g$ and the points $S_1$ and $S_g$ lie very near another. but as a rule so that $S_1$ lies below $S_g$. In this investigation, particular attention will therefore be given to the movements of this kind of vessel during the time of turning.

We assume that the points of action of the forces lie as explained above. Such a vessel having heeled, immediately after the rudder was put over, towards the turning centre, inwards, it heels by the action of the gradually increasing centrifugal force outwards, rolls for a moment to both sides of its position of equilibrium and finally remains definitely at an outward heel. The amplitude of the first roll outwards is determined by the work done by the heeling moment and the counteracting moments, the position of stable equilibrium is determined by the amounts of these moments.

If the rudder of a turning vessel is suddenly put over to the other side, the moment of the rudder pressure, which has suspended the action of a part of the centrifugal force moment, vanishes — we assumed that $S_g$ lay below $S_1$, and in its stead a new moment of the force of inertia arises. For these reasons the heel, which has reached its permanent value during the turning, increases momentarily, until the forces due to the new turning movement change their direction, and the vessel heels to the other side, again for a moment rolls to both sides of its position of equilibrium, and remains during the continuation of the new turning direction finally at a permanent heel.

Therefore, in studying the vessel’s stability the first object is to find among the vessel’s movements explained above the one that causes the greatest momentary heeling angle. In the technical literature on the subject is generally assumed that the most dangerous of the forces arising when a vessel turns is the centrifugal force, and as the greatest heel it brings about has been assumed the statical angle of equilibrium which it causes or the dynamical roll which it might effect by sudden action. In the latter manner the greatest heel is determined i. a. in Pierrotti’s judging method [P 3], and the same calculating method has been applied by Kempf in examining into the accident to the Rau III. The author having come, on the basis of his experience, to doubt very much the adaptability of this kind of calculating method to all vessels, it has been necessary to have recourse to experiments.

In the summer of 1938 two series of turning trials were performed with a large number of vessels in calm water. Among the vessels there were both lake and coastal boats. The programme for the trials and the angles measured during them were as follows:

**Trial series I:**
- Straight ahead
- Rudder suddenly to P.
- Turn to P.

**Trial series II:**
- Straight ahead
- Rudder suddenly to SB.
- Turn to SB.
- Rudder suddenly to P.
- Turn to P.
- Rudder suddenly midsh.
- Straight ahead

**Measured heel:**
- $\varphi_1$
- $\varphi_2$
- $\varphi_3$
- $\varphi_4$
- $\varphi_5$

By using the heeling indicator designed by the author [R 9], a curve illustrating the vessel's heelings in each trial series was drawn, and an explanatory diagram with the symbols corresponding to the trial programme is given in Fig. 42. The heeling curves of ten vessels tried are given in Figs. 43 to 62. All of the vessels were normal passenger vessels for our inner waters. From the curves the values of different angles of heel have been taken and gathered together in table 14, in which also the height difference $l$ between the centres of gravity $S_g$ and $S_1$ is shown.
Of the heeled measured the angles $\psi_3$ and $\psi_4$ are statical angles of equilibrium; the others are dynamical amplitudes of roll. For comparing these angles with one another table 15 has been calculated, where the values of the greater dynamical amplitudes are presented as percentages of the statical angles of equilibrium.

When examining the diagrams and tables attention is drawn to the comparatively great irregularity of the trial results. This is due to the fact that, although the conditions in which most experiments were made were most ideal, there always arise of necessity certain disturbing factors.

### Table 15.

Differences between the dynamical and statical angles of heel in percentages of the statical angles of heel.

<table>
<thead>
<tr>
<th>Name of vessel</th>
<th>$(\psi_3 - \psi_2)$</th>
<th>$(\psi_3 - \psi_2)$</th>
<th>$(\psi_4 - \psi_4)$</th>
<th>$(\psi_4 - \psi_4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of $\psi_2$</td>
<td>% of $\psi_2$</td>
<td>% of $\psi_4$</td>
<td>% of $\psi_4$</td>
</tr>
<tr>
<td>Exp.</td>
<td>I</td>
<td>II</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>Taru .</td>
<td>43</td>
<td>50</td>
<td>91</td>
<td>133</td>
</tr>
<tr>
<td>Kaima .</td>
<td>89</td>
<td>0</td>
<td>233</td>
<td>218</td>
</tr>
<tr>
<td>Taranne .</td>
<td>23</td>
<td>14</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Pokjola .</td>
<td>25</td>
<td>32</td>
<td>100</td>
<td>121</td>
</tr>
<tr>
<td>Kuru .</td>
<td>27</td>
<td>0</td>
<td>255</td>
<td>290</td>
</tr>
<tr>
<td>Leppävirto I .</td>
<td>7</td>
<td>27</td>
<td>72</td>
<td>60</td>
</tr>
<tr>
<td>Leppävirto II</td>
<td>41</td>
<td>36</td>
<td>186</td>
<td>132</td>
</tr>
<tr>
<td>Karjalankoski</td>
<td>12</td>
<td>17</td>
<td>131</td>
<td>200</td>
</tr>
<tr>
<td>Louhi .</td>
<td>43</td>
<td>25</td>
<td>164</td>
<td>87</td>
</tr>
</tbody>
</table>

N. B. The vessel Jyväskylä has been left out of the table because of the inexactitude of the experiment.

such as the torsional moment of the propeller and its possible variation, some person moving from his place during the test, etc. From the results, although they cannot be held to be very exact, several interesting conclusions may be drawn, which greatly explain the question under debate. A brief summary of the observations is given here.

1. The first angle of heel $\psi_1$ of a vessel, to the side to which the rudder is put over suddenly, is comparatively great. Out of twenty experiments, this angle was in five (25 %) greater than or equal to the sudden outward heel $\psi_1'$ caused by the centrifugal force and in twelve (60 %) it was greater than the statical angle of equilibrium $\psi_2$, which is maintained unaltered during the whole of the turn.

2. The dynamical angle of heel $\psi_3$, by which the vessel inclines outward immediately when the centrifugal force begins to act, is rather
slight compared with the statical angle of equilibrium $\varphi_s$. The difference between these angles was greater than 50% of the statical angle only in two experiments out of 18 (appr. 11%), and it was only 25% or less in 9 experiments (50%). The result is amazing, because if the centrifugal force should begin to act suddenly and if the frictional force be left out of account, the difference would be about 100%. The phenomenon is doubtless due to the fact that the centrifugal force begins to act, particularly upon the examined ships that have a hand-rudder, slower than expected.

3. As stated already, the angle of heel of a vessel making a turn to port (starboard) increases momentarily outwards, to starboard (port), if the rudder be suddenly put hard over to starboard (port). The increase of the heel ($\varphi_s - \varphi$) is remarkably great, so great that the result was practically without exception for all the experiment vessels the greatest heel $\varphi_s$ of the whole manoeuvre. The increase of the heel was in only 5 experiments (appr. 28%) less than 100% of the statical angle, and similarly in 5 experiments it was 200% or greater, in 2 trials even above 250%. When the rudder of a vessel turning to port (starboard) is suddenly put hard over to starboard (port), the vessel thus heels just before the turning direction is changed for a moment outwards from the former turning centre, to starboard (port). One might presume that the centrifugal force arising due to the new turning movement would therefore incline the vessel very much in the opposite direction, i.e. that the dynamical angle of roll $\varphi_H$ would have to be far greater than the statical angle of equilibrium $\varphi_s$. According to the results of the experiments, this is however by no means the case. The difference between the angles $\varphi_s$ and $\varphi_H$ was comparatively small: only in two experiments (appr. 11%) it was greater than 50% of $\varphi_s$, and a difference under 25% was found in 10 trials (appr. 55%). The result was thus exactly the same as when the rudder was put over from the midship position. This is due to the simple reason that, when gradually changing the turning direction of the vessel, the earlier centrifugal force first vanishes, and a new one begins to act in the opposite direction at the same relative instant in regard to the turning motion as when turning from the straight course. This is also evident from the curves drawn with the help of the heeling indicator, these curves proving that for different vessels the heeling velocity becomes slower when the vessel has reached its upright position.

5. When the rudder of a turning ship is suddenly righted, the heel outwards still increases for a moment. This increase of the angle of heel ($\varphi_s - \varphi$) is comparatively great. It must be observed that this heel belongs to the same size as the dynamical heel caused by the rudder of a turning vessel being put hard over to the other extreme position. Even this increase of angle of heel was only in five trials (appr. 28%) smaller than 100%, and it was 200% or more in 5 trials. This is a proof that the incline is principally due to the vanishing of the moment caused by the rudder pressure and the lateral resistance of the hull. The action of the moment caused by the rudder pressure and the force of inertia of the ship on the amount of incline is instead smaller.

Provided this is correct, both the angle ($\varphi_s - \varphi$) and the angle ($\varphi_s - \varphi_H$) ought to increase in comparison to the statical angles of equilibrium $\varphi_s$ and $\varphi_H$, with the increase of the moment raised by the rudder pressure and the lateral resistance. This moment again is proportional to the vertical distance $l$ between the centres of gravity $S_s$ and $S_H$. If the distance $l$ of one vessel is greater than that of another, the difference between the said angles ought also to be greater. We see by the experiments that such a law prevails. This is clearly shown by table 16, where the experiment ships are arranged in the order of the increasing distance $l$, and at the side is indicated for each vessel the average difference between the dynamical and statical angles of heel, in percentages of the average of the latter heels.

Table 16.

<table>
<thead>
<tr>
<th>Name of ship</th>
<th>Distance $l$ m</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pohjola</td>
<td>0.074</td>
<td>132</td>
</tr>
<tr>
<td>Leppävirta I</td>
<td>0.193</td>
<td>67</td>
</tr>
<tr>
<td>Taru</td>
<td>0.208</td>
<td>109</td>
</tr>
<tr>
<td>Louhi</td>
<td>0.208</td>
<td>118</td>
</tr>
<tr>
<td>Tärjanne</td>
<td>0.236</td>
<td>126</td>
</tr>
<tr>
<td>Karjalankoski</td>
<td>0.310</td>
<td>137</td>
</tr>
<tr>
<td>Leppävirta II</td>
<td>0.354</td>
<td>192</td>
</tr>
<tr>
<td>Kuru</td>
<td>0.357</td>
<td>232</td>
</tr>
</tbody>
</table>

The experiment with the S.S. Kaima is omitted from the table, because the distance $l$ of this ship could not be determined, as well as the experiment with the S.S. Jyväskylä, because it is not reliable, having been performed in narrow waters.

The table shows that the dynamical angle of heel generally increases with an increasing distance $l$. An exception is only found in the experiment with the S.S. Pohjola; this exception is due to some accidental circumstance, some error in drawing, or possibly some slight motion of waves while the trial was performed.
If the calculated results of table 16 are presented graphically, we see that, when the distance \( l \) approaches zero, the said \% value approaches about 30 \% to 40 \%, or a figure which is far smaller than the \% values obtained in the experiments. The conclusion drawn above, regarding what mainly causes the dynamical angle of heel of a vessel when the rudder is put midships or hard to the opposite position, can thus be held to be proved.

6. The experiments show that, when the rudder of a vessel is put midships or hard to the opposite position, a dynamical inclining directed outwards arises (\( \varphi_y - \varphi_2 \) and \( \varphi_z - \varphi_3 \)) the amount of which is far greater than the statical angle of equilibrium (\( \varphi_2 \) and \( \varphi_3 \)), which is caused by the centrifugal force of the turning vessel, and also far greater than the dynamical angle of heel (\( \varphi_y - \varphi_1 \) and \( \varphi_z - \varphi_1 \)), which arises on first putting the rudder over. The selection of the latter angle, as the greatest heel arising during the period of the turning manoeuvre, does not seem correct according to the trial series. — The experiments also show that, assuming the vessel's centrifugal force to begin to act suddenly, as for instance Pierrot has done [P 3], one obtains as the result of the calculation a heel, which exceeds by far the value of the actually produced heel. Even for this reason the determining by calculating the maximum heel (\( \varphi_y' \) and \( \varphi_z' \)), first brought about by the centrifugal force and its application as a basis for the study of stability, is uncertain.

The examination has been performed above by using percentage figures. This has been possible because the amount of stability of the vessels examined is approximately the same, and the angles of heel of the vessels do not differ very much from one another. If the initial stability were to vary so much that the statical angles of equilibrium would be of unequal size in different ships, the use of percentage figures for a comparison between the dynamical and statical heels would not be possible.

For all the experiment vessels the most dangerous rudder manoeuvre is the one, in which the rudder of a turning vessel is suddenly put midships or to the opposite side. This observation cannot be generalized, nor can one say that it applies even to the experiment ships, when their stability has been considerably reduced, for instance by a deck cargo. Despite that, this rudder manoeuvre is used as the foundation for the present study of the stability on account of a practical point of view. If once a vessel's stability is poor, its master will generally avoid making a sudden turn, i.e. he will at the beginning of a turn put the rudder gradually to the other side. For that reason, one may say that the first dynamical angle of heel \( \varphi_y' \) is in practice only very slightly greater than thestatical angle. Instead, the master may at the end of a turn more carelessly put the rudder quite suddenly midships; this he can do especially when he is afraid of his vessel beginning to heel outwards from the turning centre for some other reason, for instance the action of the wind. Then the manoeuvre concerned may become dangerous to the vessel. — The second reason for choosing the method is the difficulty in theoretically determining the angle \( \varphi_y' \).

In the following the closer study of the heeling moment brought about by the said rudder manoeuvre, and the amount of work done by that moment, will be presented, and on that basis will be calculated the minimum value of the dynamical lever required by this work.

After the rudder is put over and the vessel being on the turning circle, the vessel is heeled only by the moment \( M_i \) due to the centrifugal force acting upon the centre of gravity \( G \) and the pressure of water acting upon the centre of area of the submerged middle line plane \( S_c \). The action of this moment is counteracted by the moment \( M_2 \) due to the rudder pressure, and the statical stability moment \( M_{st} \). The statical state of equilibrium is thus reached, when:

\[
M_{st} = M_i - M_2. \tag{40}
\]

We denote the heeling angle corresponding to this state of equilibrium with \( \varphi_h \) (= angle \( \varphi_3 \) in Fig. 62 and in the tables of the results of the experiments). If hereupon the rudder be suddenly put over to the opposite side or midships, which manoeuvres according to the experiments performed cause a heel of approximately the same amount, the vessel remains momentarily subjected to the influence of moment \( M_i \) only. The vessel therefore heels so much that the work done by this moment and the stability moment are of the same amount. Thus the vessel reaches the heel \( \varphi_h \) (Fig. 63). This angle is, on the principle stated above, determined by the equation:

![Fig. 63](image-url)
\[ \int_{\varphi_0}^{\varphi_0} M_{\varphi} d\varphi = \int_{\varphi_0}^{\varphi_0} M_{\varphi} d\varphi. \]  (41)

The equation is not exact, because one active force, the friction between the water and hull, is neglected. It must be said in addition that the putting of the rudder midships naturally takes a certain time, wherefore the steadying effect of the moment \( M_{\varphi} \) is not removed in an instant.

Equation (41) is fit for use, when we wish to determine the greatest heel arising in the turning of our lake vessels. But in estimating a stability, it must be assumed that the vessel is heeled by other moments as well as by the centrifugal force and the rudder pressure, and that the heel in the most unfavourable case continues to the greatest allowed heeling angle \( \varphi \). Here the moment of the centrifugal force does the work:

\[ L_{\varphi} = \int_{\varphi_0}^{\varphi_0} M_{\varphi} d\varphi, \]  (42)

and the part of the dynamical lever which is sufficient for nullifying this work is:

\[ e_{\varphi} = \frac{L_{\varphi}}{D}. \]  (43)

This dynamical lever corresponds to the heel \( \varphi_{\text{eq}} \rightarrow \varphi_{\text{eq}} \); if we denote the dynamical lever corresponding to the state of equilibrium \( \varphi_{\text{eq}} \) with \( e_{\varphi_{\text{eq}}} \), then the sufficient minimum value of the dynamical lever, which a turning vessel heeling in the most unfavourable circumstances must have, is:

\[ e_{\varphi} = e_{\varphi_{\text{eq}}} + e_{\varphi}. \]  (44)

For using the equations, we must know the functions \( M_{\varphi} \) and \( M_{\varphi_{\text{eq}}} \). When determining the heeling moment caused by the centrifugal force, we may abandon the exact calculating method presented by Pollard & Dudderidge [P 5, Tome IV, pages 90 to 94], and assume approximately that the drift angle of the vessel is zero. This assumption is made generally in all handbooks on stability of ships (for instance [H 4]), and it has also been agreed upon in official examinations of accidents [R 18]. The heeling moment caused by the centrifugal force acting upon the vessel's centre of gravity \( G \) and the water pressure acting upon the centre of the lateral plane \( S_{\lambda} \) is thus:

\[ M_{\varphi} = \frac{D v_{b}^{2}}{g} \cos \varphi, \]  (45)

where \( v \) is the vessel's mean speed on the circle (m/sec), \( b \) the vertical distance (in m) between the centre of gravity \( G \) and \( S_{\lambda} \), \( g \) the acceleration due to gravity (m/sec\(^2\)) and \( \varphi \) the radius of the vessel's turning circle (m). For the graphical solving of the equation, we write:

\[ k_{\varphi} = \frac{v_{b}^{2}}{g} \cos \varphi = \frac{1}{k_{1}} \frac{v_{b}^{2}}{g} \]  (46)

where \( v_{b} \) is the vessel's speed in knots, and draw a diagram for the variations of the factor \( k_{\varphi} \cdot \cos \varphi \), wherein \( k_{1} \) obtains the values 0.02 to 0.10 (Fig. 64). If the vessel's stability is fairly great, so that the value of \( \varphi_{\text{eq}} \) is comparatively small, we can without committing any great error write \( \cos \varphi = 1 \) and use instead of the curve group of Fig. 64 the group of the horizontal straight lines \( k_{1} = 0.02 \), \( k_{1} = 0.03 \), etc. The curves (or the horizontal straight lines) may well be drawn on transparent paper in the same scale as the stability arm curves of the vessel are drawn.

Table 17.

<table>
<thead>
<tr>
<th>( \varphi )</th>
<th>0°</th>
<th>2.5°</th>
<th>5.0°</th>
<th>7.5°</th>
<th>10.0°</th>
<th>12.5°</th>
<th>15.0°</th>
<th>17.5°</th>
<th>20.0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{1} )</td>
<td>0.02</td>
<td>0.0200</td>
<td>0.0199</td>
<td>0.0198</td>
<td>0.0197</td>
<td>0.0195</td>
<td>0.0193</td>
<td>0.0191</td>
<td>0.0188</td>
</tr>
<tr>
<td>0.03</td>
<td>0.0200</td>
<td>0.0300</td>
<td>0.0299</td>
<td>0.0298</td>
<td>0.0297</td>
<td>0.0296</td>
<td>0.0294</td>
<td>0.0292</td>
<td>0.0289</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0400</td>
<td>0.0400</td>
<td>0.0398</td>
<td>0.0397</td>
<td>0.0396</td>
<td>0.0395</td>
<td>0.0394</td>
<td>0.0392</td>
<td>0.0389</td>
</tr>
<tr>
<td>0.05</td>
<td>0.0500</td>
<td>0.0499</td>
<td>0.0498</td>
<td>0.0497</td>
<td>0.0496</td>
<td>0.0495</td>
<td>0.0494</td>
<td>0.0493</td>
<td>0.0491</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0600</td>
<td>0.0599</td>
<td>0.0598</td>
<td>0.0597</td>
<td>0.0596</td>
<td>0.0595</td>
<td>0.0594</td>
<td>0.0593</td>
<td>0.0591</td>
</tr>
<tr>
<td>0.07</td>
<td>0.0700</td>
<td>0.0699</td>
<td>0.0698</td>
<td>0.0697</td>
<td>0.0696</td>
<td>0.0695</td>
<td>0.0694</td>
<td>0.0693</td>
<td>0.0692</td>
</tr>
<tr>
<td>0.08</td>
<td>0.0800</td>
<td>0.0799</td>
<td>0.0798</td>
<td>0.0797</td>
<td>0.0796</td>
<td>0.0795</td>
<td>0.0794</td>
<td>0.0793</td>
<td>0.0792</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0900</td>
<td>0.0899</td>
<td>0.0898</td>
<td>0.0897</td>
<td>0.0896</td>
<td>0.0895</td>
<td>0.0894</td>
<td>0.0893</td>
<td>0.0892</td>
</tr>
<tr>
<td>0.10</td>
<td>0.1000</td>
<td>0.0999</td>
<td>0.0998</td>
<td>0.0997</td>
<td>0.0996</td>
<td>0.0995</td>
<td>0.0994</td>
<td>0.0993</td>
<td>0.0992</td>
</tr>
</tbody>
</table>

For determining the heeling moment \( M_{\varphi} \), caused by the rudder pressure acting in the centre \( S_{\varphi} \) of area of rudder and the counter force acting upon the centre \( S_{\varphi} \) of the lateral plane, we may use Rankine's equation modified by Middendorf [J 2], according to which the amount of the perpendicular pressure against the rudder surface is (in tonnes):

\[ Q = 0.011 F (1.2 v_{b})^{2} \sin^{2} \alpha, \]  (47)

and thus the heeling component of this force:

\[ Q' = 0.011 F (1.2 v_{b})^{2} \sin^{2} \alpha \cos \alpha. \]  (48)

In the equations, \( F \) is the area (m\(^2\)) of the rudder and \( \alpha \) the rudder angle. The upsetting moment arising is doubtless in some way dependent
upon the vessel's angle of heel, but no great error is committed when we assume that the moment remains, within the bounds of so small angles as come into question when determining the angle $v$, a constant. If we denote the vertical distance between $S_r$ and $S_t$ with $l$ (in m), and write:

$$k_2 = 0.011 \left(1.2 v_2\right)^3 \sin^2 \alpha \cos \alpha,$$

(49)

we obtain:

$$M_\alpha = k_2 \cdot Fl.$$

(50)

For facilitating the solving of this equation as well, a diagram is drawn from which the value of factor $k_2$ can be measured, when the rudder angle $\alpha$ and the vessel's speed $v_2$ are known (Fig. 65). The values of the factor are also obtained from table 18.
### Table 18.

Values of factor \( k_0 \)

<table>
<thead>
<tr>
<th>( v )</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16 knots</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>0.219</td>
<td>0.278</td>
<td>0.343</td>
<td>0.415</td>
<td>0.494</td>
<td>0.580</td>
<td>0.672</td>
<td>0.772</td>
<td>0.875</td>
</tr>
<tr>
<td>35°</td>
<td>0.273</td>
<td>0.346</td>
<td>0.427</td>
<td>0.517</td>
<td>0.615</td>
<td>0.721</td>
<td>0.837</td>
<td>0.960</td>
<td>1.093</td>
</tr>
<tr>
<td>40°</td>
<td>0.321</td>
<td>0.406</td>
<td>0.501</td>
<td>0.607</td>
<td>0.722</td>
<td>0.847</td>
<td>0.983</td>
<td>1.128</td>
<td>1.283</td>
</tr>
<tr>
<td>45°</td>
<td>0.358</td>
<td>0.454</td>
<td>0.560</td>
<td>0.678</td>
<td>0.806</td>
<td>0.946</td>
<td>1.098</td>
<td>1.260</td>
<td>1.434</td>
</tr>
<tr>
<td>50°</td>
<td>0.382</td>
<td>0.484</td>
<td>0.597</td>
<td>0.723</td>
<td>0.860</td>
<td>1.010</td>
<td>1.171</td>
<td>1.344</td>
<td>1.530</td>
</tr>
<tr>
<td>55°</td>
<td>0.390</td>
<td>0.494</td>
<td>0.610</td>
<td>0.738</td>
<td>0.878</td>
<td>1.030</td>
<td>1.195</td>
<td>1.372</td>
<td>1.561</td>
</tr>
<tr>
<td>60°</td>
<td>0.380</td>
<td>0.481</td>
<td>0.594</td>
<td>0.719</td>
<td>0.855</td>
<td>1.004</td>
<td>1.164</td>
<td>1.337</td>
<td>1.521</td>
</tr>
<tr>
<td>65°</td>
<td>0.352</td>
<td>0.445</td>
<td>0.550</td>
<td>0.663</td>
<td>0.792</td>
<td>0.929</td>
<td>1.076</td>
<td>1.237</td>
<td>1.468</td>
</tr>
</tbody>
</table>

As the stability curves are most generally presented as stability arm curves, it is best to change the heeling moments due to the centrifugal force and the rudder pressure into expressions of the moment arm, assuming that the upsetting force equals the displacement of the vessel. Thus we find the moment arm due to the centrifugal force to be:

\[
 h_c = h_1 \cos \varphi \approx h_1,
\]

and the moment arm due to the rudder pressure:

\[
 h_r = h_2 \frac{F_l}{D},
\]

As the statical state of equilibrium, i.e. the heeling angle \( \varphi_b \), is reached when the vessel's stability arm \( h \) fulfills the condition:

\[
 h = h_b - h_{33}
\]

we obtain the value for \( \varphi_b \) by placing a diagram according to Fig. 64 drawn on transparent paper, or the line-group \( h_1 = 0.02, h_2 = 0.03 \ldots \) upon the stability arm curve drawn to the same scale, so that the \( \varphi \) axis of Fig. 64 lies a distance \( h_b \) lower than the \( \varphi \) axis of the stability arm curve and parallel to it, and then seeking the point of intersection between the stability arm curve and the curve corresponding to the true value of \( h_1 \). If necessary, one can by interpolation draw in the diagram a part of the actual \( h_1 \) curve (Fig. 66).

Once we know the angle \( \varphi_b \), we obtain the dynamical lever \( e_b \) corresponding to it, either directly from the dynamical lever curve or by planimetering the hatched area of Fig. 66.

For the determining both of \( \varphi_b \) and \( e_b \) one may also use the initial metacentric height method, under assumption that the statical angle of heel arising is not greater than from 5 to 10 degrees. The value of the heel can then be calculated from equation:

\[
 h_l = h_2 \frac{F_l}{D} \sin \varphi_b = \frac{c_0}{c_0} (1 - \cos \varphi_b),
\]

and the value of \( e_b \) from equation:

\[
e_b = c_0 \int_0^{\varphi_b} \sin \varphi d\varphi = c_0 (1 - \cos \varphi_b).
\]

There still remains the dynamical lever \( e_b \) to be determined, when the limits \( \varphi_b \) and \( \varphi_b \) of the dynamical heeling are known. As \( \varphi \) is always comparatively great, \( \cos \varphi_b \) is not allowed to be given as 1. On the basis of equations (43), (45) and (46), we obtain:

\[
e_b = h_1 \int_{\varphi_b}^{\varphi} \cos \varphi d\varphi = h_1 (\sin \varphi_b - \sin \varphi_b).
\]

The equation can be quickly solved with the help of the group of curves Fig. 67. The lever \( e_b \) can be obtained direct from it by drawing ordinate lines corresponding to \( \varphi \), and \( \varphi \), in it and measuring the vertical distance between the points of intersection of the ordinates and the curve corresponding to the right coefficient \( h_1 \).

Thus we finally get to know the sufficient minimum value of the dynamical lever required for the turning manoeuvre:

\[
e_b = e_b + e_r.
\]
When using equations (46) and (49) as well as tables 17 and 18 or diagrams 65 and 67, it must be noted that the vessel’s mean speed on the turning circle is not the same as the speed when running straight ahead. Comparatively few investigations regarding how much less the mean speed on the circle is than the approach speed have been made, nor has the author had opportunities for performing any. Some guidance is obtainable, however, from technical literature on the subject.

Table 19.  
Expression $k_1 \cdot \sin \varphi$.

<table>
<thead>
<tr>
<th>$\varphi$</th>
<th>$5^\circ$</th>
<th>$10^\circ$</th>
<th>$15^\circ$</th>
<th>$20^\circ$</th>
<th>$25^\circ$</th>
<th>$30^\circ$</th>
<th>$35^\circ$</th>
<th>$40^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.0017</td>
<td>0.0033</td>
<td>0.0052</td>
<td>0.0066</td>
<td>0.0084</td>
<td>0.0100</td>
<td>0.0115</td>
<td>0.0129</td>
</tr>
<tr>
<td>0.03</td>
<td>0.0026</td>
<td>0.0032</td>
<td>0.0078</td>
<td>0.0103</td>
<td>0.0137</td>
<td>0.0169</td>
<td>0.0200</td>
<td>0.0229</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0033</td>
<td>0.0069</td>
<td>0.0103</td>
<td>0.0137</td>
<td>0.0169</td>
<td>0.0200</td>
<td>0.0229</td>
<td>0.0237</td>
</tr>
<tr>
<td>0.05</td>
<td>0.0032</td>
<td>0.0087</td>
<td>0.0129</td>
<td>0.0171</td>
<td>0.0211</td>
<td>0.0250</td>
<td>0.0287</td>
<td>0.0321</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0032</td>
<td>0.0104</td>
<td>0.0135</td>
<td>0.0203</td>
<td>0.0254</td>
<td>0.0300</td>
<td>0.0344</td>
<td>0.0386</td>
</tr>
<tr>
<td>0.07</td>
<td>0.0032</td>
<td>0.0122</td>
<td>0.0151</td>
<td>0.0239</td>
<td>0.0296</td>
<td>0.0350</td>
<td>0.0402</td>
<td>0.0450</td>
</tr>
<tr>
<td>0.08</td>
<td>0.0032</td>
<td>0.0139</td>
<td>0.0207</td>
<td>0.0274</td>
<td>0.0338</td>
<td>0.0400</td>
<td>0.0459</td>
<td>0.0514</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0032</td>
<td>0.0156</td>
<td>0.0233</td>
<td>0.0308</td>
<td>0.0380</td>
<td>0.0450</td>
<td>0.0516</td>
<td>0.0579</td>
</tr>
<tr>
<td>0.10</td>
<td>0.0032</td>
<td>0.0174</td>
<td>0.0259</td>
<td>0.0342</td>
<td>0.0423</td>
<td>0.0500</td>
<td>0.0574</td>
<td>0.0643</td>
</tr>
</tbody>
</table>

According to Bertin’s information [B 40], the ratio between the said speeds of the battleship Henri IV was 0.537 and 0.577; the rudder angle was then 28°. Doyère [D 5] gives the ratio as 0.7 to 0.75, if the rudder angle is 35°, but, if the area of rudder is very large and the vessel’s turning radius small, the ratio may according to one test be 0.43 to 0.50 only. Lamouché says [L 1] that this ratio may be as high as 0.70, and Mackerrow-Woollard [M 1] states that the speed on the circle after turning 180° drops to one half; even to one third of the approach speed. According to the model trials made by Kempf with the Rau III, the said ratio was 0.58 [R 18], but it must be observed that the area of that vessel’s rudder was abnormally large. In conclusion may be mentioned the experiments made by Cole with destroyers [C 12]. According to them, the ratio of the speeds in question varied from 0.70 to 0.76, when the vessel’s approach speed varied from 6 to 32 knots and the rudder angle was 35°.

In virtue of all these data gathered from literature one may assume for the ratio, between the speeds of a turning vessel and one running straight ahead, the figure 0.75. It is possible that the ratio may be smaller in some vessel, but it is safest to choose for general use so high a figure that it will probably never be exceeded. As the speed, which must be inserted in the $k_1$ and $k_2$ equations and the tables, we may therefore write

0.75 $v_c$.

§ 3. The Drawing of the Work Lever Curve due to the Wind Pressure.

The exact determining of the heeling moment due to the wind and the work done by it is not easy. Already the right choice of the unit pressure is difficult, because the exposed surface of a vessel is made up of so many different parts. In addition ought also to be made clear: the relation between the wind pressure and the vessel’s heeling angle, the choosing of the maximum wind pressure, the variation of the wind’s velocity and pressure at different heights, the influence of the vessel’s speed, etc. All this makes the complete solving of the question not only difficult but also extremely complicated; one must therefore to begin with agree upon certain assumptions for facilitating the solution.

1. A steady wind is assumed to remain steady, and a gust assumed to reach its full force immediately and to maintain a constant speed during the whole time of the vessel’s heel.
2. The diminishing of the relative velocity of the wind due to the vessel's heel is left out of account.

3. It is assumed that the wind blows perpendicularly to the vessel's middle line plane and that the vessel's speed has no influence on the wind pressure.

4. It is assumed that the unit pressure of the wind is independent of the nature of the different parts of the exposed surface of the vessel, the so-called wind surface, and also independent of the inclination of the surface to the wind.

5. The vessel's heeling resistance is left out of account.

All above assumptions are such as are almost always made when examining the heeling effect of the wind. In addition to the above, certain investigators have made further assumptions, which have led to different expressions for the heeling moment. In the following will first be examined the movements of a vessel in a wind, assuming that the expression for the heeling moment \( M_1 = f(\psi) \) is known, and then investigated what is the situation most dangerous to the vessel's stability.

We assume that the vessel is subjected to a steady beam wind and that the heeling moment caused by it is \( M_1 \); the vessel then gets a steady heel of the value \( \psi \), (Fig. 68). When the wind then suddenly increases to a gust, whose heeling moment is \( M_{1g} \), the vessel heels dynamically over in the same direction, until the work done by the new heeling moment and that done by the vessel's stability moment are equal, i.e. that the hatched surfaces in Fig. 68 are of equal size. The vessel thus heels over to the angle \( \psi_g \) which is the extreme heel it can get in the wind in question. A condition for this assumption is naturally that the speed of the sudden gust is the greatest possible.

In this investigation we assume that the heel is brought, under the influence of the various upsetting moments, as far as the limit angle \( \psi \). The influence of a gusty gale is the most unfavourable to the vessel, if

the ship, when it, for some reason or other, leaves its state of equilibrium \( \psi_g \) and at the same time is subjected to the most strong gust possible, which acts the whole time up to the limit angle \( \psi \). It is therefore necessary to determine separately, for explaining the state of equilibrium, the expression for the heeling moment of a steady wind, and separately the work done by the sudden gust of wind between \( \psi \) and \( \psi_g \).

We get to know angle \( \psi \), by writing the apparent moment arm due to the wind equal to the vessel's stability arm:

\[
h = \frac{M_1}{D} = h.
\]  

(56)

The work done by the wind between \( \psi_1 \) and \( \psi \), again is:

\[
L_1 = \int_{\psi_1}^{\psi} M_1 \, d\psi = \int_{\psi_0}^{\psi} M_1 \, d\psi - \int_{\psi_0}^{\psi_1} M_1 \, d\psi.
\]  

(57)

To this amount of work corresponds the dynamical lever \( e_1 \), the value of which is, if the displacement is assumed as the force doing work:

\[
e_1 = \frac{L_1}{D}.
\]  

(58)

If the dynamical lever corresponding to the steady angle of heel \( \psi_0 \) is \( e_{20} \), the total amount of the dynamical lever that the vessel must have for withstanding the influence of a gusty gale is:

\[
e_2 = e_{20} + \eta.
\]  

(59)

For solving the equation, the relation between the heeling moment due to the wind and the heeling angle must be determined. Before doing this, there is reason to find out what forms of functions other investigators have used.

One assumes in general, when examining the heeling influence of the wind, that the centre of wind pressure remains in the same place during the heel of the vessel, and that the centre of lateral resistance is situated at half draught of the vessel; and the centre of wind pressure one imagines to the centre of gravity of the surface exposed to the wind. — These general assumptions are also approved as foundations for the present investigation, excepting the last named. As the centre of wind pressure a point is chosen, which lies nearer the true centre of pressure than the centre of gravity of the exposed surface.

In shipbuilding handbooks the form of the heeling moment due to the wind is very generally given as:

\[
M_1 = \rho l R_1 \cos^n \psi,
\]
where \( p \) is the unit pressure of the wind, \( F_i \) the area of the wind surface
and \( l \) the vertical distance between the centre of pressure and half the
mean draught when the vessel is in an upright position. This form of
equation, which we arrive at when assuming a plane, instead of the vessel's
actual wind surface, has also been used in a stability investigation by
Holt [H 7]. Most investigators, however, abandon this form of equation
—which is adaptable for purposes of instruction—and write the heeling
moment due to the wind simply to be independent of the angle of heel.
That has been the procedure of L. a. Pierrrot [P 3], W. S. Abell
[W 6], Wall [W 6], Ott [O 3], Commentz [C 13] and Watanabe
[W 7]. All are not satisfied with such a simple expression for the heeling
moment; they wish, as Biles [B 24], Schwarz [S 43] and Cagnotto
[C 16], to calculate for each ship the wind surface's actual dependence
of the angle of heel.

None of the forms of functions or methods of procedure used pre-
viously suit the purpose of the present investigation. It is characteristic
of the vessels on our inner waters that the nature of their deck houses
varies very much. The passenger boats on the lakes, which must be
particularly observed in this study, are often built with the deck full
of houses, which reach from broadside to broadside and almost from
to stern of the vessel. If we were to imagine the wind surface of
such a vessel as a plane, which is situated on the vessel's middle line, this
would lead, when the vessel has a heel, to a far too small expression for
the heeling moment. To assume the moment arm of the wind moment
constant and independent of the angle of heel, is again a very uncertain
approximate method, which is not well grounded. Finally, to leave the
form of the expression of heeling moment for each vessel dependent
on its deck houses, etc., would lead to the judging of the stability
becoming too difficult in that part.

For that reason, the equation for the heeling moment due to the wind
pressure will in the following be formulated so that the action of the
width of the deck houses, upon the increase of the wind surface when
the vessel is inclined, will be taken into account.

In formulating the equation, it is presumed that the distance above
water of the centre of wind pressure is always proportional to the average
height of the wind surface and that the centre of lateral resistance is situated
at half draught of the vessel. The true total wind surface of the vessel
is substituted by a rectangular plane of the height \( H_1 \) and the distance of
this plane from the vessel's middle plane is \( B_1/2 \). It is further assumed
that the vessel's heeling axis is the line of intersection between the water
line and the middle line plane, and that it remains the same.

Fig. 69

We denote the actual wind surface when the vessel is upright by
\( F_i \), and the vertical distance of the centre of pressure from the vessel's
water line by \( nH_1 \). We further denote by \( \alpha \) the angle between the plane
going through the heeling axis and the upper edge of the assumed wind
surface, and the middle line plane (Fig. 69). When the vessel is heeled
to the angle \( \alpha \), the projected area exposed to the wind is:

\[
F_i' = \frac{F_i}{\cos \alpha}
\]

and as the angle of heel is \( \varphi \), the projected wind surface is:

\[
F_i'' = \frac{F_i \cos (\alpha - \varphi)}{\cos \alpha}.
\] (60)

The distance of the centre of pressure from the water line follows, on
the principle of the above assumption, the same law, so that the vertical
distance between the centre of pressure of a vessel having the angle of
heel \( \varphi \) and the water level is:

\[
nH_1'' = \frac{nH_1 \cos (\alpha - \varphi)}{\cos \alpha}.
\] (61)

It must be noted that the coefficient \( n \) ought really to be a function
of \( H_1 \), as will be shown later on. The variation of the coefficient is
however within the limits of \( H_1 \) here in question so slight, that the
coefficient may be considered constant.
The moment arm of the wind moment while the vessel is upright is \( nH_k + T/2 \), the part of the moment arm above water follows the law (61) and the submerged part is proportional to the cosine of the angle of heel. The following equation for the wind moment arm is then obtained:

\[
l = \frac{nH_k \cos (a-\varphi)}{\cos \alpha} + \frac{T}{2} \cos \varphi.
\] (62)

This being the case, and if \( p \) is the wind pressure per area unit, the heeling moment due to the wind then obtains the form:

\[
M = pF_k \left[ \frac{nH_k \cos^3 (a-\varphi)}{\cos^3 \alpha} + \frac{T}{2} \cos \varphi \cos \cos (a-\varphi) \right],
\] (63)

which is modified to the form:

\[
M = \frac{pF_k}{\cos^3 \alpha} \left[ nH_k \cos^3 (a-\varphi) + \frac{T}{2} \cos \varphi \cos \cos (a-\varphi) \right].
\] (64)

In determining the work done by this heeling moment, the work corresponding to the heel \( \varphi = \varphi \), can be obtained according to equation (57) by calculating separately the work corresponding to the heels \( \alpha = \varphi \), and \( \alpha = -\varphi \). We consider therefore hereafter the work quantity corresponding to the heel between the angles \( \alpha = \varphi \). The heeling work done by the wind then is:

\[
L = \int_{0}^{\varphi} \left[ \frac{nH_k \cos^3 (a-\varphi)}{\cos^3 \alpha} \cdot \cos \varphi + \frac{T}{2} \cos \varphi \cos \cos (a-\varphi) \right] d\varphi.
\] (65)

The definite integrals contained in the equation obtain the following values:

\[
\int_{0}^{\varphi} \cos^3 (a-\varphi) d\varphi = \frac{\sin 2\alpha}{4} \sin 2(a-\varphi) + \frac{\varphi}{2} + \frac{\sin 2\alpha}{4} \sin \varphi + \frac{\varphi}{2} \sin^2 \sin \alpha.
\]

The expression for the work done by the wind thus obtains the form:

\[
L = \frac{pF_k}{\cos^3 \alpha} \left[ \frac{nH_k \sin 2\alpha}{4} \sin 2(a-\varphi) + \frac{\varphi}{2} + \frac{T}{4} \left( \sin \varphi \cos \varphi + \varphi + \sin^2 \varphi \tan \alpha \right) \right].
\] (66)

For determining the steady angle of heel due to a steady wind, the state of equilibrium \( \varphi \), the equation (63) is divided by \( D \):

\[
h = \frac{pF_k}{D} \left[ nH_k f_1 (\varphi, \alpha) + \frac{T}{2} f_2 (\varphi, \alpha) \right],
\] (67)

in which

\[
f_1 (\varphi, \alpha) = \frac{\cos^3 (a-\varphi)}{\cos^3 \alpha}
\]

and

\[
f_2 (\varphi, \alpha) = \frac{\cos \varphi \cos (a-\varphi)}{\cos \alpha}.
\]

For determining the dynamical lever corresponding to the amount of dynamical stability, which is sufficient to absorb the whole work done by the wind, the equation (65) is divided by \( D \):

\[
e_i = \frac{pF_k}{D} \left[ nH_k f_1 (\varphi, \alpha) + \frac{T}{4} f_2 (\varphi, \alpha) \right],
\] (68)

where

\[
f_1 (\varphi, \alpha) = \frac{1}{2} \cos \alpha \sin 2\alpha \sin \varphi + \frac{\sin 2(a-\varphi)}{2} + \frac{\varphi}{2}
\]

and

\[
f_2 (\varphi, \alpha) = \sin \varphi \cos \varphi + \sin^2 \varphi \tan \alpha + \varphi.
\]

For a quick solving of the equations, tables giving the functions \( f_1 \), \( f_2 \), and \( f_1 \) have been calculated and the curve drawn (tables 20, 21, 22 and 23) and Figs. 70, 71, 72 and 73), from which the values of these functions are obtained for \( \varphi \) varying between \( 0^\circ \) and \( 40^\circ \) and \( \alpha \) obtaining the values \( 20^\circ \), \( 25^\circ \), \( 30^\circ \) . . . \( 55^\circ \).

<table>
<thead>
<tr>
<th>Table 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expression ( f_1 (\varphi, \alpha) = \frac{\cos^3 (a-\varphi)}{\cos^3 \alpha} ).</td>
</tr>
<tr>
<td>( a )</td>
</tr>
<tr>
<td>( 0^\circ )</td>
</tr>
<tr>
<td>( 5^\circ )</td>
</tr>
<tr>
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</tr>
<tr>
<td>( 35^\circ )</td>
</tr>
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<td>( 40^\circ )</td>
</tr>
</tbody>
</table>
Table 21.

Expression \( f_1(\varphi, \alpha) = \frac{\cos \varphi \cos (\alpha - \varphi)}{\cos \alpha} \)

<table>
<thead>
<tr>
<th>( \varphi )</th>
<th>( 20^\circ )</th>
<th>( 25^\circ )</th>
<th>( 30^\circ )</th>
<th>( 35^\circ )</th>
<th>( 40^\circ )</th>
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<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
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<td>1.033</td>
<td>1.043</td>
<td>1.053</td>
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<tr>
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<td>1.069</td>
<td>1.090</td>
<td>1.113</td>
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<td>1.143</td>
<td>1.183</td>
<td>1.231</td>
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</tr>
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<td>1.033</td>
<td>1.069</td>
<td>1.108</td>
<td>1.153</td>
<td>1.204</td>
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<td>1.043</td>
<td>1.090</td>
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<td>1.204</td>
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</tr>
</tbody>
</table>

Table 22.

Expression \( f_2(\varphi, \alpha) = \frac{1}{2 \cos^2 \alpha} \left[ \frac{\sin 2\alpha}{2} - \frac{\sin 2(\alpha - \varphi)}{2} + \varphi \right] \)

<table>
<thead>
<tr>
<th>( \varphi )</th>
<th>( 20^\circ )</th>
<th>( 25^\circ )</th>
<th>( 30^\circ )</th>
<th>( 35^\circ )</th>
<th>( 40^\circ )</th>
<th>( 45^\circ )</th>
<th>( 50^\circ )</th>
<th>( 55^\circ )</th>
</tr>
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<td>0.0000</td>
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<td>0.0092</td>
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</tr>
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</tr>
</tbody>
</table>

Table 23.

Expression \( f_3(\varphi, \alpha) = \sin\varphi \cos \alpha + \sin^2 \varphi \tan \alpha + \varphi \)

<table>
<thead>
<tr>
<th>( \varphi )</th>
<th>( 20^\circ )</th>
<th>( 25^\circ )</th>
<th>( 30^\circ )</th>
<th>( 35^\circ )</th>
<th>( 40^\circ )</th>
<th>( 45^\circ )</th>
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<tbody>
<tr>
<td>0°</td>
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<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>5°</td>
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<td>0.0179</td>
<td>0.0180</td>
<td>0.0185</td>
<td>0.0187</td>
<td>0.0183</td>
</tr>
<tr>
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<td>0.0363</td>
<td>0.0367</td>
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<td>0.0386</td>
</tr>
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<td>0.0535</td>
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<td>0.0540</td>
<td>0.0550</td>
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</tr>
<tr>
<td>20°</td>
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<td>0.0730</td>
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<td>0.0753</td>
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</tr>
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<td>1.6037</td>
<td>1.6829</td>
<td>1.7806</td>
</tr>
</tbody>
</table>

The values of the factors \( F_x, H_x, \psi \) and \( \alpha \) depend upon the manner in which another plane is substituted for the vessel's actual wind surface. The place and dimensions of this plane must be chosen so that one approaches the true circumstances as near as possible. Some rules for determining the wind plane are given hereafter, intended to be used...
especially for studying the capability of our lake passenger vessels to weather a gale. The rules can be applied to other vessels as well.

For the vessel's wind surface is substituted a rectangular-shaped wind plane whose surface area is equal to the vessel's actual side surface $F$, exposed to the wind, and whose length is equal to the mean $L'$ of the length of the actual deck houses and the extreme length of the vessel. The height of the plane will accordingly be:

$$H_s = \frac{F}{L'}$$

and such parts of the vessel's actual wind surface as the funnel, masts, rails of the bridge, etc., will thus be distributed partly on the vessel's length; thus such empty areas as remain at the forward and after parts of the deck houses will be partly filled out. The vessel's wind surface will thus be reduced at the top, where it is most exposed to the wind, but the error thus arising is not very great in our lake passenger steamers, as they are built, as stated already, with very crowded deck erections.

The wind plane is imagined to be standing at the other side of the vessel, parallel to the vessel's middle line plane. The distance of this plane from the middle line plane is $B_s/2$, where $B_s$ is the extreme breadth of the deck houses, provided this breadth does not vary much, or the average breadth of the deck erections, if the vessel has several deck houses of different breadth. When calculating the average breadth the following equation may be used:

$$B_s = \frac{B_1L_1 + B_2L_2 + \ldots}{L_1 + L_2 + \ldots}$$
where $B_1$, $B_2$, ... are the breadths of the different parts of the deck houses, and $L_1$, $L_2$, ... their lengths. It is evident that in estimating the breadth of the deck crests as shade-decks, boat bridges, etc. must be taken into account. It is quite as obvious that only the highest deck houses, their lengths and breadths, are to be measured when determining the magnitude of $B_i$.

When the value of $B_i$ is measured or calculated we obtain the value of angle $a$ from the equation:

$$
tan a = \frac{B_i}{2H_i}
$$

Any errors made in estimating the size of $B_i$ may appear very great and the whole determining of the breadth of the deck crests uncertain. The drawings of the vessel, however, being available for use, it is easy to imagine the wind plane in question placed so that it very exactly corresponds to the average wind surface. On the other hand, we know that — according to Figs. 70 to 73 — any small errors in the angle $a$ have no great influence on the equations of the moment arm of the wind moment and the work lever.

For determining the factor $n$, which indicates the relation between the height of the centre of wind pressure and the height of the wind surface, the law ought to be known according to which the wind's speed diminishes by the action of the frictional forces when approaching the water surface. With the help of meteorological and technical experiments Schönherr has determined such a law, and Commentz [C 13] has published curves indicating the relation between the wind pressure and the height of measuring calculated according to that law. With the help of these curves, the author has calculated the ratios between the heights of the centres of wind pressure and the heights of some rectangular-shaped planes, for a wind speed of about 30 m/sec, and the result is that this ratio varies very slightly within the limits of the variations of height that come into question for our lake vessels. If the height $H_i$ of the wind surface is for instance 3.0 m, the ratio is 0.594, and if the height is 5.0 m, the ratio falls to 0.588. We can on that basis denote for the height of the centre of wind pressure on all our lake vessels 0.59 · (the average height of the wind surface), i.e. we can write in equation (66) and (67):

$$
n = 0.59.
$$

There still remains to estimate the wind pressure per unit of area, which may come into question under conditions prevailing here.

The pressure due to a steady wind acting perpendicularly upon the surface unit of a plane is commonly written:

$$
p = k \cdot v^2,
$$

where $v$ is the speed of the wind and $k$ a coefficient to be experimentally determined. On the basis of experiments made by several investigators, Mackrow & Woollard [M 1, page 405] give in their handbook the average value of $k$ now usually employed for large plates as 0.0032 — velocity in feet/sec and pressure $p$ in Engl. lbs/sq. foot — which equals a value of 0.0782 for $k$, if the velocity is in m/sec and the pressure in kg/m². This same value for the coefficient has been used by Holt [H 7] as well, and it can also be taken into use in this investigation.

The wind speeds, which according to different investigators should be used for the study of the stability of vessels, vary to an astonishing degree. As proof of this may be given a short summary; where the force of the wind has been given in the sources as a pressure, the corresponding velocity of the wind has been calculated with the use of the coefficient $k = 0.0782$.

Holt [H 7] uses for seagoing vessels a velocity of 58.5 m/sec. In the English Channel 50 m/sec. is enough and in harbours and estuaries 43-3 m/sec.

According to Berry [H 7] a 1/4th of the pressure used by Holt is sufficient; that pressure corresponds to the wind speed of 29.2 m/sec.

According to Biles [B 44], the pressure of the strongest wind registered corresponds to a velocity of 46 m/sec and the average values registered in gales to a velocity of 39 m/sec.

Wall [W 6] uses the same large maximum value as Holt (about 59 m/sec), but he also studies the sufficiency of the stability on the basis of velocities of 49 and 39 m/sec.

Cagnotto [C 16] has chosen as the basis for a complete calculation example a wind of 33.3 m/sec., which according to his statement does not exceed the measurements made at Triest. This would appear to concern the velocity of a steady wind.

According to Castello [C 1], the velocity of the wind in most harbours of the world must be estimated at 32—36 m/sec., although at Triest gusts have been measured in which the pressure has risen to 200 kg/m²; that corresponds to a wind velocity of 50.6 m/sec.

Most of the wind velocities enumerated are far too great for being applied to vessels navigating in our conditions. According to Franssila [F 9], at the meteorological observatory Ilmna, winds of 17.45 m/sec. or stronger have blown during the period 1921—39 on the average
not more than about an hour a year. The greatest average velocity for an hour appearing in our country is, according to various informations gathered by the author, $\text{2} \text{to} 20$ to $35 \text{m/sec.}$ measured at a height of about $20 \text{m.}$ If the said maximum values be reduced by the use of SCHONEICH's curves [C 13] [2; page 544], for a height of $5 \text{m}$ above the water level, we obtain for the strongest wind in our country, appearing at that height, an average hourly velocity of $16$ to $20 \text{m/sec.}$ Although these figures only give an indication of the magnitude of the winds that come into question, and not their actual exact value, the higher of the figures can be taken in this study as the highest value appearing for a steady wind.

The velocity of gusts during gales is considerably greater than that of the mean value of a wind blowing for an hour. It is difficult to estimate the actual ratio between the said wind speeds. According to one datum available, the velocity of a gale gust can rise to double the value of the average velocity of the wind, according to another, the ratio of the velocities is $1 : 1.4$ only. WATANABE gives in one of his studies [W 7] this ratio as $1 : 1.3$, but for safety's sake he himself uses the coefficient $1.4$. It would thus appear to be sufficient, if we assume as the highest velocity appearing in our country in gusts during gales $28 \text{m/sec.}$ measured at a height of $5 \text{m}$ above water level, which equals a wind of $35 \text{m/sec.}$ measured at a height of $20 \text{m}$.

On the above basis we choose for the use in studying the stability as the maximum velocity of a steady wind $20 \text{m/sec.}$ and as the extreme value for the velocity of a sudden gust during a gale $28 \text{m/sec.}$

The highest value of $p$, which we may insert in equation (66) for determining the steady angle of heel of a vessel is thus $$p = 0.0782 \cdot 20^2 = 31 \text{ kg/m}^3 = 0.031 \text{ t/m}^2$$ and the highest pressure per unit area that can be taken into account in calculating the work done by the wind, equation (67), is $$p = 0.0782 \cdot 28^2 = 61 \text{ kg/m}^2 = 0.061 \text{ t/m}^2.$$ If the examined vessel will have to navigate on protected waters only, the values given for $p$ are excessive; in their stead lower values for $p$ must be given, which are determined by taking local conditions into account, starting from the velocity of a steady wind, and assuming that the velocity of a gust is at the utmost $1.4$ times greater than that of a steady wind, i.e. that the pressure in a gust is $1.96$ times greater than the pressure of a steady wind.

$\S$ 4. The Drawing of the Work Lever Curve due to the Movements of People on board.

The crowding of people on a vessel at one side or a sudden movement among them, due for instance to a panic, are factors that cannot be neglected altogether when studying a vessel's stability. In this connection we will not investigate, whether the movements of people on board are to be assumed to take place simultaneously with the vessel's turning and a heel due to wind, or whether such an assumption may be too unfavourable; we will only show how great heeling moments and dynamical works can be produced by the movements of passengers. At the same time some simple diagrams will be given, by means of which the calculations may readily be done.

Theoretically the solving of this question is extremely simple and does not give rise to any new expounding. If the number of moving people be $n$, their aggregate weight is about $0.075n$ tonnes, and if the average distance these people move along the deck athwart-ships is $b$ metres, the heeling moment arising is: $$M_n = 0.075nb \cos \varphi.$$ (68)

A gradual crowding of these people to one side of the vessel raises the heel $\varphi_n$, the value of which is obtained from equation: $$h_n = \frac{0.075nb \cos \varphi_n}{D} = h.$$ (69)

The angles arising may be so large that the metacentric method cannot be used for determining $h$, so the equation must be solved graphically by drawing a curve of values $h_n$ according to Fig. 74 on the same diagram as the stability arm curve, and measuring direct therefrom the heeling angle arising. The coefficient $k_0$ used in the diagram is: $$k_0 = \frac{0.075nb}{D}.$$ (70)

For drawing Fig. 74, table 24 is given, from which the product $k_0 \cdot \cos \varphi$ can be obtained direct for the variations of $k_0$ between the values $0.07$ and $0.15$. 
Table 24.

Expression \( h_\infty = k_3 \cos \phi \).

<table>
<thead>
<tr>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_3 )</td>
</tr>
<tr>
<td>0.07</td>
</tr>
<tr>
<td>0.08</td>
</tr>
<tr>
<td>0.09</td>
</tr>
<tr>
<td>0.10</td>
</tr>
<tr>
<td>0.11</td>
</tr>
<tr>
<td>0.12</td>
</tr>
<tr>
<td>0.13</td>
</tr>
<tr>
<td>0.14</td>
</tr>
<tr>
<td>0.15</td>
</tr>
</tbody>
</table>
If the arising angle is small, not more than 5° to 10°, the metacentric method may be used; then the angle $\varphi_m$ is determined by the equation:

$$\operatorname{tg} \varphi_m = \frac{0.075 n b}{D c_0} = \frac{k_3}{c_0}. \quad (71)$$

From diagram 75, drawn according to this equation, may be estimated how great angles of heel a crowding of people at one side of the vessel may cause for different values of $k_3$ and $c_0 (\equiv M_O)$. The same estimation may be made with the help of table 25 as well.

### Table 25.

**Expression** $k_3 = c_0 \operatorname{tg} \varphi$.

<table>
<thead>
<tr>
<th>$c_0$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.007</td>
<td>0.009</td>
<td>0.010</td>
<td>0.012</td>
<td>0.014</td>
<td>0.016</td>
<td>0.017</td>
</tr>
<tr>
<td>2°</td>
<td>0.003</td>
<td>0.007</td>
<td>0.010</td>
<td>0.014</td>
<td>0.017</td>
<td>0.021</td>
<td>0.024</td>
<td>0.028</td>
<td>0.031</td>
<td>0.033</td>
</tr>
<tr>
<td>3°</td>
<td>0.005</td>
<td>0.010</td>
<td>0.016</td>
<td>0.021</td>
<td>0.026</td>
<td>0.031</td>
<td>0.035</td>
<td>0.039</td>
<td>0.042</td>
<td>0.047</td>
</tr>
<tr>
<td>4°</td>
<td>0.007</td>
<td>0.014</td>
<td>0.021</td>
<td>0.028</td>
<td>0.035</td>
<td>0.042</td>
<td>0.049</td>
<td>0.056</td>
<td>0.063</td>
<td>0.070</td>
</tr>
<tr>
<td>5°</td>
<td>0.009</td>
<td>0.018</td>
<td>0.026</td>
<td>0.035</td>
<td>0.044</td>
<td>0.054</td>
<td>0.065</td>
<td>0.076</td>
<td>0.089</td>
<td>0.097</td>
</tr>
<tr>
<td>6°</td>
<td>0.011</td>
<td>0.021</td>
<td>0.032</td>
<td>0.042</td>
<td>0.053</td>
<td>0.063</td>
<td>0.074</td>
<td>0.084</td>
<td>0.095</td>
<td>0.105</td>
</tr>
<tr>
<td>7°</td>
<td>0.012</td>
<td>0.023</td>
<td>0.037</td>
<td>0.049</td>
<td>0.061</td>
<td>0.074</td>
<td>0.086</td>
<td>0.098</td>
<td>0.111</td>
<td>0.123</td>
</tr>
<tr>
<td>8°</td>
<td>0.014</td>
<td>0.028</td>
<td>0.042</td>
<td>0.056</td>
<td>0.070</td>
<td>0.084</td>
<td>0.098</td>
<td>0.112</td>
<td>0.126</td>
<td>0.141</td>
</tr>
<tr>
<td>9°</td>
<td>0.016</td>
<td>0.032</td>
<td>0.048</td>
<td>0.063</td>
<td>0.079</td>
<td>0.095</td>
<td>0.111</td>
<td>0.127</td>
<td>0.143</td>
<td>0.158</td>
</tr>
<tr>
<td>10°</td>
<td>0.018</td>
<td>0.035</td>
<td>0.053</td>
<td>0.071</td>
<td>0.088</td>
<td>0.106</td>
<td>0.123</td>
<td>0.141</td>
<td>0.159</td>
<td>0.176</td>
</tr>
</tbody>
</table>

If the passengers make a sudden rush in panic, they give rise to a upsetting moment which is capable to do a work $L_m$ during the rotation from 0 to $\varphi$; the amount of this work is:

$$L_m = \int_0^\varphi M_m \, d\varphi.$$

This work is absorbed at an angle, to which corresponds the dynamical lever:

$$e_m = \frac{L_m}{D} = k_3 \sin \varphi, \quad (72)$$

which may be measured direct from diagram 76 or table 26.

A condition for using the equations is that one is able to determine the factor $k_3$ to correspond to the actual prevailing circumstances. The coefficient must be determined with the following conditions in view: the build of the vessel to be examined, the sizes and space of the.
accommodation for passengers, the location of benches, railings and other objects that may serve as hindrances for a sudden rush of passengers, etc. For facilitating the determining of the coefficient, and as a comparison, may be mentioned a few proposals made abroad regarding this question.

The American Marine Standards Committee assumed in its proposal [A 10] [D 7] that the total number of passengers of a vessel, equally distributed, fill all such open and enclosed promenades, public rooms, lobbies, etc., where one might assume passengers would crowd, on one side of the vessel, but not such public rooms and lobbies which are not directly accessible from the open or enclosed promenades, nor the dining saloons and passageways. In the equation (70) n would according to this be the greatest allowed number of passengers for the vessel, and the distance b is given a value, which depends mainly on the location of the promenades, lobbies, etc. on board, and which must be determined for each vessel individually. It is probable that the value of b by this rule will generally be greater than 1/4 B. The coefficient obtained should be used according to the proposal quoted only for determining the vessel’s statical heeling angle.

Perronnet [P 3] proposed that as the number for the suddenly moving people the aggregate number of crew and passengers be assumed and as the distance they move on all vessels 3/8 B. The said coefficient should be used for calculating the dynamical angle of heel given to the vessel.

Albrecht [A 6] proposed that the greatest statical heel caused by the passengers should be determined by assuming all passengers moving the distance 1/4 B.

The vessels on our inner waters are constructively so different from one another that it is difficult to give any general rule for the values of the figures n and b. For instance, the circumstance whether the vessel has one deck or two has great influence on the judging. If the vessel has two decks, the figure 3/8 B for b would seem absolutely excessive. On the other hand, for short voyage vessels with one deck, on which by far the greater number of passengers remain on deck during the trip, possibly even standing, so large a value of b as 3/8 B can come into question.

The presented equations, tables and diagrams may also be used in studying whether on a certain vessel, whose dynamical lever or initial metacentric height is known, as large a number of passengers may be safely accommodated as the vessel’s deck space corresponds to. Here, first of all, the greatest heeling angle is determined which the vessel may obtain by the movement of the passengers, and on its basis are then calculated the corresponding figures for n and b. On the result of the calculation are then based the necessary safety measures to be taken, such as placing of benches or rails on the deck so that the movement of passengers is restricted.

By reason of the indefiniteness of coefficient k, the great exactitude applied in the equations may appear to be excessive. It must be observed, however, that the intention has been to draw the diagrams to correspond to actuality as far as possible. Once they have been drawn, a greater or less exactitude is of no effect upon the facility for using them.

§ 5. The Influence of the Waves on our Inland Waters on the Judging of the Stability.

According to the presentation of the problem, this chapter treats only such vessels as navigate waters where heavy seas do not prevail to any extent worth mentioning. This does not mean that the influence of wave motion may be left out of account altogether when judging the stability of vessels on our inland waters. If this be done, the motives must be given.

Wave motion may endanger the safety of a vessel in two different ways. It may cause a rolling motion of the vessel, the amplitude of which may finally increase to a value that is dangerous to the ship, or the waves may break over the vessel, fill parts of it and thus reduce the vessel’s stability. In the following each of the two said influences of the wave motion will be treated separately.

The rolling of a vessel among waves cannot be studied without knowing on the one hand the form and size of the waves, and on the other the laws for the vessel’s rolling motion and the value of the extinction.

There are very few data available on the measuring of the wave motion on the inland waters of Finland. The author has only found one statement in literature on this subject. Honken has mentioned that Streng had found the measure of the wave-length on Lake Lohjanjärvi to be 6 m in the spring and 8 m in the autumn [H 177 page 144], which figures would appear to apply to some kind of average maximum values.

Failing actual measurements, one would be obliged to have recourse to mathematical equations, by means of which one might determine the sizes of the waves when the velocity of the wind, the time of its action and the length of the open sea-room — the fetch — are known. There are certainly some equations of this nature (for instance those of Cornish, Zimmermann, Borgen), but they are not very reliable. Holt in his stability investigation [H 7] used Stevenson’s old equation by help of which some estimations may be made also here.
According to Stevenson, the extreme height of a storm wave \( [T \, 3] \) is:

\[
H_s = 1.57 \sqrt{\frac{l}{2}} \quad \text{(in feet)} \\
= 0.457 \sqrt{\frac{l}{2}} \quad \text{(in m)}
\]  
\((73)\)

where \( l \) is the fetch in nautical miles. In spite of such an important circumstance as for instance the depth of the water not having been taken into account in the equation, it nevertheless gives an idea of the order of magnitude of the wave motion. For instance, for the greatest wave height on Lake Leman a value of about 2 m is obtained by the equation, as the length of the fetch on that lake is about 20 naut. miles; the highest wave measured on the lake is according to Forel \([F \, 10]\) 1.7 m. The great inconstancy of the ratio of the height to the length of the waves is a hindrance for applying the said equation to the purpose of this investigation. According to the handbooks in shipbuilding, the height-length ratio of smaller waves is \( H_s/L_w = 1/8 - 1/10 - 1/20 \) \([C \, 1]\) \([J \, 2]\) \([M \, I]\).

The ratio, corresponding to the maximum wave measured on Lake Leman as above, was appr. 1/20. As shorter waves are generally steeper than the long ones, and as such wide open sea-rooms as on Lake Leman are not found on our inland waters, the ratio 1/20 is too small for our conditions. The highest wave to be found on Lake Lohijärvi, by calculating according to Stevenson’s equation, would be about 0.75 m and its height-length ratio on the basis of the said length measurements about 1: 9.5. In estimating the measure-ratio of the waves in gales on our inland waters, the height-length ratio of 1/10 would appear the most suitable.

On our inland waters, with the exception of Lake Laatokka which in this investigation is considered as a sea, there are very few open fetches of sufficient length for forming heavy seas. According to Renqvist \([R \, 21]\), the radii of the open sea-rooms in our larger lakes do not exceed 5 kilometres, i.e. the diameters are not above 5.4 nautical miles. The length of open fetches without islands or shoals on the navigating channels is nowhere more than about 15 km or about 8 nautical miles according to the author’s measurements. According to these values and to Stevenson’s equation, the highest waves in gales on our inland waters belong to the class 1.1—1.3 m, and the greatest length thus to class 11—13 m.

Between the length and the period of the wave, the following well known law applies:

\[
L_w = 1.56 \, T_s^2, \quad \text{(74)}
\]

which is one of Gerstner’s fundamental equations for the trochoidal wave theory \([F \, 10; \, \text{page 233}]\). The greatest wave periods appearing here are according to the above and this equation 2.6—3.0 sec.

In table 27 are given the main measures of the bigger waves of different waters, calculated with the help of equations (73) and (74). As the height-length ratio of the waves has been assumed 1/10 and as the fetches exposed to the wind the diameters of the widest open sea-rooms according to RENQVIST’s publication. Only a relative meaning may be given to the wave measures in the table. As the variation of the periods according to the table is slight, their values may be considered sufficiently reliable as a basis for judging the stability.

Referring to the table, it is to be noted that there are very few of such open sea-rooms, whose diameters are given in the table, on the various lakes in our country. It is therefore quite possible that many of the boats navigating particular waters will never meet waves of the magnitude which may appear on those waters according to the table.

<table>
<thead>
<tr>
<th>Name</th>
<th>Max. dia. of open sea-room</th>
<th>Wave height m</th>
<th>Wave length m</th>
<th>Wave period sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oulujärvi</td>
<td>10.0</td>
<td>5.4</td>
<td>1.06</td>
<td>10.6</td>
</tr>
<tr>
<td>Saimaa (Paanisv.</td>
<td>8.4</td>
<td>4.5</td>
<td>0.97</td>
<td>9.7</td>
</tr>
<tr>
<td>Päijänne</td>
<td>6.6</td>
<td>3.6</td>
<td>0.87</td>
<td>8.7</td>
</tr>
<tr>
<td>Höyryläinen</td>
<td>5.8</td>
<td>3.1</td>
<td>0.80</td>
<td>8.0</td>
</tr>
<tr>
<td>Näsijärvi</td>
<td>5.2</td>
<td>2.8</td>
<td>0.76</td>
<td>7.6</td>
</tr>
<tr>
<td>Pielenin</td>
<td>4.6</td>
<td>2.5</td>
<td>0.72</td>
<td>7.2</td>
</tr>
<tr>
<td>Iso-Kalla</td>
<td>4.2</td>
<td>2.3</td>
<td>0.69</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The rolling of the vessel due to the waves depends intimately on the wave slope. According to the fundamental formulae of the trochoidal wave theory, the slope of the wave-surface depends solely on the height-length ratio:

\[
\theta_{w} = \pi \frac{H_s}{L_w}.
\]  
\((75)\)

When the ratio \( H_s/L_w \) is 1/10, the slope \( \theta_{w} \) is thus 0.314 \( \approx 18^\circ \). The effective wave slope is according to Fouqué \([M \, 1; \, \text{page 149}]\) approximately the slope of the wave subsurface through the centre of buoyancy of the vessel. On the basis of the draught of the vessels on our inland waters one can estimate the effective wave slope \( \theta_{w} \) at not more than 10°, but always more than 5°. These angles are hereafter considered as the limit values of the effective wave slope.

The above seems to show that the length of the bigger storm waves appearing in our inland waters is comparatively small. If we compare
the wave lengths and the most prevalent beams of the vessels, which vary between 5 and 7 metres, we find that the amplitude of the forced rolling among waves cannot be very great. The length of the waves is so very little more than the beam of the vessels that a theoretical study of the rolling motion is hardly possible. In the following it is the intention, however, to show, for the sake of completeness, what size of rolling amplitude the vessels might attain if their breadths should not be taken into account at all.

For that reason it was first of all necessary to find out the values of the periods of waves for our lake vessels and of the coefficients of extinction of the vessels. As no earlier investigations were known of the rolling of this kind of vessels, rolling experiments had to be made. For the experiments, 11 lake passenger steamers were chosen, both with one deck and with two. The experiments were made in the summer of 1938 in calm water. The vessels were brought to roll by having men on deck to run to and fro, in synchronism with the vessel's own rolling motion. A curve was drawn of the rolling motion, with the help of the rolling indicator of the author. From the curve it was possible to determine both the vessel's period, amplitude and the coefficient of extinction. The first two could be read direct from the curve, the coefficient of extinction again was determined as follows.

From the curves, drawn with the help of the rolling indicator, was measured for each single roll the corresponding reduction of \( \bar{\psi} \), and the average amplitude of the roll \( \bar{\psi} = \frac{\bar{\psi}_n + \bar{\psi}_{n+1}}{2} \). The results of the measures \( \Delta \bar{\psi} \) were plotted as dots in the diagram, the ordinate being the extinction and the abscissa the amplitude of roll. According to the distribution of the dots one could conclude that the relation between the extinction and amplitude of our lake vessels follows very nearly the so-called French law of extinction (the quadratic law of extinction) [D 5; page 357]:

\[
\Delta \bar{\psi} = k_2 \bar{\psi}^2. \tag{76}
\]

In the equation the angles must be given in degrees. For the extinction coefficient \( k_2 \) new diagrams were drawn, where the ordinate was the extinction and the abscissa the square of the amplitude, and in which points corresponding to the measurement results were plotted. In the diagrams were drawn straight lines through the origin and the point groups; their direction coefficients, i.e. the coefficients \( k_2 \) were determined.

The results of the experiments and measurements are given in table 28.

<table>
<thead>
<tr>
<th>Name of vessel</th>
<th>Compl. period of roll ( T ) sec.</th>
<th>Coeff. of extinction ( k_2 )</th>
<th>Max. amplit. of experim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leppävirta I</td>
<td>7.4</td>
<td>0.0200</td>
<td>6.0°</td>
</tr>
<tr>
<td>Leppävirta II</td>
<td>7.3</td>
<td>0.0200</td>
<td>8.2°</td>
</tr>
<tr>
<td>Karjalanka</td>
<td>6.5</td>
<td>0.0175</td>
<td>7.8°</td>
</tr>
<tr>
<td>Louhi</td>
<td>5.9</td>
<td>0.0125</td>
<td>6.0°</td>
</tr>
<tr>
<td>Suomi</td>
<td>6.1</td>
<td>0.0207</td>
<td>5.2°</td>
</tr>
<tr>
<td>Jyväskylä</td>
<td>7.3</td>
<td>0.0207</td>
<td>5.7°</td>
</tr>
<tr>
<td>Tämä</td>
<td>6.8</td>
<td>0.0200</td>
<td>5.4°</td>
</tr>
<tr>
<td>Kaisa</td>
<td>5.0</td>
<td>0.0286</td>
<td>4.4°</td>
</tr>
<tr>
<td>Tarjanne</td>
<td>7.3</td>
<td>0.0300</td>
<td>4.9°</td>
</tr>
<tr>
<td>Pehjola</td>
<td>6.9</td>
<td>0.0318</td>
<td>5.5°</td>
</tr>
<tr>
<td>Kuria</td>
<td>5.8</td>
<td>0.0390</td>
<td>3.5°</td>
</tr>
</tbody>
</table>

The coefficient of extinction is according to the experiments rather high in general, and with the exception of two vessels it varies very little. The average value of the coefficients is approximately:

\[ k_2 = 0.025, \]

which may be used when the actual coefficient of extinction of the vessel is not known.

When comparing the periods of the vessels with those of the bigger waves, we find that on our inland waters no synchronism can arise between a vessel lying broadside onto waves and the wave motion. On the other hand, the vessel may naturally come into synchronism with the wave roll, if the waves are coming about the beam. Such a synchronism, however, cannot be considered to be dangerous, because the inconstancy of the wave motion, which for its shortness already is great, increases hereunder. On this basis the examination in this investigation may be limited to the asynchronous rolling of a vessel lying broadside onto the waves.

As the basis for the examination may be taken BERTIN's theory in the form in which DOYÈRE has published it [D 5; pages 392 to 403]. This theory is adaptable for that reason that it is built on the quadratic law of extinction, which law has been proved to apply to our vessels on the inland waters.

According to BERTIN's theory, the relative maximum value of the amplitude of an asynchronous rolling is
\[ \overline{\varphi}_{w} = K \left( \frac{\theta_{w}}{x_{2}} \right) \]  

(77)

where

\[ K = \sqrt{\frac{2 \cos 2\frac{T}{2} - \frac{T}{2}}{1 - \left( \frac{T}{2} \right)^{2}}} \]

and where \( \theta_{w} \) is the maximum wave slope (in degrees) and \( \upsilon_{2} \) the coefficient of extinction of the quadratic extinction law. The factor \( K \) obtains the value 0 when the ratio between the vessel and wave periods \( T/T_{w} \) is 3 and 5, which means that the relative amplitude of roll is here = 0. When the ratio \( T/T_{w} = 1 \), \( K \) obtains the value 1.250 (= 0/0).

To obtain a general idea of the values \( \overline{\varphi}_{w} \), to which the equation leads, the author has drawn diagram 77. Its right-hand side contains three curves, which correspond to the effective wave slopes 10°, 7 1/2° and 5°; on the absciss axis in this part of the diagram is the scale corresponding to the coefficient of extinction of the rolling motion. A definite horizontal line in the diagram corresponds to a definite wave slope and coefficient of extinction; by extending this line to the left-hand side of the diagram one can read directly from the vertical scales there, how great the maximum value of the relative amplitude is, when one knows the ratio \( T/T_{w} \). As an example, a line has been drawn in the diagram to correspond to the values \((\theta_{w} = 7 1/2°; \upsilon_{2} = 0.025)\), whose points of intersection with the lines \( T/T_{w} = 1.0, 2.0, 3.0, 4.0, 5.0 \) and 6.0 show the corresponding maximum relative amplitudes of roll to be 21.5°, 14°, 6.2°, 0° and 4.1°.

From tables 27 and 28 can be concluded, what values the ratio \( T/T_{w} \) can obtain on our various waters. For instance, we see that on the waters of Iso-Kalla this ratio varies for the examined vessels between 2.8 and 3.5, on the Lake Päijänne from 2.5 to 3.0, although for one vessel the value is about 2.0; and on Lake Näsiäjärvi between 2.6 and 3.3. By using these values one can, when examining diagram 77, estimate that the greatest relative amplitudes of roll that the passenger vessels navigating our more open waters obtain may vary between 5 and 10 degrees. The greatest effective wave slope having also been assumed to be 5°—10°, the greatest absolute amplitudes of roll would thus be 10°—20°.

In the above estimations the beam of the vessel has been left out of consideration altogether. The wave in our waters being relatively
short, one cannot however do so. If the breadth of the vessel is great as compared with the length of wave, according to Bertin [D 5; pages 409–410], $\Theta_n$ must be multiplied by the diminishing coefficient $\mu$, which according to the results of his experiments can have the value 0.82, but which in his own words is considerably smaller when the vessel's breadth is great. At the time of Bertin's theory, say in 1893, the greatest breadth of any vessel was 25 m (Great Eastern). The average length of waves in storms varied according to the same investigator on different seas between 52 and 141 m [D 5; page 304]; according to Bertin, a vessel's beam must thus be considered very large already when it is about 1/3rd to 1/6th of the length of generally appearing storm waves. As the corresponding ratios on our waters can be 1:1.5—1:1.0 only, it is evident that when calculating both the relative and the absolute maximum amplitude the value of $\Theta_n$ would have to be multiplied by the coefficient $\mu$, which would be very low.

Failing suitable experimental material it is impossible to determine theoretically the real value of the maximum amplitude of roll for the vessels on our inland waters. According to the above, one can nevertheless assume that our lake vessels of medium and large size cannot, even in the worst conditions, obtain a roll of more than 5 to 10 degrees solely by the action of the waves.

The amount of the maximum amplitude thus being so uncertain, it is futile to begin to calculate the dynamical lever which the vessel ought to have, so as to be able to withstand the rolling action due to the waves. One is forced to leave that part of the investigation open.

The author's opinion is nevertheless that, even if the examination should be amplified later on in that respect, it would not bring about any modifications worth mentioning in the final results of the judging method here in question. As the foundation for that opinion may be again emphasized the small extent and scarcity of open fetches on our inland waters, and the low value of the ratio between the length of the waves and the breadth of the vessels.

The second form of action by which rolling waves may diminish a vessel's stability is the breaking of water on deck.

Water breaking over a vessel's gunwale may give the vessel both a dynamical and statical heel. By the former is here meant the shock that strikes the vessel by the water meeting an obstruction in its way, the latter is due to the fact that water momentarily remaining on the deck, reduces the vessel's stability both by means of its weight and through its free water surface.

By reason of the small size of the waves appearing on our inland waters, the dynamical shock action of the water can be left altogether out of account. A few words must be said on the statical action, especially because it has been the principal factor in certain accidents to vessels in our country.

Our waters being narrow and the wave roll slight, a breaking of water on deck hardly comes into question in other cases than when the vessel steers against a head sea. The water may fill the fore deck, which on some of our lake vessels is fairly low. The vessel's stability is secured, if the initial stability while the water remains on deck is kept positive and the stability moment is so great that it is able to overcome the simultaneous action due to the other heeling moments. The vessel being in a head wind, gusts of wind need not be considered. Even a sudden turning manoeuvre lies outside the bounds of possibility. There remains the possible heeling moment due to the passengers moving on deck.

The reduction of the initial stability due to the water on deck can be calculated by using elementary equations. If the weight of the water on deck is $p$ and its volume $V$ ($V = p$, when $\gamma = 1$), and if the transverse moment of inertia of its surface area is $i$, the new initial metacentric height (Fig. 78) is:

$$i = r - a = \frac{1}{V + v}$$

![Fig. 78](image_url)
In the equation, \( I \) is the transverse moment of inertia of the original water line, which has been assumed to remain unchanged, \( V \) the volume of the original displacement, \( h \), the vertical distance between the centre of gravity of the water on deck and the centre of gravity \( G_0 \), and \( b \), the vertical distance between the centre of gravity of the additional displacement and the centre of buoyancy \( F_0 \).

When the vessel heels, both the quantity of water on deck and the moment of inertia of its upper surface diminish. The form of the stability moment curve depends on the speed at which the water runs off the deck; this again depends both on the height of the gunwales and the size of the freeing ports. If the ports are very large, and if the water remains on deck only for a moment, a sufficient condition for judging the stability is that the initial stability is every moment positive. If again the ports are small, the water has a reducing action upon the stability even while the vessel is heeling; in that case a special investigation is required for finding out the form of the stability moment curve.

The use of the method, which has been applied in the other paragraphs of this chapter for judging the stability, cannot be applied for studying the action of water breaking on deck. This is not necessary, when the freeing ports of the vessel are large and in good condition. Ever since the accident to the S. S. Kuru (cf. p. 178) had drawn greater attention to this circumstance in our country than previously, one may say that the determining of the statical initial stability is an adequate method for determining the action of water on deck.

§ 6. The Definitive Determination of the Adequate Dynamical Lever corresponding to the Limit Angle.

When determining the minimum stability by using the equations given above, the most unfavourable circumstances must be chosen to which the vessel can possibly be exposed. In this selection one must, however, not proceed too strictly, which is a mistake one is apt to make.

The master may often be compelled to make a sudden turning manoeuvre, without being able to pay attention to any other unfavourable circumstances. Similarly, a squall may strike a vessel at any time, for instance just at the moment when at the end of the turn the rudder is put over midships and the vessel thereby suddenly heels over outwards from the turning centre. If the master of the vessel does not know the danger of that manoeuvre, he may even himself create such a dangerous situation, by stopping his turning and thus trying to avoid the danger called forth by the squall.

A co-operation of the heeling moments caused by the action of the turning and the wind is therefore quite possible, for which reason it is also absolutely unavoidable to unite them in judging the stability.

The collective movements of passengers on board are generally called forth either by curiosity or panic. The former makes the passengers to move gradually, the latter may cause a rush to one side of the vessel. Curiosity appears as an active factor mostly when the vessel is approaching a landing stage, in canals etc., thus not when the vessel is on a steady route across open water or in a fairway, the only places where a simultaneous action due to the wind and turning can come into question. It is therefore not necessary to pay attention in judging the stability to the gradual movements of passengers to one side of the vessel. Passengers may become struck by panic for instance through a sudden heel of the vessel or when seeing water break upon deck. In both cases the people rush to the higher side, their movement reduces the heel brought about by the co-action of wind and turning. It may naturally come to happen that just at the moment when passengers rush to the higher side, the squall ceases, or that the vessel has begun to turn in the opposite direction; both these cases must, however, be considered to be so very rare that in the author's opinion they need not be taken into account as foundations for judging a vessel's stability. If waves again are the cause of the vessel's heel, it is an altogether different case. Then a rush of passengers to one side causes an impulse, whose influence may coincide with that of the waves, because the direction of the latter varies periodically. Therefore it is by no means wrong in examining the stability of seagoing vessels and in adding up the heeling work to take the movements of passengers as well into account, as for instance Pierrot has done [P 3]. In treating the case of vessels on inland waters it is, on the contrary, not necessary to assume a simultaneous occurring of turning, a sudden rise of wind and a movement of passengers on deck. Naturally, this does not imply that the movements of passengers may be without further left out of account; its separate investigation is very necessary, especially for such passenger vessels as have many passengers.

The action due to the waves upon the heel of the vessel can therefore, according to what is stated in the preceding paragraph, be left aside altogether. If the bow of the vessel is low and surrounded by closed bulwarks, it is nevertheless very well to examine whether the vessel's initial stability remains positive when the fore deck be filled with water, completely or partly, depending upon the build.
The minimum stability of a vessel on inland waters must thus be determined in such a manner that one assumes the simultaneous occurrence of the heeling actions of the most unfavourable turning manoeuvre and the wind. First of all is determined the angle $\phi_{\text{eq}}$ of statical position of equilibrium, which arises by the action of a steady turning manoeuvre and a steady wind. It is found by drawing in the diagram of the stability arm a curve which indicates the sum of the moment arm:

$$h_s = h_p + h_z$$

$h_s$ is obtained from equation (51) and table 17, $h_p$ from equation (52) and table 18, and $h_z$ from equation (66) with the help of the tables 20 and 21. Then the greatest allowed angle of heel is determined, the limit angle $\phi_{\text{l}}$, by applying the rules given in § 1. Finally the sum of the work lever is calculated:

$$e_\Sigma = e_s + e_\Sigma$$

$e_s$ is obtained from equation (55) and table 19 and $e_\Sigma$ from equations (57), (58) and (67) with the help of the tables 22 and 23. Instead of all the said tables one may use corresponding diagrams.

A vessel is sufficiently stable if the work lever $e_s$ corresponding to the limit angle is equal to or greater than the sum of the dynamical lever $e_{\text{s,eq}}$ that corresponds to the angle of equilibrium $\phi_{\text{eq}}$ and the work levers determined in the manner indicated above:

$$e_s \geq e_{\text{s,eq}} + e_\Sigma . \quad (79)$$

The method presented does not involve the use of any kind of safety coefficient. The safety coefficient is partly compensated by the passive resistances, arising during the time of the vessel's heel, not having been taken into account, partly by the assumed particularly unfavourable circumstances, especially the great speed of the wind.

If the relation contained in equation (79) is fulfilled, if further the gradual movement of the passengers or their rush to one side does not lead to excessive heelings, and if finally the initial stability remains positive when water fills such parts of the deck, whose filling must be feared, a vessel navigating our inland waters must be held to be sufficiently stable.

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Chapter VI.


By applying the new methods for judging the stability, the author has studied a very large number of coastal and inland vessels in Finland. Out of this extensive material, which will be presented in another connection, certain numerical examples have been selected for illustrating the application of the methods. Of the vessels examined, first of all is given a judging of the stability of a lake passenger vessel, and then is shown how the judging methods may be used for explaining the reasons for capsizings and losses.

The stability qualities of the examined vessels have been determined by the use of the body plans of the ships and by performing inclining experiments on the vessels. The dynamical lever curves have been calculated by using partly the integragraph methods already known, partly by using a new rapid integragraph method given by the author [R 10]. In the latter case the stability arm curves have been drawn by differentiating the dynamical lever curves, and then the result has further been controlled by integration. The rudder areas, the centres of gravity for various loading conditions, etc. have been calculated from the general drawings of the vessel.

Passenger boat for inland waters, single deck and no hold.

Main dimensions of vessel:

- Length over all .................. 24.7 m.
- Beam .................................. 5.33 m.
- Depth moulded .................... 2.66 m.

The initial stability factors of the vessel are, when the vessel has 3.5 tonnes' ballast:
<table>
<thead>
<tr>
<th></th>
<th>I: In light condition</th>
<th>II: During incl. exper.</th>
<th>III: Fully loaded cond.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>65.92</td>
<td>72.55</td>
<td>96.82 t</td>
</tr>
<tr>
<td>Centre of buoyancy ab. keel</td>
<td>0.869</td>
<td>0.917</td>
<td>1.082 m</td>
</tr>
<tr>
<td>Init. metac. radius</td>
<td>1.989</td>
<td>2.045</td>
<td>2.174 m</td>
</tr>
<tr>
<td>v above keel</td>
<td>2.888</td>
<td>2.889</td>
<td>2.946 m</td>
</tr>
<tr>
<td>Vessel's c. of gr. above keel</td>
<td>2.849</td>
<td>1.985</td>
<td>2.434 m</td>
</tr>
<tr>
<td>Init. metac. height</td>
<td>0.769</td>
<td>0.844</td>
<td>0.292 m</td>
</tr>
</tbody>
</table>

Full load includes 169 passengers and 7 tonnes of deck cargo.

The stability arm and dynamical lever curves corresponding to the table are given in Fig. 79.

The judging of the curve II corresponding to the inclining experiment is done by applying the method for judging the stability of lake vessels.

Mean draught of vessel ... 1.443 m.
Rudder area ............... F = 1.05 m².

The vertical distance between the centres of rudder area and the lateral plane \( l = 0.208 \) m.

Speed on turning circle \( v \), not more than 8 knots.

Turning radius \( r \approx 74 \) m.

Rudder angle \( \alpha \approx 45° \).

Vert. height betw. vess. centre of gr. and. lat. pl. centre \( b = 1.20 \) m.

From equation (46) ............... \( k_1 = 0.028 \).
From table 18 ............... \( k_0 = 0.358 \).

For controlling the above the statical angle of equilibrium caused by the turning alone is calculated; this angle will be small by reason of the great initial stability. The metacentric method is therefore applicable.

From equation (51) ............... \( h_1 = 0.028 \) m.
From (52) ............... \( h_2 = 0.0011 \) m.
\[ \sin \varphi_s = 0.0343, \varphi_s = 1.83°. \]

The average value of four experiments made on the same vessel was \( 1.4° \).

The heel is calculated, which the vessel obtains when turning in a steady 20 m/sec. beam wind; corresponding pressure \( p = 0.031 \) t/m².
Total wind surface of vessel $F_t = 89.9 \text{ m}^2$.
Av. length of wind surface $L' = 19.85 \text{ m}$.
Av. height $H' = 4.53 \text{ m}$.
Height of centre of wind press. above water $\ldots nH_1 = 2.67 \text{ m}$.
Av. breadth of deck build. of vessel $B_1 = 4.12 \text{ m}$.

From equation (68): $\tan \alpha = 0.4557$. $\alpha = 24.5^\circ$.

\[
\frac{pF_t}{D} = 0.0384.
\]

The sum of the moment arms due to the centrifugal force, the rudder pressure and the wind $(h_l - h_p + h_t)$ is best calculated in table form.

<table>
<thead>
<tr>
<th>Angle of heel $\varphi$</th>
<th>$10^\circ$</th>
<th>$15^\circ$</th>
<th>$20^\circ$</th>
<th>Rem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1(p, a)$</td>
<td>1.132</td>
<td>1.175</td>
<td>1.200</td>
<td>From table 20</td>
</tr>
<tr>
<td>$f_2(p, a)$</td>
<td>1.048</td>
<td>1.047</td>
<td>1.030</td>
<td>From table 21</td>
</tr>
<tr>
<td>$nH_1 - f_2(p, a)$</td>
<td>3.022</td>
<td>3.136</td>
<td>3.204</td>
<td></td>
</tr>
<tr>
<td>$T/2 - f_3(p, a)$</td>
<td>0.736</td>
<td>0.735</td>
<td>0.743</td>
<td></td>
</tr>
<tr>
<td>Expr. in parenth. of equat. (66)</td>
<td>3.778</td>
<td>3.891</td>
<td>3.947</td>
<td></td>
</tr>
<tr>
<td>$h_l$</td>
<td>0.145</td>
<td>0.149</td>
<td>0.152</td>
<td>From equat. (66)</td>
</tr>
<tr>
<td>$h_p$</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>From equat. (61)</td>
</tr>
<tr>
<td>$(h_l - h_p + h_t)$</td>
<td>0.172</td>
<td>0.173</td>
<td>0.177</td>
<td></td>
</tr>
</tbody>
</table>

By drawing through the points on the last line corresponding to the moment arm sums a curve in the diagram of the vessel's stability arm, one finds the statical angle of equilibrium $\varphi_{by}$. Its value will be $\varphi_{by} = 14.0^\circ$.

The adequate dynamical lever corresponding to the limit angle is determined, under assumption that the turning vessel is struck by a gust of wind of a speed of 28 m/sec. and corresponding pressure of 0.061 t/m². It is immaterial if the rudder be put over to midships at the same time, because the moment arm of the rudder is very small in this vessel.

The vessel's deck is immersed at an incline of $30^\circ$ and the angle of maximum stability is $40^\circ$. Assuming that the vessel has no easily shifting cargo, $30^\circ$ may be chosen as limit angle; if the deck be allowed to dip into the water, the limit angle may be $40^\circ$ without risk. The determining of the minimum value of the dynamical lever is done, so as to comply with these two limit angles.

Work lever of centrifugal force between the limits $14^\circ - 30^\circ$ and $14^\circ - 40^\circ$.

From equation (55): $e_i = 0.007 \text{ m} | 0.011 \text{ m}$

From tables 22 and 23 are obtained:

<table>
<thead>
<tr>
<th>Angle of heel $\varphi$</th>
<th>$14^\circ$</th>
<th>$30^\circ$</th>
<th>$40^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_3(p, a)$</td>
<td>0.2675</td>
<td>0.6018</td>
<td>0.8052</td>
</tr>
<tr>
<td>$f_4(p, a)$</td>
<td>0.5817</td>
<td>0.7016</td>
<td>0.3790</td>
</tr>
<tr>
<td>$nH_1 - f_3(p, a)$</td>
<td>0.714</td>
<td>3.560</td>
<td>3.150</td>
</tr>
<tr>
<td>$T/2 - f_4(p, a)$</td>
<td>0.182</td>
<td>0.386</td>
<td>0.497</td>
</tr>
<tr>
<td>Expr. in parenth. of equat. (67)</td>
<td>0.896</td>
<td>1.392</td>
<td>2.647</td>
</tr>
<tr>
<td>$e_i = 0.0756 \times$</td>
<td>0.068</td>
<td>0.131</td>
<td>0.200</td>
</tr>
</tbody>
</table>

The work lever due to the wind is thus between the limits $14^\circ - 30^\circ$ and $14^\circ - 40^\circ$.

$e_i = 0.083 \text{ m} | 0.132 \text{ m}$

The amount of the vessel's dynamical lever ought to be, within the limits $14^\circ - 30^\circ$ and $14^\circ - 40^\circ$, equal to the sum of the work levers due to the centrifugal force and the wind pressure, or thus $0.090 \text{ m}$ and $0.143 \text{ m}$.

The vessel's dynamical lever being $0.020 \text{ m}$ at a heel of $14^\circ$, adequate minima of the dynamical levers would be:

0.110 m, if the limit angle is $30^\circ$; and 0.163 m, if the limit angle is $40^\circ$.

The values of the vessel's dynamical lever are at the $30^\circ$ angle $0.105 \text{ m}$ and at the $40^\circ$ angle $0.200 \text{ m}$. The vessel is therefore sufficiently stable with the cargo loaded as stated, although it may even be possible that a very violent storm gust presses the edge of the main deck slightly under water.

In fully loaded condition the vessel will obviously not be able to withstand the pressure of the storm gust referred to. Let us calculate whether the vessel even in a $15 \text{ m/sec.}$ steady wind and in the accompanying $21 \text{ m/sec.}$ gust is sufficiently stable.

The calculations are done exactly as above. The initial values are now:

Wind surface $F_t = 83.8 \text{ m}^2$.
Average length of $L' = 19.85 \text{ m}$.
Average height of $H_1 = 4.22 \text{ m}$.

$nH_1 = 2.49 \text{ m}$. 
Average breadth of deck buildings $B_h = 4.12$ m.
\[ a = 26^\circ. \]
\[ T = 1.707 \text{ m.} \]
\[ h_1 = 0.0359. \]
\[ h_2 = 0.358. \]

When $q = 15^\circ$ $20^\circ$ $25^\circ$,
\[ h_3 = 0.093 \quad 0.093 \quad 0.093 \text{ m.} \]

The heel due to the steady wind and the turning is
\[ \varphi_{h_3} = 20^\circ. \]

We choose $35^\circ$ for the limit angle, because at that angle the deck has just dipped into the water and because it is at the same time the statical critical heeling angle of the vessel.

The sum of the work levers due to the centrifugal force and the wind pressure is $0.039 \text{ m}$, when the ship heels from $20^\circ$ to $35^\circ$. As the dynamical lever of the vessel corresponding to an angle of heel of $20^\circ$ is $0.016 \text{ m}$ (measured from the dynamical lever curve), the dynamical lever corresponding to the limit angle would be $0.055 \text{ m}$. According to the dynamical lever curve it is $0.054 \text{ m}$. The vessel therefore just manages to withstand the gust of wind considered.

The S.S. Kariu, lake passenger vessel, capsized on 7. 9. 1929 on Lake Näsijärvi off Tampere in heavy head-sea, by water having filled the fore deck, which was surrounded by closed bulwarks, and having flowed through the open doors at the front of the deck building to the middle-deck. The force of the wind was at the moment of the accident $23 \text{ m/sec}$, at the meteorological station at Tampere, and the direction NE. The vessel capsized to port within a couple of minutes. The vessel carried over one hundred passengers, 2.05 tonnes of cargo in the fore hold and a few hundred kilos on deck. There was no ballast.

The main dimensions are:

- Length of L. W.: $L = 28.346$ m.
- Length over all $L' = 30.480$ m.
- Beam $= 5.486$ m.
- Depth moulded $= 2.489$ m.

At the time of the accident the initial stability factors were:

- Displacement $D = 122.48$ tonnes.
- C. of buoyancy above keel $F_RK = 1.130$ m.
- Init. metacentric radius $M_{hF_R} = 1.600$ m.

The above numerical values are based on the inclining experiment performed by the author in the summer of 1938, the drawings of the shipyard and the records of the court proceedings regarding the accident being available.

Let us see whether the vessel's initial stability remains positive with the fore deck filled with water. According to the evidence of witnesses, the after part of the fore deck was completely filled.

The surface area of the filled part of the fore deck $35.0 \text{ m}^2$.

Transverse moment of inertia of upper surface of filled part $i = 70.0 \text{ m}^4$.

Average height of bulwarks about $0.385$ m.

Volume of filled part about $13.5 \text{ m}^3$.

We assume, however, that only 10 tonnes of water remain on deck at one time.

The numerical values to be inserted in equation (78) are:

$\varphi_{h_3} = 0.765 \text{ m} \quad \varphi_{h_3} = 0.752 \text{ m}; \quad I = 196 \text{ m}^4; \quad i = 70 \text{ m}^4$.

At the moment when the fore deck is filled, the initial metacentric height diminishes according to this to the value $-0.357 \text{ m}$. The vessel
would therefore have lost all its initial stability, even if the water had not been able to flow onto the middle-deck. As the bow, according to the evidence of witnesses, remained covered with water during the time of three waves, and as the door to the middle-deck broke, the water was able to flow to the middle-deck, from where it could not very well run off during the vessel's heel. The filling of the foredeck and the flow of water onto the middle-deck were quite sufficient reasons for the vessel's capsizing.

Let us see whether the vessel was sufficiently stable in the event of the foredeck not having been filled with water.

The stability curves corresponding to the moment of the accident are given in Fig. 80. According to them the deck is immersed at an angle of heel of 14.2 degrees, \( \varphi \approx 20.2 \) degrees and the first non-watertight hatch comes into water already at an inclination of 22.8 degrees. The capsizing angle is 28.2 degrees.

The vessel's stability was so poor that we can base the investigation on determining the statical angle of equilibrium when the vessel is proceeding without turning in a 20 m/sec. beam wind.

Vessel's wind surface \( F_t = 116 \text{ m}^2 \) (partly measured, partly estimated).

Aver. length of wind surface \( L' = 24.89 \text{ m.} \)

- \( h = 4.66 \text{ m.} \)
- \( B_d = 4.5 \text{ m.} \)
- \( a = 25.8^\circ. \)
- \( nH_i = 2.77 \text{ m.} \)
- \( T/2 = 0.905 \text{ m.} \)
- \( pF_t = 0.0294. \)

At an inclination of \( 20^\circ \) we obtain the moment arm of a steady wind: \( 0.127 \text{ m.} \). As the vessel's greatest stability arm at 20.2 degrees was only \( 0.085 \text{ m.} \), the vessel could not have withstand a steady beam wind of 20 m/sec. As the vertical distance between the examined vessel's centre of the wind pressure and centre of the lateral plane is \( 4.325 \text{ m.} \) at a heel of \( 20^\circ \), the vessel could have withstood a pressure of steady wind

\[
p = \frac{h \cdot D}{4.325 F_t} = \frac{0.085 \cdot 122.48}{4.325 \cdot 116} = 0.0208 \text{ t/m}^3,
\]

which corresponds to a wind of 16.3 m/sec. near the water surface or about 20 m/sec. at a height of 20 m (at normal observation height). The vessel's stability was therefore in every respect too low to be able to withstand the pressure of a storm gust striking the large deck buildings.

Louhi, lake passenger steamer, capsized on the 15.5.1934 south of Kuopio while turning to starboard when running at full speed. The vessel had already a bad heel to port and had turned about \( 15^\circ \) to \( 20^\circ \) from its original direction to starboard, when the master first put his rudder over to midships and then to the opposite side. The object of this manoeuvre was to bring the vessel back into its upright position, but she heeled still more to port, sinking in 2 to 3 minutes. At the time of the accident 9 bull's-eyes on the port side were open; the diameter of these bull's-eyes was 27 cm and there were 11 of them all told on the port side. The weather was calm at the time of the accident. The vessel carried 55 passengers, some 9 tonnes of deck cargo and 1.04 tonnes ballast, the latter being 2.46 tonnes less than the ballast should have been according to the requirements of the surveyor.

The vessel's main dimensions are:

- Length between perp. \( 23.0 \text{ m.} \)
- Length over all \( 24.7 \text{ m.} \)
- Beam \( 5.3 \text{ m.} \)
- Depth moulded \( 2.66 \text{ m.} \)

The initial stability factors were at the time of the accident:

- Displacement \( D = 96.22 \text{ tonnes.} \)
- Centre of buoyancy above keel \( F_{JK} = 1.076 \text{ m.} \)
- Init. metac. radius \( M_{F} = 1.667 \text{ m.} \)
- Above keel \( M_{K} = 2.743 \text{ m.} \)
- Vess. c. of gr. above keel \( G_{K} = 2.529 \text{ m.} \)
- Init. metacentric height \( M_{G} = 0.214 \text{ m.} \)

The determination of the factors has been based on official inclining experiments made on the 27.5.1934, the body plan of the vessel and — while estimating the distribution of the weights — the court records of the accident proceedings.

Let us examine how far the vessel would heel when turning at full speed.

The vessel's mean draught \( T = 1.723 \text{ m.} \)

- Area of rudder \( F = 1.05 \text{ m}^2 \)

Vert. dist. betw. c. of rudder area and later. plane \( l = 0.348 \text{ m.} \)

Speed in turning \( \psi \), max. 8 knots.

- Turning radius \( a \approx 74 \text{ m.} \)
- Rudder angle \( \alpha \approx 45^\circ \).
Vert. dist. betw. c. of gr. of vessel and after. plane \(b = 1.606\) m.

\[
\begin{align*}
    k_1 &= 0.0375 \\
    k_2 &= 0.358 \\
    k_3 &= 0.0014 \text{ m.}
\end{align*}
\]

For determining the statical angle of equilibrium \(\varphi_s\) due to the turning, the diagram 64 is laid on top of the stability arm curve (Fig. 80), so that the abcissa axis of the diagram lies at the distance \(h_s\) below the \(\varphi\) axis of the curve.

We obtain

\[\varphi_s = 10.0^\circ.\]

On account of the moment arm of the rudder pressure being so small, the increase of the heel brought about by putting over the rudder midships is not very great. On account of equation (41) and the stability arm curve we see that the increase of this heel does not exceed a couple of degrees. The initial stability being very small the dynamical roll, which arises immediately after putting the rudder over, may be greater. The angle beyond which this heel cannot go we get to know with the help of Fig. 67, by measuring therefrom the values of \(h\), corresponding to the value of \(k_1 = 0.0375\) and the different angles of heel, and then drawing the work lever curve corresponding to them together with the vessel's dynamical lever curve in the same diagram. We find that the dynamical heel cannot have been greater than \(21^\circ\). The real extreme heel due to the turning cannot, however, have been as great as this even, as both the putting over of the rudder and the beginning of the turning took place slowly. The determination of the actual amount of the dynamical heel in question does not belong to the object of this investigation. It is sufficient here to establish whether the Louhi would not have capsized from the effect of turning, if the bull's-eyes had been closed.

The stability arm curve of the Louhi being very flat we may be content with determining the force of a steady wind, which the vessel can stand statically. The vessel's wind surface \(F_t = 110\) m\(^2\) (partly measured, partly estimated).

Av. length of wind surface \(L' = 21.2\) m.
Av. breadth \(B_t = 4.0\) m.
C. of. pressure of wind above water level \(nH_3 = 3.06\) m.
C. of. of deck buildings \(H_4 = 5.18\) m.

The deck of the vessel is immersed at an angle of heel of \(24^\circ\). We determine how strong a steady wind is required for heeling the vessel so far.

The values of the functions \(f_1(\varphi, \alpha) = 1.145\) and \(f_2(\varphi, \alpha) = 0.977\) correspond to angles \(\alpha = 21.1^\circ\) and \(\varphi = 24^\circ\). The moment arm of the wind moment is therefore:

\[h_s = 4.972\ \text{m.}\]

By writing it equal to the vessel's stability arm at the same heel, \(h = 0.092\), we obtain for the wind pressure \(p = 0.0185\) t/m\(^2\), to which corresponds a wind of \(15.4\) m/sec.

The greatest stability arm of the vessel is \(0.136\) m at a heel of \(34.5\) degrees. We determine what speed of wind effects a moment arm of the wind moment of the same size, and therefore indubitably capsizes the vessel. The values of the functions are now \(f_1(\varphi, \alpha) = 1.088\) and \(f_2(\varphi, \alpha) = 0.839\). The moment arm of the wind moment is thus \(h_4 = 4.069\) m. By writing it equal to \(0.136\) m, we obtain for the wind pressure \(p = 0.0334\) t/m\(^2\), to which corresponds a wind speed of \(20.7\) m/sec.

A wind of such strength being possible to occur here, we can state that the stability of the Louhi was insufficient.

The lake passenger steamer Tuiristi capsize south of the town of Mikkeli, at the western end of Louhisesi, by the action of a gust of wind. The vessel capsize very shortly after turning from a head wind to a beam wind. There were 40 persons on board at the time of the accident, 144 tonnes of cargo on deck, and 2,112 tonnes ballast in the bottom.

The vessel's main dimensions were:

- Length over all \(213.67\) m.
- Beam \(4.41\) m.
- Depth moulded \(1.85\) m.
- Mean draught at the time of the accident \(1.260\) m.

The initial stability factors at the time of the accident were:

- Displacement \(D = 61.14\) t.
- C. of buoyancy above keel \(F_0/K = 0.983\) m.
- Init. metacentric radius \(M_G/F_0 = 1.160\) m.
- metacentre above keel \(M_K/K = 2.143\) m.
- Vessel's c. of gr. above keel \(GK = 2.104\) m.
- Initial metacentric height \(M/G = 0.039\) m.
The determination of the above numerical values has been based on an inclining experiment, which the author performed on the sister-ship of the Turisti, the body plan of the vessel, the measurements of the deck buildings of Turisti and — while estimating the distribution of the weights — the records of the court proceedings on the accident. According to the said values the vessel’s stability arm curve (Fig. 88) was drawn; the curve is so flat and short that one can hardly talk of any stability at all. The maximum of the stability arm was already reached at 7.2 degrees, and its amount is only 0.005 m. The capsizing angle is also very small, 11° only. When the vessel heels further the immersion of the raised after deck makes the stability again positive, but that is of no avail because the non-watertight hatches are already immersed at an incline of 25°.

Let us see how strong a steady beam wind the vessel can withstand at the utmost.

The vessel’s wind surface was \( F_i = 56.5 \ \text{m}^2 \).

Aver. length of \( a \) 18.2 m.

Height of \( a \) 3.1 m.

Vert. distance of pressure of wind above water \( H_k = 1.83 \ \text{m} \).

Aver. breadth of deck build. (estimat.) \( B_k = 3.6 \ \text{m} \).

\[ \alpha \approx 30°. \]

When the angle of heel is 7.2 degrees, the functions \( f_1 \) and \( f_2 \) obtain the following values:

\[ f_1 (\alpha, \phi) = 1.131; \quad f_2 (\alpha, \phi) = 1.054. \]

The moment arm of the wind pressure is therefore:

\[ h_k = 2.525 \ \rho \ \text{m}. \]

By writing it \( h_k = 0.005 \), we obtain the value 0.00198 t/m² for \( \rho \), which equals a wind of 5.03 m/sec. A wind of that force would thus have been able to capsize the vessel. According to information from the meteorological station, the speed of the wind was measured, 1 1/2 hours after the accident occurred, as follows:

at the station of Mikkeli \( 9 \ \text{m/sec} \), and

9 m/sec.

Lappeenranta 4 m/sec.

We see that it was fully possible for the vessel to capsize, under the circumstances prevailing, through the effect of the steady beam wind alone. Taking the gusts of the wind into account, we may say that the vessel was so loaded that its capsizing was inevitable.

The passenger and cargo vessel Kustavi capsized in a gale in the roads off Hankoniemi on 5.11.1921, from the effect of a heavy beam-swell. The vessel carried at the time of the accident in both her holds altogether 48.4 t herring in barrels and 12.35 t general cargo on deck, of which quantity 7.5 t iron. The passengers and crew numbered 30. The after hold was full, the fore hold not; the cargo in the fore hold was not secured at all. The deck cargo was only partly secured. At the sides of the deck buildings, amidships, there were ports, which were not fastened during the journey. On the vessel heeling over and capsizing to port, the door on that side opened.

The vessel’s stability curves and the dynamical levers corresponding to the limit angle have been determined on the basis of the inclining experiment, which the author performed on the vessel’s sister ship in the summer of 1938; the determining of the distribution of the cargo is based on the records of the proceedings when enquiring into the accident. The quantity of the vessel’s ballast not being known with certainty, the calculations were made parallelly under the assumptions that there was no ballast and that there was 5.5 t, i.e. the same quantity of ballast as on board the vessel’s sister ship.

The initial stability factors corresponding to the moment of the accident are under these assumptions:

<table>
<thead>
<tr>
<th>No ballast Ballast 5.5 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement .............. ( D ) 161.6 167.1 t</td>
</tr>
<tr>
<td>C. of buoyancy above keel ( F_K ) 1.419 1.441 m</td>
</tr>
<tr>
<td>Metacentric radius ( M_{FB} ) 1.479 1.477 m</td>
</tr>
<tr>
<td>Metac. above keel ( M_{KB} ) 2.898 2.918 m</td>
</tr>
<tr>
<td>Vess. c. of gr. above keel ( G_K ) 2.022 1.959 m</td>
</tr>
<tr>
<td>Init. metacentr. height ( M_{KG} ) 0.876 0.949 m</td>
</tr>
</tbody>
</table>

The curves corresponding to these numerical values are given in Fig. 81. We see from the curves that, although the vessel’s initial stability is irreproachable, the values of the stability arms and the dynamical levers at the heeling angles are very small. The vessel’s non-watertight hatch is immersed at an incline of 23.6 degrees, if the vessel has no ballast, and at 22.4 degrees if there are 5.5 t of ballast. The corresponding dynamical levers are 0.033 and 0.031 m, or far from what they ought to be according to the new minimum rule for dynamical stability. The vessel’s \( p_m \) being 19.5 degrees only, the limit

\[ 1) \] In the records of the enquiry is stated that the ballast amounted to 25 t, but that cannot be possible as the vessel could hardly have taken more than a 80 t total load. The figure should obviously read 2.5 t.
angle ought not to be greater; the corresponding dynamical lever is then 0.026 m only, thus so small that the vessel’s stability must be held to be absolutely insufficient.

The vessel’s two maxima of the stability arm curve are due to the vessel’s forecastle and poop. The non-watertight deck erection amidstships was not taken into account when drawing the curves.

The auxiliary vessel of fleet tug type B 2 capsized in the autumn of 1931 off Helsinki. The capsizing took place in a heavy sea when the vessel was turning for returning to port. The vessel, which had no hold, had taken 1.03 t of potatoes, 5.0 t of cement and 1.8 t of iron on deck.

\[ m \]
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\[ 0^\circ \]
\[ 30^\circ \]
\[ 15^\circ \]
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\[ 180^\circ \]
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\[ 0^\circ \]
\[ 90^\circ \]
\[ 180^\circ \]
\[ 0^\circ \]
\[ 90^\circ \]
\[ 180^\°

The vessel’s length about 17.0 m.

Vessel’s initial stability factors were at the time of the accident:

| Displacement | \( D \) | 62.4 t.
|--------------|--------|--------
| C. of buoyancy above keel | \( F_K \) | 1.012 m.
| Metacentric radius | \( M_{F_0} \) | 0.961 m.
| Metac. above keel | \( M_K \) | 1.973 m.
| Vess. c. of gr. above keel | \( G_K \) | 1.655 m.
| Initial metacentric height | \( M_{G} \) | 0.318 m.

The numerical values given are determined partly by estimating, partly by using the vessel’s body plan, and on the basis of the records of the enquiry into the accident. It has not been possible to perform any inclining experiment.

The stability curves applying to the moment of accident are given in Fig. 81. The vessel’s deck is already immersed at a heel of 15.1 degrees, and the static critical heeling angle is 35°. The corresponding dynamical levers are very small, only 0.008 and 0.061; they do not comply with the demand of the enquiry — at any rate with such a heavy deck cargo — fit for navigating along open coasts.

The vessel’s deck was surrounded by closed bulwarks with freeing ports.

The auxiliary vessel of fleet tug type B 6 capsized on 7. 1. 1936 off Hanko in a beam—sea. The vessel had at the time of the accident 1.8 t of deck cargo. The door on the after deck to the crew’s quarters was open, and its sill was only 0.01 m high. The bulwark had the usual freeing ports.

The stability factors corresponding to the time of the accident have been determined on the basis of the vessel’s inclining experiment, the body plan and records from the enquiry.

| Displacement | \( D \) | 66.7 t.
|--------------|--------|--------
| C. of buoyancy ab. keel | \( F_K \) | 1.314 m.
| Metacentric radius | \( M_{F_0} \) | 0.961 m.
| Metac. above keel | \( M_K \) | 2.274 m.
| Vess. c. of gr. ab. keel | \( G_K \) | 1.985 m.
| Initial metacentric height | \( M_{G} \) | 0.289 m.
The stability curves for the moment of the accident are seen in Fig. 81. The deck is already immersed at a heeling angle of 8.2 degrees, and the stational critical heeling angle is 20 degrees only. The corresponding dynamical levers are 0.008 and 0.040 m. As we may choose as limit angle the greater of the said angles, we may say that the vessel's stability is obviously insufficient for navigating in open sea. The vessel's deck being very low, the stern broad and the edge of the deck immersing very early, the deck is easily filled with water in a rolling sea, and the stability thus becomes dependent on the condition and size of the freeing ports and the nature of the vessel's closing arrangements. In all these respects the boat cannot be called a seagoing vessel. The direct cause of the accident was the breaking of water on deck and then through the open door into the crew's quarters.

The torpedo-boat S 2 capsized in a severe storm in the Gulf of Bothnia on 4. 10. 1925. The vessel had been built in 1900. Her principal dimensions were:

- Maximum length .......... 58.0 m.
- Maximum breadth .......... 5.6 m.
- Moulded depth .......... 3.14 m.
- Displacement fully equipped .......... 260.0 t.

At the time of the disaster there were 53 men on board; the amount of coal was probably exceedingly small. At least the fore-peak had been filled with water. The initial stability factors of the ship were (partly estimated, partly calculated):

- Displacement .......... $D = 240.0$ t.
- C. of buoyancy above keel .......... $F_3K = 0.943$ m.
- Init. metacentric radius .......... $M_0F_3 = 1.752$ m.
- Init. metacentre above keel .......... $M_0K = 2.695$ m.
- Vessel's c. of gr. above keel .......... $GK = 2.085$ m.
- Initial metacentric height .......... $M_0G = 0.610$ m.
- The corresponding mean draught .......... 1.55 m.

The determination of the mentioned numerical values is based on the assumption that the distance from the keel to the centre of gravity of the fully equipped vessel, in accordance to certain information received, would be 2.175 m; the new position of the centre of gravity as well as the metacentric height were determined by calculations. The corresponding stability curves are shown in Fig. 81. According to these the deck of the vessel is immersed at a heeling angle of 33.2° and the stational critical angle of heel is 40.6°. As limit angle of heel may be thus chosen 40° or possibly 33.2°, if the deck's closing arrangements had not been in good condition. The dynamical levers corresponding to these angles are 0.130 and 0.088 m. Thus, if there was no other leakage in the ship than that in the forepeak, the stability would have been sufficient. The sister ship of the torpedo-boat S 2 also passed through the same storm, and water penetrated into her even into other compartments, i.e. into the engine-room. For this reason, it is probable that in the hull of the S 2 there was also free water which impaired her stability properties so much that they, at the time of the disaster, were not by far in accordance with the curves of Fig. 81. The stability could easily become so much reduced from the effect of the leakage water that, at the time of the disaster, it was no more sufficient, and the ship capsized when it got into a steep bottom swell.
Appendix 1.

Collection of Examples of Capsized and Lost Vessels.

In this collection are brought together a number of such accidents at sea, occurring abroad, which have been caused, for certain or at least presumably, by the effect of the respective vessel’s stability properties.

**Example 1.** The monitor Captain, a British low freeboard battleship, provided with sail rigging and steam-driven, capsized and sank in 1870 when sailing in the Bay of Biscay. Among others COLES, the vessel’s designer, was drowned. The ship was booming along in a strong wind and at a heel ing angle of 45° when a squall capsized her. Next she sailed the monitor Monarch, designed by REED, which had a higher freeboard; she endured the wind well. In the ensuing investigation it was ascertained that the general stability properties of the Captain were, in spite of her larger initial stability, much worse than those of the Monarch. The difference is to be observed from the following table as well as from the stability arm curves of the vessels (Figure 18, page 50).

<table>
<thead>
<tr>
<th></th>
<th>Buoy.</th>
<th>M G</th>
<th>h n</th>
<th>$\gamma$</th>
<th>Displ. in tonn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captain</td>
<td>1869</td>
<td>15</td>
<td>1.98</td>
<td>0.79</td>
<td>21°</td>
</tr>
<tr>
<td>Monarch</td>
<td>1869</td>
<td>17</td>
<td>2.82</td>
<td>0.73</td>
<td>35°</td>
</tr>
</tbody>
</table>

The accident attracted great comment and was the direct cause that the stability arm curve was adopted as a basis for the judging of stability of warships.

Sources: [H 9], [H 10], [E 9], [N 3], [P 4] and [R 14].

**Example 2.** S. S. Daphne, a small vessel built on the Clyde, capsized in 1883 immediately after being launched. The following has been stated about the accident: This was probably the greatest mishap that had occurred up to then in the shipbuilding trade; certainly it was an occurrence that meant the commencement of a new era in the designing of merchant ships. The strong phraseology is due to this accident’s large number of victims.

Source: [N 4].

**Example 3.** The torpedo-boat Frâmeè collided with the French battleship Brennus during the night of 11. 8. 1900, capsized and sank. The ship’s principal dimensions were: length 56.0 m, breadth 6.0 m, draught 3.0 m, displacement 314 t.

The Frâmeè got in front of Brennus’s bow in such a manner that the latter’s bow struck the former approximately amidships. The angle between the courses was 30°, the Frâmeè’s speed 16 kts; it had been possible to reduce Brennus’s original speed of 10 kts so that the estimated encounter speed — a relative one — was less than 3 kts. According to ERNST, Frâmeè’s very small stability was the reason that the light blow, caused by such a small encounter speed together with a possible effect of the rudder and the small bow-wave of the Brennus, could capsize the vessel. Reasons for the small stability are the small B/T and the high placed weights. The measurements of the German D 16-type boats of the torpedo division, built in England, are: $L = 6.0$ m, $B = 5.9$ m, $T = 2.3$ m, $D = 355$ t, wherefore the $B/T = 2.565$, while Frâmeè’s $B/T = 2.0$. Still the stability of D 16 has been considered to be so small that it has often been felt to be unpleasant. Besides, Frâmeè’s shape was such that the broadside, already at 0.5 m above the waterline, commences to curve strongly inwards so that the stability hardly increases with any larger angles of the heel. The weights were situated specially high; at a height of 0.75 m above the deck another one of perforated sheeting was erected, which among other things raises the deck houses, ventilators, the artillery and the torpedoes, the sun roof and other equipment correspondingly higher. The deck weight was still increased by two other deck houses, four funnels, the high foot of the standard compass and two boats in their davits. — The ship’s sinking bow first is in all probability caused by the fact that at the collision a small leak occurred in the foreship. ERNST considers it absurd that the ship should capsize so quickly merely because of a leak. She had been finished in the preceding year.

Source: Schiffbau 1900—01, page 123 and [E 8].

**Example 4.** The disappearance of six German fishing boats during the winter of 1902—03. Of the boats the St. Johann was fishing off Iceland, nearly fully loaded, Balder and Georg Adolff were on their way to Iceland, the Kommandant and Uranus intended to fish in the North Sea and the sixth of the destroyed vessels, by the name of Neck, was returning to her home port. Owing to the accidents the Germanischer Lloyd made an investigation with vessels of the same type, altogether 15 ships. The lengths of these ships varied between 31.32—41.00 m, displacements 255—550 m³ and the metacentric heights, two to three days after the departure of the vessels from the home port, 0.715—0.885 m. Stability curves were also drawn for ten of these ships, part of which appear in Fig. 13 (page 43) transformed into stability arm curves.

As a result of the investigation it was reported that the destroyed vessels have in all probability capsized. The capsizing could be caused by water swamping the deck and thereafter penetrating into the interior of the ship in conjunction with the wind and the rough sea. It is specially stressed that the capsizing could have occurred even though the metacentric heights of the ships have been very large. Because of this it is emphasized that for judging the stability one ought not to be satisfied only by determining the initial metacentric height.

Source: [S 31].

**Example 5.** A small Danish torpedo-boat No. 10, of the Thornycroft type, capsized when turning in a not particularly rough sea in the Bay of Copenhagen.
The displacement of the boat type was 17 tons, the centre of gravity very high, 33 % from the draught above the water-line, the freeboard was high and the breadth more than thrice the draught. The metacentric height was 0.254 m, \( p_m \) 35° and the corresponding stability arm only about 0.1 m. The range of stability theoretically exceeded 90°, but the stability arm decreased to nearly zero at 60° and at larger angles. The stability arm curve is shown in Fig. 18 (page 50).

The boat had two large rudders the upsetting moment of which, on the rudders being put hard over, was much larger than the moment of centrifugal force. For this reason, the boat heeled sharply when the rudder was put over amidsthips. On a vessel of the same type the list was 13°, although the area of the rudders had been decreased by 33 % and the ballast in the boat increased.

The cause of the accident was considered to be the just mentioned large angle of heel caused by the sudden cessation of the turning movement as well as the fact that the boat seemed to have got into synchronism with the swell. Source: [11].

Example 6. S. S. Göta Elif, a passenger steamer. The vessel capsized on April 15, 1906, on leaving one of the piers at Gothenburg. The reason for the accident is considered to be the fact that an unsuitable distribution and stowage of the cargo has decreased her stability to the greatest extent so that even the smallest cause was sufficient to capsize her, such as for instance the upsetting moment that was brought about by the steamer leaving the pier stern first and with rudder turned.

Source: [N 3].

Example 7. S. S. Margarita Rus, a cargo steamer with a deck cargo of timber, sank in 1912.

According to the legal investigation the ship had a cargo of 4,200 t of pine wood, the metacentric height was 0.030 m and the corresponding displacement about 6,540 t. The court pronounced that it seemed very suspicious whether the ship’s stability was sufficient.

Benjamin has written an article in the newspaper Hansa [B 22] with reference to the accident. If the court’s supposition regarding the cargo and the size of the initial stability holds good, and if the buoyancy of the deck cargo is not at all taken into consideration, then the stability arm curve of the ship would have been like that of Fig. 19 curve A (page 50). As the hold could only take about 3,200 t then the size of the deck cargo was about 1,000 t if the buoyancy of this deck cargo is taken into consideration in the calculations then curve B is obtained. According to Benjamin curve A indicates an extremely dangerous stability while curve B a fully sufficient one. If the latter curve holds good then the ship would easily but not suddenly roll within the limits of small heeling, but she would not list very easily even in a rough sea. Curve B approximately corresponds to the most unfavourable circumstances that could have prevailed at the time of the accident. If a favourable distribution of the cargo in the hold an approximately 150 t smaller displacement be chosen as a basis then the freeboard is about 0.150 m larger and the metacentric height is 0.320 m, and then curve C is obtained. The actual stability curve of the ship was probably somewhere between curves B and C, may be like curve D, i.e. in an unfavourable case the ship’s stability was quite sufficient, in a favourable one very large; in no case it was not insufficient.

If the whole deck cargo had gone overboard the stability curve would have been E shaped. If that is compared to curve D it is discovered that the deck cargo has in no way impaired the ship’s stability properties. The dynamical stability has remained nearly constant. Source: [B 22].

Example 8. The salvage vessel Untersee, built at Kiel in 1903, gross tonnage about 626 and net tonnage about 287 reg. tons. The lifting bunks in the stern can lift altogether 500 t. In order to subdivide the weight during lifting the vessel has 20 tanks, the water capacity of which is altogether 1,200 tons.

On the morning of May 5th, 1913, the Untersee was anchored, together with her sister ship Oberelbe, in the vicinity of the sunk torpedo-boat S. 178, about 5 nautical miles to the east of Heligoland. The Untersee was riding on her starboard anchor; 137 m of chain had been run out. In the forenoon the weather was fine and the wind moderate, direction between S and ESE. About noon the strength of the wind grew stormy, direction ESE. At 12:30 it was discovered that the lifting engine room, situated between-decks at the fore ship, which yet at 11 o’clock had been quite empty, was nearly half filled with water and that the ship’s bow had sunk. As the room had no pumping arrangements one tried to open the manhole in the floor, so that the water could run through it to the lower part of the ship wherefrom it could be pumped out. However, before one had time to open the manhole, and before one could attach the tow-rope of the tug that had come to her assistance at 13 o’clock, the Untersee suddenly capsized onto her starboard side at 13:15 and sank immediately thereafter.

The Seamen’s Hamburg, which investigated the accident, could not discover the reason for the penetration of the water. Had the iron hatch on the deck above the engine room, which had been screwed fast in the forenoon, been opened, or had it broken, that had not been observed by anyone because much water continued to pour over the bow. The court considers it to be unlikely that the water penetrated through the hatch or the anchor pipe; in what manner the water has got to the engine room remains unsolved. According to the court’s decision the cause of the accident is the flooding of the engine room for owing to this the ship had become top heavy. It is recommended to equip the engine room with pumping arrangements.

Sources: [S 39] as well as Schiffbau 1912–13, pages 688, 753 and 509.

Example 9. S. S. Narvik, a Lubeck turrent ship, built in 1903. Gross tonnage 3,776 reg. t., net tonnage 2,300 reg. t. The ship went to the bottom during the night of 15. 12. 1913 on her way from Aussenanseland towards Hubert gate; the weather was stormy.

The accident was investigated by the Seamen’s Enden, L. Benjamin and Schmidt acting as experts. On the ship leaving Enden she had a coal cargo of 5,599 tons, 478 t of bunker coal and 33 persons on board. In port the captain had hesitated to put out to sea because the vessel was so cramped. He stated that previously in a storm at sea the ship had got so large a list that even he had stood up to his waist in water. However, she left in the company of another vessel. During the voyage they anchored at Aussenanseland and the wind having slightly abated continued during
the night, the Narvik turning towards Hubergate. Later on the Narvik was discovered bottom side up on shore at the mouth of the Fis.

BENJAMIN considers the turret ship's stability to be smaller than that of an ordinary vessel, but not so much so that there would be a difference in the ships' seaworthiness. Narvik's fault was that the double bottom was very high (1.7 m). Because of this the stability was probably too small. Perhaps ballast ought to have been taken, but the accident could also have been caused through other faults than stability. — SCHMIDT also complained of the high double bottom. The shifting of the cargo is very injurious: the cargo having moved the capsizing angle is 15°. He does not solely accuse the small stability. — The Seaman gave as its opinion that the reason was presumably the shifting of the cargo, either alone or together with some other cause. The accident would have been probably averted if, according to previous experience, ballast or a correspondingly lesser cargo had been taken.

The case was afterwards investigated by HERNER, who wrote on the subject in the newspaper Hansa. In his opinion there is no reason to claim about the stability properties of turret vessels. Owing to these ships' peculiar construction the stability curves are special ones: they attain two separate maxims, one at comparatively small angles of heel, the other at a larger one. Vessels of such a type being flush-decked, and waves flooding the deck not finding any adhering points, turret ships need only half of the stability necessary for normal vessels. Owing to this the small surface stability of a turret ship at the small angles of heel is quite fully compensated. A result of this is that one has begun to contemplate measures for the decrease of these ships' stability and not for the increase thereof. The ship's double bottom is made higher than usual so that the centre of gravity is raised. The stability of the turret ships has never been complained of and their stability properties have been judged as they should be judged, i.e. by means of dynamical stability curves and not by statical ones.

According to HERNER Narvik's draught in brackish water, before leaving for the fateful voyage, was 7,074 m, which corresponds to a draught of 6,944 m in sea water. The corresponding displacement of the ship is 8,720 t. The cargo was stowed according to regulations nor had the small vacuums, that remained in the holds under the harbour deck, any effect on the stability. According to exact calculations the ship's centre of gravity was 5.42 m above the keel. The corresponding stability arm curve is shown in Fig. 20 (page 51). Calculated according to this, the dynamical lever corresponding to 50° was 0.095 m and to 60° 0.190 m, the former nearly double as large and the latter nearly once as large as the dynamical lever, which BERNHARD had proposed to be chosen as minimum values of dynamical lever. Referring to his statement BERNHARD considers Narvik's stability as being quite sufficient. The reason of the accident should be sought elsewhere not from the stability properties. It is possible that because of the weather becoming continuously worse the pilot has tried to find shelter and has driven the ship onto a bank. This has so decreased the stability that waves sweeping over have been capable of capsizing the ship. This opinion is supported by the fact that one has had to leave three lifeboats. One could not have done that if the vessel had suddenly capsized.

Sources: [B 8], Schiffbau 1913—14, pages 248 and 876 as well as [H 16].

Example 19. S. S. Askal, cargo and passenger ship. Principal dimensions: length between perpendiculars 133.50 m, breadth 17 m, moulded depth to main deck 11.54 m, gross tonnage 8,287 reg. t., deadweight about 8,000 t., maximum number of passengers 1,310. The ship capsized in Hamburg harbor, on being towed out of dock, on June 16th, 1922. At the same time as the dock sank one commenced to fill the bottom tanks of the ship. On the vessel floating at the light water line she began to heel to port, continuing to lean against the port side dock supports. The dock personnel ordered the ship to be righted, wherefore the filling of the port side tanks was discontinued and that of the starboard tanks was continued. The ship gradually righted herself but she still had a list to port when the tugs commenced to tow her out of dock. In the middle of the fairway the ship suddenly capsized with a violent jolt to starboard, presumably from the effect of the tug's pull, lifted herself for an instant and then capsized onto her starboard side. Judging from the vessel's movements one must come to the conclusion that the starboard tanks were still at the time of the accident more filled than the port ones and that in many of the starboard as well as port tanks there were free water surfaces, which quite upset the already otherwise small stability of the ship. A typical accident caused by unsteadiness is thus under consideration.


Example 11. S. S. Herbert Stavber, constructed in England in 1909, gross tonnage 2,451 reg. t. The vessel, having a coal cargo, capsized and sank on 31. 11. 1922 in the North Sea. The accident was investigated by the Seaman Hamburg, FOERSTER acting as expert.

The ship was on her way from Hamburg to Hamburg. On the day preceding the accident the wind's strength grew from 6 to Beaufort to 10 Beaufort, its direction being NW. On the morning of the mishap the ship listed 15° to 16° to starboard. The holds were gauged but no water was discovered. One began to shift the coal cargo to port. In the midst of the work the seas swept over the fore ship and the hatch, the list increased to 24°. The work of shifting the cargo was discontinued and through an oversight the hatch was left open. The ship was no more under control and after a quarter of an hour she sank. Three hours had elapsed from the first listing of the vessel.

In FOERSTER's opinion the accident was caused by the formation of the heel, its expansion and finally through the capsizing of the ship, all of which had been caused by certain construction points, dangerous to the ship, namely her shape and the non-division of the tanks. The capsizing was either caused by a leakage in the bottom tanks or their flooding, or possibly by the breaking of the outside plating on the top of the tanks. If the bottom tanks had been of ordinary type and if the transverse bulkheads had been watertight, in a normal manner, then one could not have been able to explain the accident at all.

According to the decision of the Seaman the cause of the accident is the fact that water has in some unexplained manner penetrated either into one or several of the bottom tanks, which had strongly affected the ship's stability. The shape of the bottom tanks has been such that on their being partly flooded they had a comparatively much more injurious effect on the ship's stability and on the list, than normally shaped bottom tanks would have had.

Source: Schiffbau 1922—23, page 479.
Example 12. A cargo boat of spar-deck type, length 104 m, breadth 13.7 m, moulded depth to spar-deck 8.25 m, lengths of forecastle, bridge and poop 8.25 m, 27.5 m and 9.0 m. The ship’s cargo was composed of grain in bulk and bags of grain on the poop and bridge. In especially bad weather the rudder chain broke; before one had time to repair it and to turn the ship onto her course again she capsized. A shifting of the cargo was improbable. The vessel’s stability arm curve, partly estimated, is shown in Fig. 16 curves B (page 48). When drawing curve B 1 the deck erections have been considered; curve B 2 corresponds to the vessel’s hull up to the spar-deck, but without deck erections; curve B 3 has been estimated by multiplying the part of the deck erections with the multiplier in question when determining the freeboard. The changing over from curve B 1 to B 3 means decrease of stability to the critical area. The $M_G$ value was 0.200 m. It is not absolutely certain that the $M_G$ value or the range of stability were too small, but the stability in its entirety is clearly insufficient according to the stability arm curve. 

Source: [C 4] and [B 10].

Example 13. Cargo boat, deadweight 840 t. The vessel had a grain cargo in bulk. The accident occurred in such a manner that the ship listed onto her side, because of a gust of wind and an unexplained effect of the rudder, and then capsized slowly by water penetrating through the deck openings. The vessel was without doubt wrongly loaded. The ship’s $M_G$ was 0.075 m. In Fig. 16 (page 48) the stability arm curves are shown. Curve C 1 is estimated by using the same multiplier that is mentioned in the rules for determining the freeboard; curve C 2 corresponds to the vessel’s hull without the deck erections. The ship’s stability is in every respect insufficient. The curves show what small stability ships can have when going out to sea. In this case, as the foremost principal reason for the basis of the accident’s course, must be considered the small metacentric height and not the too small range of stability. 

Source: [C 4].

Example 14. S. S. Nordenham II, a Nordenham tugboat. The vessel capsized and sank when towing a cargo steamer. The reason for the accident was the fact that the tow hook did not open when the vessel got into such a position that the severing of the rope should have been imperative. The hook was a Ristau model. There was no fault in its condition and construction; it might possibly have been squeezed from the effect of some small object. The Seeamt that investigated the accident puts forth in its statement that the towing arrangements should be absolutely so constructed that the hook cannot be subject to squeezing, even in the most unfavourable situation; when using a steel rope in tugging a short manilla rope bit should be fixed between the hook and the steel rope. — The accident occurred in 1925. 

Source: Schiffbau 1925, page 485.

Example 15. S. S. Galion, cargo boat, raised quarter-deck type, built at Schuy in 1923. Principal dimensions: length 54.90 m, breadth 8.85 m, moulded depth up to the main deck 4.11 m, gross tonnage 724 t, net tonnage 349 t, summer freeboard 1.26 m, corresponding mean draught 3.98 m and deadweight 925 t, winter freeboard 1.31 m, corresponding mean draught 3.93 m and deadweight 903 t. The ship had three watertight steel bulkheads. The height of the well-deck’s gunwale was 1.14 m; on both sides there were three 0.76 x 0.46 m freeing ports. The height of the quarter-deck’s gunwale was 1.07 m and on both its sides there were also three freeing ports. The Galion sank on the north-eastern coast of England, presumably on November 25—26, 1925; her cargo consisted of coal. In consequence of the accident the Board of Trade carried out an investigation and stated that the vessel sank in a gale, for owing to her too large trim by the stern she was incapable of freeing herself from the weight of the water masses that had covered the deck in the form of continuous waves. In the investigation the following became clear: 

The ship had a cargo of 801 tons and 80 tons of fuel. On leaving the port — Bith — the draught forward was 3.48 m and that aft 4.39 m, so that the load-line mark was just on the surface. The deck was nearest the water at 1/8 L from the stern, at which point the freeboard was 0.05 m smaller than the freeboard amidships should have been according to regulations. When one still takes into consideration the coal consumption from the port of departure to the presumably scene of the accident, then the different parts of the ship are immersed according to the following enumerated angles of heel, presuming that there was no water on the deck: 

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<tr>
<td>well-deck in</td>
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<td>front of the</td>
<td>6°</td>
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<td>fore bridge</td>
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<td>the well-deck’s</td>
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<td>gunwale</td>
<td>20°</td>
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<td>the well-deck’s</td>
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<td>hatch coaming</td>
<td>33°</td>
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<td>the quarter-deck’s</td>
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<td>lowest point of</td>
<td>16°</td>
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<tr>
<td>the deck</td>
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<td>the quarter-deck’s</td>
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<tr>
<td>gunwale</td>
<td>27°</td>
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<tr>
<td>the quarter-deck’s</td>
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<tr>
<td>deck, the sill</td>
<td>45°</td>
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<tr>
<td>of the engine</td>
<td></td>
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<td>and boiler room</td>
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<tr>
<td>the quarter-deck’s</td>
<td></td>
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<tr>
<td>hatch coaming</td>
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<td>the ventilation</td>
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<td>pipes on the</td>
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<td>sides of the</td>
<td>45°</td>
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<tr>
<td>quarter-deck</td>
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There is space for 55 tons of water on the well-deck, 100 tons on the quarter-deck. The size of the freeing ports does not seem to have been sufficient: their combined area on the quarter-deck was only less than 4% of the gunwale’s area although, according to Lloyd’s regulations, it ought to have been 10%. No inclining experiment has been performed on the ship but after the accident such was made on the vessel’s sister boat, the Blue Galion. According to it the ship’s $M_G$ is 0.396 m when she is loaded with a homogeneous cargo up to the winter load-line. The largest stability arm, 0.140 m, is attained at a 34° heel, the range of stability is 56° and at a 90° angle of heel the upsetting stability arm is 0.389 m. The ship’s stability arm curve (Fig. 16, curve A, page 48) has been drawn according to these particulars. The trim by the stern slightly improves the quality of the curve but the fact that water penetrates more easily into the stern deck makes it again worse. If there are 30 tons of water on the deck of a ship having a 15° list, then the upsetting moment caused by that is larger than the stability moment at 15° and the largest moment of statical stability at 30°.

The ship had a double bottom, which is not usual on coastal vessels; for this reason the cargo’s centre of gravity on the Galion was about 0.15 m higher than on an ordinary coastal cargo boat. The double bottom has thus caused an impairing of the stability properties. To the cargo itself, i.e. the coal cargo in bulk, the court has not bestowed much.
attention, though on behalf of the Board of Trade a list was presented showing 45 vessels with coal cargoes that had been lost after 1912. The court recommended such an alteration in the construction of such vessels that the well-deck be equipped with a partly open gunwale. Regarding the 3-foot trim by the stern the court stated: "not in proper trim." The metacentric height was not criticized but the range of stability was; it was considered to be insufficient. It was established that the shipyard had not made any complete stability investigation, wherefore the captain of the vessel had no data by which to judge the stability points. Finally, the court severely criticized the fact that the upper ends of the ventilating pipes leading to the tanks and fuel bunkers had no closing arrangements.

According to SCHRODER the Galleon's initial stability, taking into consideration that it belonged to class 5, must be considered as being fully sufficient while, on the contrary, the stability arms are exceedingly small.

Sources: [C 4] and [S 24].

**Example 16.** S. S. Negros, a small coastal cargo and passenger vessel. Principal dimensions: length over all 45.11 m, length between perpendiculars 42.67 m, extreme breadth 7.62 m, moulded depth 3.58 m, mean draught at the time of the accident 3.17 m, trim by the stern 0.534 m, corresponding displacement 608.2 t. The vessel sank at the Philippines on 26.5.1927 on turning back from the sea to return to port because the storm was too severe.

In the performed investigation the following became clear: the vessel was originally built as a coastguard cutter for the account of the Philippine Government. In her original form the vessel was sufficiently stable and seaworthy. Curve I (Fig. 17, page 48) shows the stability arm curve. On the ship being acquired by the Bureau of Commerce and Industry alterations were made: the upper deck was continued up to the vessel's sides from the stern part of the bridge to the stern, a new upper deck construction was executed and guard-rails, an awning and two pairs of boat davits were added to the upper deck. The additional weight totalled 17.8 t and the height of its centre of gravity from the keel was 6.86 m. Stability arm curve II. According to this curve the stability stipulations, demanded from a seaworthy vessel, are no longer complied with. If 50.8 tons of ballast had been added to the keel then the ship's stability curve would have been of form III and the old seaworthy position would have been thus attained. In such a case the ship could not have taken any cargo only passengers. — When a private person bought the vessel the following alterations were made: the stern part of the main deck's deck house was shortened also its fore part. The liggerman was removed. The upper-deck house was somewhat altered, its roof was extended up to the ship's sides and it was furnished with guard-rails. Two small wooden masts for the crew were built on the main deck's after part.

The alterations made did not direct the vessel's displacement or stability but they enabled the ship to take much more deck cargo and, because of the new promenade deck, the passengers sojourned higher up than previously. At the time of the accident the ship's stability arm curve was according to curve IV. The weight of the cargo in the hold was 132 t, on deck and at the site of the ship's centre of gravity 98 tons. This quantity of cargo made the ship lie 0.46 m deeper than the constructional water-line. According to curve IV the stability amount was much smaller than that demanded from a seaworthy vessel. Further, the main deck was not waterproof as presumed in the estimates and already at a 5° angle of heel the door sills were immersed in water.

The principal reasons for the accident: a too great depth and a too small freeboard, both caused by overloading of the ship; erroneous storage of the cargo and the alterations in the ship made by the Bureau of Commerce and Industry.

The stability factors of the vessel are given in table 4, page 49.

Source: [M 6].

**Example 17.** S. S. Rote Gertrud, a cargo steamer of quarter-deck type. The vessel was on 6. 1. 1928 on her way in the eastern part of the Baltic at a speed of 7 knots she had a wheat cargo. The wind's strength was 6 Beaufort and in direction 2 points from the port-quarter the swell was moderate. The ship did not have a noticeable initial list. Suddenly, she heeled over about 60° to port, i.e. windwards, soon capsizing onto her side and sank. The Seamen investigated the accident, SCHWARZ acting as expert. According to his calculations the reason was the water that had poured onto the deck; the water had decreased the metacentric height from 0.396 m to 0.375. The loss of initial stability was the cause for the sudden heeling over of the vessel.

Source: [S 9].

**Example 18.** S. S. Rita Larson, cargo steamer. The vessel had a cargo of pulp-paper and was outward bound from Oslo Fjord on 8. 1. 1928. As a strong south-western wind was prevailing the captain turned back the ship to the shelter of the shore. The swell coming from port-quarter the ship turned sharply to port from the effect of the sea, even though the rudder had been put over to starboard, the waves filled the quarter-deck and heeled the ship sharply to starboard. The vessel remained on her side, sinking gradually deeper, bow first. During the night the ship's bow had sunk so deep that even the upper deck edge of the well-deck was immersed. On the crew getting into the boats from the starboard side of the vessel, while putting them out, the ship suddenly capsized onto her port side at an angle of 60° and sank. The peculiar movements of the ship are stated to have been caused by two unstability situations the first of which being caused by the deck water — the heeling over to starboard — and the second by the immersion of the well-deck — the heeling over to port.

Source: [S 9].

**Example 19.** S. S. Venetis, a British passenger and cargo steamer, gross tonnage 15,494 and net tonnage 6,622 reg. tons, built at Belfast in 1912. The Venetis was a shelter-deck vessel. The ship's length was 140.6 m, breadth 18.54 m, largest permitted mean draught in summer in sea-water 8.173 m, the corresponding freeboard 1.562 m, largest allowed mean draught in winter in sea water 8.008 m. The ship had left New York harbour on 10. 11. 1928 with full cargo; on departing she had a slight list to port. On leaving fine weather prevailed. During the morning of the following day the north-east wind freshened; in the beginning the vessel listed 3°—4° to starboard. Early in the morning water was discovered in the coal bunker on the starboard side of the shelter deck and by
means of the ash ejector pipe water also penetrated into the keel; this leakage was repaired during the day. In the course of the day it was observed that water had got into the ship through other leakage spots. The wind and swell increased, attaining during the evening possibly the strength of a gale. As the list still increased the two starboard tanks, that had been flooded in harbour, were pumped out, however not dry. In the evening two waves, following each other and coming from port, filled the fore deck and encountered a fore hatch; the ship suddenly took a sharp list to starboard. In the morning of the following day, November 12th, the water penetrated into the engine room through the bulkhead as well as from the deck. Still another starboard tank was pumped out. The ship already then having a list of about 20° the emptying of the tank only increased it. The list having increased during the previous night to 32° SOS signals were sent out.

The vessel capsized during the day, 18 hours after the start of the first list.

The accident was investigated by the Board of Trade, several engineers acting as experts. Of these two obtained the figures 0.404 and 0.375 m when establishing the metacentric height value. If these figures had really been correct values then, in the opinion of the Board of Trade, the stability would be sufficient if the ship's sides and all the hatches had been watertight. The court, however, doubts these calculation results on the following grounds: 1. The vessel got a 3°-5° list in a beam wind though the wind was a fresh breeze only; the list was measured by a competent person. 2. The metacentric height values are calculated presuming that the vessel had a draught of 8.185 m; according to the Board of Trade's investigations the draught on departure was 8.293 m. Further, it is possible that there were free water surfaces in several or in all the double bottom tanks. Accordingly the court the causes of the accident were i. a.:

1. Overloading of the ship.
2. The ship's cranking.
3. Insufficient stability and the reserve displacement.
4. The stormy weather and high swell that gave the ship a list to starboard.
5. Several leakages.

As proof of the ship's weak stability is, in the opinion of the Board of Trade, also the fact that the persons, who were responsible for the stability of the vessel, considered it necessary to leave 390 tons of sea water in a tank although the ship was already overloaded. In accordance with the first mate's statement this was performed bearing in mind the ship's stability and trim.

According to the investigation the emptying of the first starboard tank was not wrong as one had already previously taken water from it and thus there was already a free liquid surface. The emptying of this tank caused a decrease in the list, but that of the second one was unsuitable; the emptying would have caused an increase in the list if it had already attained the value of 12 1/2°, if the list had been less than that the emptying would have decreased it. The emptying of the third tank was in any case unsuitable; the captain and the first mate were not however aware of the above-mentioned points. SCHWARZ, who has later on investigated the accident, considered the mass of water that poured onto the awning deck to be the cause of the first list; according to his calculations this mass of water has been capable of decreasing the M_G value from 0.3 m to —0.341 m. The deck water has caused a 10° list, whereas the water has poured, by means of the open freeing ports and also through the tonnage openings, onto the main deck from where it could penetrate lower by means of the unlight coal hatches. The ship's captain increased the list when endeavouring to pump out the tanks, for there remained free water surfaces in them because of the list. According to SCHWARZ the cause of the accident was the gunwale as well as the awning deck, equipped with tonnage openings.

In his opinion the tonnage openings, taken into use by the Board of Trade, made the safeguarding of human life at sea illusionary.

Sources: [B 25] and [S 9].

Example 20. The motor vessel Vulkon capsized onto her side in the inner harbour of Brunsbüttelkooog on 19. 11. 1928. The ship, which was of 989 reg. tons, had loaded 745 standards of boards at Rundvik, whereof 150 stds were on deck and the remainder in the hold. The holds and even the loading hatches were quite full. The height of the deck cargo was approximately up to the lower edge of the bridge. The double bottom's ballast tanks 1, 3 and 4 were full of water; the tanks, which were subdivided by a longitudinal bulkhead into port and starboard tanks, were only partly filled. On leaving Rundvik there were on board 11 tons of fuel oil and about 4 tons of fresh water. On the vessel reaching Holtenau there was only very little of the fuel oil and water left, wherefore 25 tons of the first and 7 tons of the latter were taken on board. During the voyage across the Baltic the winds SSW and SW prevailed, strength 5-8 Beaufort. A lot of water swept over the deck cargo wherefore a part of the cargo became loose. At Holtenau the deck cargo was tightened. When passing through the Kiel Canal it rained and the deck cargo got still wetter. In the canal the ship had a list of 2°—3° to port. At Brunsbüttelkooog, where the deck cargo was tightened once more, the representative of the See-Berufsgenosenschaft prevented the ship from going out to sea for, according to his report, her portside load mark was 0.12 m under water and she was overloaded; according to the captain's certificate overloading had not occurred, but the ship had a list of 3—4 degrees to port. After negotiations it was decided to pump out from a port side tank a similar quantity of water as the amount of fuel oil and fresh water that had been taken on board at Holtenau. Soon after the commencement of the pumping the ship listed 5 to 6 degrees to starboard, became upright, rocked several times to and fro and finally remained with a heavy list to port. In the meantime the pumping had been stopped, the engine room filled with water. When the salvage companies began their work the ship had a list of 80—82 degrees. During the work no leakages were discovered in the ship nor any open bull's-eyes.

The court (Seamst Flensburg) could not establish the cause of the accident. The ship was obviously not overloaded. According to the expert's opinion the ship was suitable, as regards her stability, to transport so large a deck cargo as she had. In the opinion of the Government Commissioner the emptying of the tank was the cause of the accident, even though he presumed that some outside factor gave rise to the capsizing, possibly passing vessels or the mooring-ropes. In his opinion the ship must have also had free water surfaces. In their decision the court stated that the reason for the capsizing of the vessel could not be definitely established, but that it is however presumable that outside, but unexplained, factors have had some effect upon it.

Sources: [R 15] and Schiffbau 1929, page 447.
Example 21. S. S. Calder, cargo steamer, built at Birkenhead in 1930. The ship's length between perpendiculars was 73.3 m, breadth 10.4 m, gross tonnage 1,107 and net tonnage 445 reg. tons. The ship had a forecastle, bridge and poop. The part of the deck between the last mentioned, the after well, had a covered gunwale of about 2.4 m in height and was quite covered with uninterrupted hatchets. The well's length was about 6.0 m. The bridge erection had no stern bulkhead so that it formed a common space together with the after well. This space had two freeing ports on both sides of the well. The height of the fore well's covered gunwale was about 2.4 m forward and about 1.4 m aft; there were three freeing ports on both sides.

The ship had loaded altogether 960 tons of general cargo at Hamburg, whereof 200 tons were on deck; the cargo was well secured. The ship left Hamburg in the evening of 17.4.1931; the pilot leaving her on the following morning at 3.30 o'clock at the lights of the steamer Elbe 3. Since then no one has seen the ship. On April 19th loose parts of the Calder were found, i. a. two lifeboats drifting in an upright position and the unfasted hatchets of the after well.

At the legal investigation of the accident one came to the conclusion that the most likely reason for this mishap was the capsizing of the ship, which is supposed to have happened on 19.4.1931 at about 5 o'clock in the morning, approximately 8-10 nautical miles westwards of the further Bowsing lightship. As at the stated time a powerful north-westly swell, and a strong north-east wind of 7 Beaufort, prevailed at the spot. The vessel had rolled heavily, every big wave had swept onto the ship and dislodged the unfasted hatchets of the after well, partly filling the bridge structure where there was no after bulkhead, and quickly destroyed the ship's stability. Because of the rolling of the boat, and as the bridge erection had no freeing ports, part of this water penetrated lower by means of the ventilation pipes and other ways whereat the stability has finally decreased. Possibly the ship has capsized very quickly.

The court drew attention to the fact that the freeing ports were equipped with closing arrangements, with which they could be shut while in port. None had not remembered to unfasten them, or if they did not remain open when putting out to sea, then the ship's danger had greatly increased. On leaving Hamburg the ship's metacentric height was between 0.526 and 0.577 m, according to calculations made afterwards. Taking the ship's quality and construction into consideration the court considered these values as sufficient, subject that no larger amount of water gets onto the bridge erection. However, if this happens then the named initial stability values are insufficient for the ship's safety. According to the pilot the ship's movements on leaving harbour were normal, when bearing the stability in mind.

The ship's captain had at his disposal a number of trim and stability drawings, which were prepared to correspond to 14 different loading conditions. Certain situations had been chosen by the captain himself and explained to him by him to the shipyard. The largest deck cargo considered in them, was 130 tons. At the time of the accident the ship had a deck cargo of 200 tons but, according to the court, the stability reserve was sufficient for such a deck cargo.

The ship's stability curves were twice calculated after the accident, firstly presuming that the water does not penetrate to the after well, or to the bridge erection, and secondly that these spaces are filled during the hoisting of the ship. The trim and stability drawings on board were calculated on the basis of the first presumption. Some witnesses considered the former method as correct and ordinary while others denied this. In the court's opinion it is wrong to keep as bearing spaces such whereto water has access either through freeing ports or unfasted upper hatchets; as the bridge erection had no after bulkhead then it as well as the after well are in the same position in this case. Because of this — in the opinion of the court — the capacity of such departments should in future either not be considered or the stability curves that are handed to the captain should be calculated on the basis of both presumptions.

If the bridge erection had been separated from the after well with a longitudinal bulkhead, similar to that which separated it from the fore well, and further if the ash ejector hatchets on the sides of the bridge erection had been water-tight, then in the court's opinion the danger of such an accident would be quite removed.

In the stability instructions no maximum limit for the deck cargo has been fixed and in the court's opinion this is even unnecessary.

The ship's stability curves are shown in fig. 25 (page 57); when drawing curve A it has been presumed that the forecastle, bridge erection and poop were buoyant; in curve B the buoyancy capacity of these spaces was not considered. According to the curves the ship's stability factors were as follows:

<table>
<thead>
<tr>
<th>Curve A</th>
<th>Curve B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_G$</td>
<td>0.235 m</td>
</tr>
<tr>
<td>$h_m$</td>
<td>0.351 m</td>
</tr>
<tr>
<td>$\phi_m$</td>
<td>50°</td>
</tr>
<tr>
<td>$\phi_a$</td>
<td>84°</td>
</tr>
<tr>
<td>$\phi_b$</td>
<td>59°</td>
</tr>
</tbody>
</table>

The upper part of the poop's door is immersed in the water at a 30° 5/8 angle of heel.

Sources: [B 27] and the letter of MITCHELL, an expert who was present at the sitting of the court.

Example 22. The Japanese torpedo-boat Tomoduru, ready on 23.2.1934 and taken into service on 6.3.1934, capsized in a strong swell on 10.3.1934 off the island of Yoto. Her principal dimensions were: length 77.42 m, breadth 7.32 m, draught 1.83 m, standard displacement 535 t, engine capacity 2000 HP, speed 26 knots, armament at the time of the accident three 12.7 cm guns and four 53.3 cm torpedo tubes.

It is generally considered that the cause of the accident was that the armament was placed too high and was too heavy. After the capsizing the armament of such as well as of other types of torpedo-boats has been reduced. The torpedo-boat Tomoduru's present armament is three 12.6 cm guns and two 53.3 cm torpedo tubes.

Sources: JAMES' Fighting Ships 1936, Schiffbau 1934, pages 111 and 125.

Example 23. S. S. La Crescenta, tanker built in 1933. The ship's length was 121.9 m, breadth 16.1 m, gross tonnage 5,880 and net tonnage 3,531 reg. tons. The vessel loaded with oil left Port San Luis on 24.11.1934, destination Japan. The stormy weather encountered the vessel in the beginning of December and after December 5th nothing was heard of her. In the region where she was then passing a precipitous swell prevailed at the time. An extensive oil patch was later on observed in the same region.
The investigation showed that the vessel had left port overloaded; the cargo exceeded the permitted quantity by 44 t and the depth the largest mean draught by 0.26 m. In the opinion of the court the ship's stability suffered but the stability amount did not, however, counteract the effect of the overloading. The presumable reason of the accident has been the fact that the swell has broken the longitudinal passageway on the deck, the water has penetrated into the boiler and engine rooms and the engines have ceased to function. The sharp swell has at last sunk the drifting vessel.

Source: [B 31]

**Example 24.** Motor sailing vessel 'Flottekbe', built in 1927 at Neustadt, tonnage 319.5/127.4 reg. tons, length 40.02 m, breadth 7.91 m, engine capacity 200 HP. Rigged as a four-masted fore-and-aft schooner. The ship had eight water ballast tanks of which there were three on each side; the volume of the last-mentioned was 18—20 m³. Their air exhaust pipes, which had stop valves to be shut from the deck, ended 3 cm lower from the gunwale’s angle bar; the distance of the pipes from the covered gunwale was 3—4 cm. In each tank there was besides a sounding opening affixed to the deck and closed by a screw plug.

At Danzig on 5.9. 1935 the ship had taken a cargo of birch logs, altogether 286 m³, whereof 195 m³ were in the hold and 91 m³ on deck. The deck cargo, which was not secured in any manner for it leaned against the rigging, was on the average not much more than 0.6 m higher than the upper angle bar of the gunwale. After taking the cargo — according to the captain’s statement — the seawater load-line was reached and after 7 tons of fuel had been taken then the fresh water load-line was also attained.

On the ship putting out to sea the wind’s strength was 5 Beaufort and direction WSW. Speed: 8 knots; the motor was running, the wind blew from port. After an hour the captain noticed that the vessel had a list of about 8°=10° to starboard; although sails were taken in and even a turn made the list gradually increased. According to the captain’s estimate the list having increased to 7° the ship capsized. The deck cargo had not then moved.

At the beginning the Seaman Hamburg investigated the disaster, DAIMANN acting as expert. It was presumed that the ship’s draught was 3.45 m, which was the average value of the draughts stated by a pilot and by the captain. Thus, the permitted maximum draught had been exceeded by 0.153 m, which corresponds to an overload of 37 t. The specific gravity of the cargo would have attained 1.27 which, according to the report of a timber firm, would be still considered as possible. In this manner the deck cargo would attain 116 t, the height of its centre of gravity from the keel 3.65 m, the hold cargo 248 t and the height of its centre of gravity from the keel, presuming that the cargo filled the whole hold, 2.68 m. The total height of the centre of gravity from the keel became 3.26 m. According to these facts the ship's stability arms and moments at different angles of heel would be the following:

<table>
<thead>
<tr>
<th>Heel</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability arm</td>
<td>0.026</td>
<td>0.056</td>
<td>0.076</td>
<td>0.085</td>
<td>0.086</td>
<td>0.024</td>
<td>0.047 m</td>
</tr>
<tr>
<td>x mom.</td>
<td>16.3</td>
<td>34.4</td>
<td>48.4</td>
<td>54.1</td>
<td>51.0</td>
<td>15.3</td>
<td>30.9 mt</td>
</tr>
</tbody>
</table>

The stability arm curve corresponding to these values is shown in Fig. 20, curve II (page 51). Curve I of the same figure is the stability arm curve, corresponding to a timber cargo of 316 t, calculated by the shipyard. According to DAIMANN the comparison of these curves with one another shows the large detrimental effect that Flottekbe's 48 t larger cargo — at the time of the disaster — had on the ship's stability. According to him curve II is to be considered insufficient in regard to the size of the moments of stability as well as in regard to the range of stability. Even though the metacentric height was about 0.29 m the largest stability moment was already reached at about a list of 20° and its size was only about 54 m. — According to DAIMANN's statement the unfavourable stability properties have not however been the primary cause of the disaster, on the contrary water must have penetrated into the ship which fact, together with the small stability, has caused the capsizing of the vessel. In his opinion water has penetrated through a broken or damaged air exhaust pipe into some side tank. The filling of the tank causes a list moment of 60 mt. The edge of the deck immerses into the water at a list of 5° and the upper edge of the gunwale at 14.5 degrees.

Based on DAIMANN's report the Seaman Hamburg gave its decision according to which it has been established, i.e. that the ship was overloaded, that the stability has been insufficient owing to overloading, that the filling of the tank would have been much less dangerous if the vessel had not been overloaded and that it has been one of the reasons of the disaster. Because of this the Seaman considered that the ship's captain was responsible for the disaster.

The Reichsbergersteet continued the investigations. D made a new statement in which he admitted that the centre of gravity of the cargo in the hold could have been slightly lower than what he has presumed in his calculations. In his opinion it has not been in any way said that the ship would have capsized if the leakage had not occurred. He also stated that the ship, if she had had no leakage in her side tanks, would otherwise under normal conditions have crossed the sea in spite of the reduced stability. Nevertheless he considers his previous report to be on the whole in force.

Using GADTGENS as expert the Reichsbergersteet attained quite divergent results than Seaman Hamburg, i.e. the Reichsbergersteet established the following:

The specific gravity of the timber cargo has been at the maximum 1.1 wherefore there were in the cargo hold, according to shipping documents and other particulars, 214.5 t and on deck 100.86 t, or altogether 315.36 t. This corresponds to a draught of 3.26 m. As the largest permitted average depth was 3.297 m the ship was not overloaded. The fact that the vessel has nevertheless been submerged up to her load line is caused by the inaccuracy of the cubing of the tanks, by the keel water and other circumstances. According to these the deck cargo has been about 105 t and the cargo in the hold about 223 t.

The size of the deck cargo, 31.8% of the total cargo, does not seem to have been excessive.

In determining the centre of gravity of the cargo in the hold one cannot suppose the cargo to have been homogeneous, as D has done; neither has the shipyard so presumed when drawing the stability arm curve (Fig. 20, curve I). In the shipyard’s calculations the size of the cargo in the hold was 215 t and the height of its centre of gravity from the keel 2.3 m; the size of the deck cargo 101 t
and its height from the keel 4.6 m. The weight of the whole ship was 589 t and the height of the centre of gravity from the keel 3.12 m. The difference in the heights of the centres of gravity in the calculations of D. and of the shipyard has caused the great disparity between curves I and II.

The height of the centre of gravity of the deck cargo from the keel has been 4.6 m, that of the cargo in the hold 2.3 m and the height of the centre of gravity of the whole ship 3.12 m. The total displacement of the ship has been 60 t. The following stability arm and stability moment values correspond to these values:

<table>
<thead>
<tr>
<th>Heel</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability arm</td>
<td>0.050</td>
<td>0.058</td>
<td>0.142</td>
<td>0.185</td>
<td>0.223</td>
<td>0.204</td>
<td>0.150</td>
<td>0.029 m</td>
</tr>
<tr>
<td>Stability moment</td>
<td>30.09</td>
<td>58.80</td>
<td>85.20</td>
<td>111.0</td>
<td>135.0</td>
<td>122.5</td>
<td>90.00</td>
<td>12.00</td>
</tr>
</tbody>
</table>

The corresponding stability arm curve is shown in Fig. 20, curve III; it also corresponds to the curve of expert G.

The capsizing of a ship is always connected with causes of stability. One only has to separate from one another the questions as to whether insufficient stability has been caused originally by the loading of the vessel or whether its reason must be put in new moments, i.e. the penetration of water into the side tank. It must be said that insufficient stability has not in this case originated from the loading.

In the Flottenk case the deck cargo should have been secured so as to prevent shifting. This has not been done, but it has not however been the cause of the disaster.

The penetration of the water into the side tank has presumably occurred through a rivet breaking. The capsizing of the vessel has in any case been caused by the pouring of the water into the side tank.

On the basis of the above the Reichsbezeaun has freed the Flottenk's captain from responsibility. The ship has not been overloaded. The stability of the loaded vessel has been sufficient.

Sources: [S 40] and [B 17].

Example 25. S. S. Vardubia, cargo steamer, built of steel at Port Glasgow in 1917. It was a two-decked vessel, subdivided into seven watertight compartments. Her length was 129.0 m, breadth 17.1 m, and draught 7.66 m; gross tonnage 5,735.4 and net tonnage 3,601.6 reg. tons.

The ship left West Hartlepool with a miscellaneous cargo on 12. 10. 1935 for the Atlantic. The cargo was well stowed and taut. The major part of it was composed of small-grained coal, which is inclined to shift in a swell. On October 19th a radio message was received from the ship wherein it was stated that she had got a dangerous list and a second message reported that the crew was abandoning the vessel. The ship was in the North Atlantic at the time and after that nothing has been heard about her or the crew. According to the report of another ship a storm prevailed at the place of the disaster on October 18—19, the wind's direction being from NW and its strength 8—9 Beaufort; rough sea.

The legal investigation did not attain any clear result. It was established that in 1930 an inclining experiment was performed on the ship, on the instigation of the owner, and that on leaving West Hartlepool her stability was sufficient, considering that the cargo was well stowed and taut. According to a theory the coal cargo had nevertheless so much space that the small-grained coal could shift and caused a heel of 31—45°, which must be considered as dangerous. Another possibility is that water has been able to penetrate into the large cargo space of the lower deck, which, according to calculations, would be capable of greatly reducing the stability. The water could have penetrated into the ship because the cargo hatches had got damaged.

Source: [B 35].

Example 26. S. S. Sheaf Brook, built of steel at Burntisland in 1924. Her length was 86.9 m and breadth 12.3 m, gross tonnage 2,179 and net tonnage 1,443 reg. tons.

The ship sailed from the Tyne on 10. 11. 1935 for Hamburg in coal cargo. On the morning of the following day the vessel had encountered a strong east wind, strength 6—8 Beaufort, and a rough head sea. According to her last radio messages she commenced to list more and more to port, the engine room began to fill with water and at last even the wireless cabin, where the ship ceased. Since then nothing has been heard of the vessel or her crew.

The investigation into this has never cleared up the mishap. The court was of the opinion that the loading of the ship had not been done properly. In the midst of the loading the ship got a list of about 4°—4° to port, wherefore a big empty space remained on the port. Because of this the cargo was inclined to shift. The ship has proceeded on her way at a speed of only five knots against a head wind and sea and because of this it has for certain often changed her direction and also rolled heavily. At South West Patch she has got into a steep low water swell. This had increased the list that the ship had already previously had. Water begins to penetrate into a ship in calm water already at a list of 26° and the air exhaust pipes of the double bottom get submerged at a list of 27°. Even though these pipes were shut with plugs and tarpsaulins water could during the storm gradually penetrate through them into the ship. Near South West Patch the vessel could have encountered some very steep waves that could have shifted the cargo to such a degree that a dangerous list had arisen, water has begun to penetrate into the ship even by means of the doors and the vessel has at last sunk. The court does not consider it probable that the ship's cargo hatches should have been forced in.

Source: [B 33].

Example 27. The lightship Elbe I — Bürgermeister O'Swold. The ship's principal dimensions are: length between perpendiculars 44.96 m, extreme length 49.00 m, breadth 7.70 m, draught 3.50 m (fully loaded 4.0 m), moulded depth 5.29 m, gross tonnage 416.43 reg. tons, engine capacity 300 HP, speed 8.75 knots, displacement 700 m³. The ship was built of steel at Stettin in 1912.

During the day of 27. 10. 1936 the ship was at anchor at the mouth of the Elbe (54°11' N.lat., 8°13' E.long.). The wind was stormy and gusty, strength 10—12 Beaufort, during gales 12 Beaufort, direction W and WSW. Just before the disaster the wind turned northwesterwards and the ship was abreast of the swell and against a strong seaward current, bow northwards. At about 14 o'clock,
according to witnesses, the port side of the ship was swept by a high, immense wave, she listed onto her starboard side, remained in that position for about ten minutes, and then disappeared from sight. At the spot a strong bottom swell prevailed. A couple of days later airplanes discovered the sunken ship’s wreck at her place of anchorage. The ship lay on the bottom on her starboard side, her anchor chain undamaged, at a depth of 21 metres. At the same time the lightship Aussenjaude was at her place; her position was also about the same, and the swell and against the current. At 14.30 o’clock quite under water and the waves flung the vessel about with such strong force that the deck mooring of the anchor chain broke away and the chain ran out overboard up to its end link. If this had not happened then, in the opinion of her captain, she would have in all probability capsized.

The disaster of Elbe I was investigated by Seeamt Hamburg, DÄHLIMANN acting as expert.

According to the expert’s statement the ship had normal bilge-keels, their height being 300 m/m. The great reducing effect of the bilge-keels has been established on a certain new lightship, the height of her bilge-keels is 980 m/m.

The ratio L/B of 3.84 of the Elbe I is large when compared with the corresponding one of other lightships. The unfavourable L/B ratio’s effect can be adjusted by the ballast, preferably fixed. Whether Elbe I had such a ballast has not been ascertained. When fully equipped and loaded the ship’s metacentric height is 0.460 m and the stability arm curve then increases up to about 60° and the range of stability is 8° (Fig. 21, curve D, page 53). According to this the stability of the fully equipped ship is sufficiently large in the opinion of the expert. On comparing the stability arm curves of the fully loaded and empty Elbe I (curves D and A of Fig. 21) with the corresponding curves of the Aussenjaude (curves F and E), that had been in the same storm, one observes that the stability properties of Elbe I were exceedingly dependent upon the weights of the stocks at the ship’s bottom, wherefore these always ought to be compensated by other weights. According to the Wasserbaun’s presumption the following quantities of stocks and water were in the ship at the time of the disaster (in brackets the maximum quantities of stocks): the forepeak, empty (19.5 t), coal 3 (30.1 t), drinking water 21 t (35), oil fuel 4.5 (61 t), washing water 26 t (26), steam water 10.5 t (10.5); further, in the Wasserbaun’s opinion, 35 tons of water had been filled into the three empty oil fuel tanks. The curve corresponding to these weight quantities is shown in Fig. 21 (curve C). DÄHLIMANN suspects whether the washing water tanks were full and also considers it uncertain that water has been taken into the oil fuel tanks. In any case he says that the ship was too lightly loaded; this statement means that the expert does not consider curve C sufficient. In his deduction the expert still emphasizes the fact that the ship, which fully loaded could have been sufficiently stable, was comparatively empty on the day of the disaster and the filling amounts of the tanks had become unfavourable. Unusually sized side breakers heavily listed the crank vessel and the upsetting and trim moments were further caused by the anchor chain.

The Government Commissioner concurred in general with the expert’s report. He said that the largest stability would be attained at a heel of 30° and the range of stability would have been approximately 75°; the actual stability arm curve could however be somewhat lower than curve C. It seems that the stability properties of an anchored lightship and of a freely rolling ship cannot be compared with one another.

The Seemann concurred in general with the expert’s statement but it did not however consider the anchor chain’s strength as being excessive. If there was no ballast water in the fuel oil tanks of Elbe I then the ship’s stability properties were such that in these circumstances — in the court’s opinion — they could not be considered sufficient (Fig. 21, curve B). If the tanks contained 35 tons of ballast water then, judged humanly, the stability would have sufficed under normal circumstances; one can however say that a stability amount corresponding to a full load would have made the vessel safer in the uncommonly bad weather prevailing at the time. In the opinion of the court the question, whether the ship even then would have remained upright, should be left open.

The court came to the conclusion that on capsizeing the ship was under the influence of the effect of the bottom swell, of the currents, of the cyclonic turning gusts of wind, and even probably of the strength of the anchor, and could not withstand this. The ship’s stability was sufficient when fully loaded; the effect on the stability of the emptying of the tanks was very great. In the ship there were no constructional defects nor were there any in the fittings, equipment or in the manning. The court expressed it as suitable that in new constructions one should strive to see that shiftings in the cargoes of lightships affect the stability as little as possible; one could even consider the advisability of building quickly filling bottom tanks in ships. The court also recommended the furnishing of stability factors — especially of stability arm curves — to the captains of lightships. Ship captains should know the basis of the theory of stability.

Sources: [R 19], Schiffbau 1937, page 63, [F 5] and [E 2].

Example 28. S. S. Stamenet (formerly Sheldrake), a one-decked cargo steamer, deck erections: forecastle, bridge and poop; built at Lowestoft in 1920. The ship’s length was 48.0 m, breadth 7.6 m, gross tonnage 462.3 and net tonnage 194.9 reg. tons. The vessel’s engine was a 65 HP steam engine. The hull was subdivided by three bulkheads into four watertight compartments; the cargo hold had two hatches, one on the fore and the other on the stern of the bridge.

While named Sheldrake the ship, after having already sailed with success for over a decade, got into a swell at the mouth of the Humber, when on her way with a coal cargo from Goole to Poole, the cargo shifted, the ship got a dangerous heel, the crew abandoned the vessel and she drifted ashore. After the salvage of the ship her stability was studied. When investigating it was found that the ship must be loaded very carefully, wherefore the Board of Trade urged that particulars of the vessel’s stability, or instructions for her loading, be given to the captain. The ship’s owner even ordered that the double-bottom’s tanks should always be kept filled and that the cargo should never be placed in the compartment under the poop. These instructions were adhered to for three years, up to 1936. Then the matter was taken up again and an investigation was made by the owner in collaboration with the Board of Trade and the owner company printed the pamphlet ‘Stability Conditions’, wherein are shown the metacentric height values corresponding to different ways of loading. After two trials, which were performed heavily loaded and the ballast tanks empty, the Board of Trade agreed that the flooding of the ballast tanks and the use of the compartment under the poop as
cargo space be left to the discretion of the captain, subject that he has a proper certificate and that the mentioned stability instructions are at his disposal.

In February 1937 the ship changed owners and was named Stancrest. The ship departed on her last voyage from Northfleet on 27. 2. 1937. The cargo was composed of cement in paper bags and it was so placed that it could not shift. The vessel was on her way to Bridgewater. At the time there prevailed a gusty, northwesterly wind of 5—7 Beaufort. Since then nothing has been known about the ship with the exception that one of her lifeboats and a cargo hatch have been found later on near West Bay.

The legal investigation did not give any definite result. On leaving for the voyage the ship's stability was sufficient, the metacentric height was 0.262 m, even though it be presumed that the ballast tanks were empty; the court makes the following statement about this value: "not less than this." This metacentric height guarantees — in the court's opinion — a sufficient quantity of stability for such a type of vessel as Stancrest, if she is loaded with cement bags in a correct manner. However, the ship's small freeboard was remarked upon. A bigger vessel than Stancrest, which was endeavouring to pass the Isle of Wight on 28. 2. 1937 in a westward direction, returned because of the bad weather; another, similar in size to Stancrest, which was in ballast and therefore had a considerably larger freeboard than Stancrest, anchored in the same region on that day in order to await better weather. The court supposed that Stancrest on having passed Purland Bill had the intention of returning, or intended to approach the shore, but that on turning water has swept onto her deck, smashed the hatch, destroyed her stability and she has capsized onto her side and sunk very quickly.

The investigation brought to light that Stancrest was a crank vessel and, according to the stability instructions, she was unstable when loaded by certain methods, which are in general considered to be normal for vessels of such a type. The fate of this ship has specially drawn the attention of the court to her stability properties but, according to the investigation, there is no reason to presume that the vessel's unusual stability properties would have been the cause of her sinking.

Source: [B 35].

**Example 29.** The whaler *Rau III*. The ship's principal dimensions: length between perpendiculars 38.4 m, moulded breadth 8.0 m, moulded depth 4.6 m. Draughts at time of accident: forward 3.055 m, aft 4.118 m, mean draught 3.610 m; corresponding displacement 532 t. The ship capsized and sank on 7. 6. 1937 on the Weser when performing the turning test, which is part of the acceptance trials. The weather was fine, the water nearly calm, no current that could have an influence on the disaster. The vessel commenced turning by making an abrupt swing to port, the speed being at least 12.8, in reality probably 13.2 knots (the largest speed attained by her was 14.1 knots); the helmsman put over the rudder in 4—5 seconds from middle to extreme position. For an instant the ship heeled at about 3° to port — already at the start she had an approx. 1°—2° list to port,— thereupon abruptly to starboard so that the deck got immersed. Some of the persons on board felt as if the vessel intended to raise herself once more upright, but she immediately heeled still further so that even the bridge was under water. The water commenced to flow into the engine room by means of the open hatch and through the skylight. At the alarming signal the helmsman tried to close the turning circle. Before the capsizing the captain ordered the helmsman to meet the helm and set the engine-room telegraph at stop, but there was no time to fulfil these commands. The ship sank stern first and remained for some hours floating bottom up, supported by her bow, and sank completely first after a hole had been punched in the bottom plate in order to save human life.

Prior to the disaster a successful turning test was made on her sister ship *Rau I* and after the mishap a similar trial was performed on *Rau IV*. However, the vessels had the following differences during the tests:

<table>
<thead>
<tr>
<th></th>
<th>Rau I</th>
<th>Rau III</th>
<th>Rau IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td></td>
<td>17 t</td>
<td>18 t</td>
</tr>
<tr>
<td>High forepeak</td>
<td>empty</td>
<td>7.5 t</td>
<td></td>
</tr>
<tr>
<td>Put up the rudder</td>
<td></td>
<td>full</td>
<td></td>
</tr>
<tr>
<td>from extreme to opposite</td>
<td>6 turns</td>
<td>20 t of water</td>
<td>empty</td>
</tr>
<tr>
<td>Ballast</td>
<td>10 turns</td>
<td>6 turns</td>
<td>10 turns</td>
</tr>
<tr>
<td>Number of engine's r. p. m.</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>Corresp. speed</td>
<td></td>
<td>approx. 130</td>
<td>130</td>
</tr>
<tr>
<td>Corresp. angle of heel when turning</td>
<td></td>
<td>130 knots</td>
<td>130 knots</td>
</tr>
</tbody>
</table>

The engine capacity of the *Rau* vessels was 1,300/1,400 HP, extreme rudder angle 42°, the area ratio of rudder to the lateral plane 1:26 (on ordinary fishing vessels 1:35—1:45), diameter of turning circle 100 m; full turn can be performed in 80 seconds, which corresponds to an average speed of 7.6 knots.

According to the inclining experiments performed by the vessels' shipyard the metacentric heights during the turning trials were: on *Rau I 0.290 m* and on *Rau III 0.239 m*. The corresponding stability curve of *Rau III* is shown in Fig. 22, curve B (page 53).

The disaster was investigated by Seasam Bremerhaven, G. KEMP acting as expert. With the assistance of theoretical calculations, model tests and renewed inclining experiments he completely unravelled the course of the disaster and its causes. By calculating he came to the conclusion that if the stability factors given by the shipyard were correct, and if the vessel begins a turn at a speed of about 13.2 knots, then the heeling moment is so large that the capsizing of the ship is within the bounds of possibility. One could not determine by calculating whether the capsizing was absolutely certain. The model tests were performed with a complete, automatically working wooden model, made in ratio 1:10. The engine speed corresponded to 13.2 knots, the putting over of the rudder from middle to extreme position took 6 seconds, which corresponds to a turning speed of 2 seconds for a full turn of the steering wheel. If the metacentric height values given by the shipyard should have been correct, then — on the basis of the performed tests — *Rau I would have heeled over 18° and Rau III 20°—21°*, but neither of them had capsized. By means of reducing systematically the stability of the model it was established that at an approach speed of 13.2 knots the ship still remained upright on turning, when the $M'G$ was 0.176 m, but
capsized when it was 0.164 m. The approach speed of the turn being 12.8 knots and the corresponding metacentric height values were 0.199 and 0.145 m. Thus, the results of the model tests was that the ship's metacentric height became in reality at least 0.075 m smaller than that calculated by the shipyard, or at the most 0.164 m. If the \( M_G \) had been 0.164–0.145 m then, according to the model trials, Rau III would have capsized for certain, merely from the effect of the turning. The vessel's stability curve corresponding to the last-mentioned value is shown in fig. 22, curve A. — On the basis of the model tests there were errors in the stability factors given by the shipyard. By means of renewed calculations and inclining experiments it was even established that at the time of the disaster the \( M_G \) value had been 0.145–0.040 m only. The shipyard had performed the inclining experiment when the ship had been very much by the stern. The full stern caused a raising of the centre of buoyancy but the shipyard did not take this into consideration and obtained as the height position of the centre of buoyancy a value about 0.075 m too small. This lead to the fact that though the \( M_G \) value, corresponding to the inclining experiment condition, was approximately correct the shipyard presumed the ship's centre of gravity to be too low. This in its turn caused errors, when determining the \( M_G \) values corresponding to the different loading conditions.

According to the investigation the actual metacentric heights of the Rau ships had been, when the vessels performed their turning trials (compare with the preceding table), for Rau I about 0.230 m, Rau III 0.145–0.040 m and Rau IV 0.143 m.

According to KEMPF the reason for the capsizing of Rau III had been insufficient stability. This was not brought about by the form of the vessel but by the loading, namely from the decreasing effect on the stability caused by the full forepeak and empty fuel tanks. Already the filling of the forepeak had diminished the metacentric height by about 0.06 m, i.e. by 26%. If the forepeak be not filled, and a fixed ballast of ten tonnes be placed on the ship's bottom, then the \( M_G \) — corresponding to that at the time of the disaster — is increased by 50%. The following should be specially observed:

1. The stability calculations cannot be executed accurately enough. The ship's trim is to be carefully noted.
2. On performing the turn the obtained heeling moments are to be considered, when estimating the permitted stability amount, especially in cases when a ship's freeboard and range of stability are small.
3. The turning trial is a typical case of a maximum strain on the stability. It is recommended to determine for this the necessary minimum stability.
4. It is also necessary to instruct the captain, during the acceptance trials, in the stability properties of the ship.

The court concurred with the expert's statement in regard to the reasons for the disaster. It added that the insufficiency of the stability had been caused by the fact that the stability reserve, which had adjusted the inaccuracies occurring in the experiments and calculations, had been too small. There have been no defects in the ship's build, fittings or condition. The disaster teaches us that more attention should be paid in future to the stability conditions of seagoing vessels than hitherto has been the case. This refers primarily to vessels to be used for special purposes.

Sources: [R 18] as well as Shipbuilding and Shipping Record 9. 9. 1937.

Example 30. Motor sailing vessel Olga capsized in Riga harbour on 28. 6. 1937, on having taken a full cargo of pine logs. The ship's dimensions were: length 34 m, breadth 7.03 m, draught 2.84 m, gross tonnage 98 reg. tons. The ship had three masts and an auxiliary motor of 150 HP. The vessel has been built at Kiel in 1921.

At the time of the disaster the ship was secured to the shore by means of two ropes at the stern; both the fore anchors were run out to keep the foreship in position. In relation to the ship the direction of the water's current was transverse. The cargo, 634 pine logs, each weighing about 500 kilograms, was placed in the hold and on deck. In the hold there were 364 logs and on deck 370. According to the captain's statement the draught was 2.96 m, i.e. some inches larger than the permitted draught. The height of the deck cargo was 1.9–2.0 m. With the help of the last two logs the ship's captain performed the usual inclining experiment and did not find that the ship listed abnormally much onto either side; on making the experiment the derrick was in such a position that between its head and the mast there were 9–10 m. — In the captain's opinion the size of the cargo was in no case 200 t.

After taking the cargo the ship listed to port and the port mooring rope tautened. The captain started the motor whereupon the vessel became upright once more; then the starboard mooring rope tautened. The captain ordered the rope to be unfastened but one had no time to do this, the ship again listed to port and capsized.

On the vessel being raised she was once more loaded. However, this time 29 logs had to be left out, for otherwise the load line would have again been immersed. Of the logs one was able to stow 422 in the hold, whereas only 183 logs remained on deck. The height of the deck cargo was only 1.4 m. Thus loaded the vessel then made a successful trip to Königsberg.

According to the court's decision the reason for the mishap was incorrect loading and stowage. The captain, who had carried such a cargo only once before, has not however been charged. The Government Commissioner and all the experts were of the same opinion as the court.

WINTER of the See-Berufsgenossenschaft, who gave evidence as expert, pointed out in his statement that since 1925 a stability calculation is performed for each vessel and is handed over to the captain. Unfortunately they cannot in general make use of the stability curves. One cannot always determine the stability curve of vessels transporting timber deck cargo for i. a. the specific gravity of timber and the method of stowing it affect the result very much. When small motor sailing ships come under consideration the loading capacity cannot be exactly calculated, for often they do not have a rectangular cargo hold. On small vessels coming into question one has to trust solely to the captain's experience.

Source: [S 41].

Example 31. S.S. Taylor, a one-decked cargo steamer without a double bottom, built in 1914. Her length was 33.5 m, breadth 6.4 m and gross tonnage 204 reg. tons. The three transverse bulkheads of the ship divided the hull into four water-tight compartments. The upper deck was edged by a covered gallery, 1.04 m high and which had the usual free ports. In the casing of the engine and boiler room there was a door on either side; the height of the sills was 0.4 m.
The vessel left Buckie on 30. 9. 1937 at 14.25 o'clock with a timber cargo of about 165 t, whereof approximately 34 t on deck. The weather was fine. In the beginning the sea was calm, afterwards a cross swell; wind weak. At about 20.05 o'clock a seaman noticed that something was wrong with the ship and ten minutes later the chief engineer discovered water penetrating into the engine room. The vessel sank between 20.15 to 20.30 o'clock, about 2 to 2 ½ nautical miles off Buchan Ness.

In the legal investigation it was established that on leaving port the ship had not been in a good nor seaworthy condition. The cargo hatches had not been tightened nor had the deck cargo been secured according to regulations. The vessel's stability was weak. However, the court was of the opinion that the lack of stability was not the reason for the disaster, but that the cause was the sudden penetration of water into the engine room. How the water got into the ship could not be explained; according to a theory the casting of the main water inlet pipe had broken, according to another a bottom plate had given way. It is to be observed that already before the bottom plates had been perceived to be thin in place.

Source: [B 36].

Example 32. M.V. Godric, built in Holland in 1904 as a sailing vessel, changed into a twin-screwed motor ship in England in 1922. Her length was 27.5 m, breadth 7.1 m, gross tonnage 160 and net tonnage 110 reg. tons. The ship's sole cargo hold had two hatches.

The vessel left Dover on 10. 12. 1937 at 10.40 o'clock with a cargo of fine-grained coal, destination Newhaven. The wind, which had been northwesterly, changed into a westerly one and freshened. Later on in the afternoon the wind and swell still strengthening the captain decided to return to Dover. On the return voyage the wind changed to southwest and attained a strength of 7 Beaufort.

The wind came in gusts and the swell was very high. At about midnight, when the ship was already off Dover, the vessel made a sharp heel to the starboard so that the gunwale became immersed. After a while the ship's list increased, she turned upside down and sank.

The investigation performed showed that the cause of the accident was the shifting of the cargo. The coal was loaded by means of a telescope pipe and the surface was only casually trimmed. The cargo was only 237 t though the hold had a capacity of 293 t. For this reason, it is certain that somewhere in the hold 0.12 % of the cargo space at one's disposal had remained unfilled. Of the amount about 7 ½ % was in the corners, which is always difficult to fill, the remainder was distributed among the coal in the shape of empty pockets. In the swell these vacant spaces caused a shifting of the cargo.

In the court's opinion the ship's initial stability was sufficient. The breadth's relation to the length was large, but the stability was such that the cargo and the method of loading easily affected it.

Source: [B 37].

Example 33. Motor ship Monica. The vessel has been built of steel at Kiel in 1936, gross tonnage 254.75 and net tonnage 142.56 reg. tons, light displacement 220.5 t and fully loaded 665 t. The ship has one cargo hold with two cargo hatches. The forecastle is stock space; the crew's quarters are in the poop. The motor is in the stern, between the cargo hold and the afterpeak.

According to the stability curve table the mean draught in light condition is 1.140 m and in full cargo 3.039 m.

On 5–7. 5. 1938 the ship had loaded in Hamburg harbour altogether 408 t of oil cakes in sacks, whereof 310 t in the hold and 98 t on deck. The whole of the deck cargo was placed on top of the cargo hatches so that it should not get wet. The height of the hatches was 1 m from the deck, the cargo's height on the fore hatch was 1.8 m and on the after hatch 2.1 m, both measurements taken from the hatches upwards. When departing for the voyage the forecastpe and the double bottom ballast tank (volume about 55 m³), situated forwards of the cargo hold, were empty; there was 8–10° of water in the afterpeak.

According to the captain's statement the remainder of the load consisted of 5 t of fuel oil and of about 1 t of drinking water. The ship was on even keel and the draught was 3.048 m. The load line was still 51 m above the water surface, which corresponds to about 12–13 t of additional cargo. If the double bottom tank were flooded then the permitted draught would be exceeded.

When making the last hoist with the derrick the captain did not notice any special list. The departure took place at 20 o'clock on 7. 5. 1938. On the engine going at half-speed ahead no crankness was observed in the ship's movements. After a while a strong gust of wind gave the ship a heavy list to port. Water flowed onto the deck; the height of the covered gunwale is 0.85 m. By means of the open bull's-eyes the water flowed into the vessels when the ship is on her way to the Baltic the bull's-eyes are usually first shut after the Kiel Canal. The vessel remained floating 3 to 2 minutes at a heel of 25°–30°. The engine was stopped. The mate loosened the deck cargo at that moment the water on the deck already reached up to the mast. From the effect of the loosening of the deck cargo, part of the cargo remained pressing against the ship's portside and the list increased. After some minutes the Monica capsized onto her portside. In a capsized condition she was then towed onto a barge.

The disaster was investigated by the Senate Hamburg with the assistance of several experts. In the possession of the ship's captain was the vessel's stability curve table, which showed the following stability arm curves corresponding to the conditions:

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Displacement</th>
<th>Mean draught</th>
<th>$M_{G}$</th>
<th>Stability arm curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship in light condition</td>
<td>220.5 t</td>
<td>1.140 m</td>
<td>0.729 m</td>
<td>Curve A, Fig 23 (page 54)</td>
</tr>
<tr>
<td>Ship in full cargo, without deck cargo</td>
<td>655.0 t</td>
<td>3.039 m</td>
<td>0.771 m</td>
<td>Curve B, Fig 23</td>
</tr>
<tr>
<td>Ship in full cargo, 20 tons of deck cargo</td>
<td>655.0 t</td>
<td>3.039 m</td>
<td>0.704 m</td>
<td>Curve C, Fig 23</td>
</tr>
<tr>
<td>Ship in light condition, tanks flooded</td>
<td>338.5 t</td>
<td>1.838 m</td>
<td>0.393 m</td>
<td>more favourable than Curve A</td>
</tr>
</tbody>
</table>

In the captain's opinion the theory and practice in regard to the curve C did not tally with one another. He had transported as timber deck cargo a similar amount as there was cargo in the hold; he has even carried 140 t of timber on deck and nothing has happened. The height of the timber deck cargo
has also been 2.1 m above the hatches, the deck cargo has filled the whole deck; it is true that when carrying deck cargo he has always flooded the bottom tank. On the fateful voyage he could not do this, for in that case the maximum draught of the ship would have been exceeded.

Oppers, the adviser of the vessel’s building shipyard, stated that she did not originally have any ballast tank; it was built later on, for she had suffered damages by sea. At the same time the ship got a fixed ballast of 12 t. The stability arm curve C being discussed, he pointed out that the forecastle and poop had not been considered when drawing the curve, wherefore the actual stability is more favourable than that shown by the curve. On the last voyage, when 24.75% of the cargo was on deck, the ballast tank ought to have been filled.

Winter, the representative of the See-Berufsgenossenschaft, said that the vessel was a typical Rhein-Baltic ship. They have at the utmost once loaded 20 tons of iron tubes or bails onto the deck. For this reason, the See-Berufsgenossenschaft had nothing to remark against the stability curve table. In his opinion the capsize of the ship has been caused by the fact that the captain had taken a high deck cargo — by reason of former large timber deck cargoes — but this time the bearing effect of the deck cargo was lacking nor had the ballast tank either been filled. One ought to have prepared a stability arm curve for the vessel carrying timber deck cargo.

According to the statement of the Germanischer Lloyd’s director the stability arm curve C was slightly more and thus but, as the Germanischer Lloyd knew that the forecastle and poop had not been taken into consideration, it was assumed that the curve was in error. If large deck cargos are carried on ships, then those corresponding to the drawn stability curves, then new curves are required; this is, however, only performed when the vessel is classified at German Lloyd’s; the Germanischer Lloyd had not classified the Monica, her classification was executed by the British Corporation. Later on the building shipyard has informed that in future, when drawing stability curves, it will also take the deck erections into consideration.

Dahlemann acted as the ship-building expert. According to his statement the ship had capsize because of the lack of stability (Bremsstabilisat); and this had been caused by wrong stowage of the cargo. When the ship had earlier carried even 143 t of timber on deck — i.e. 1/3 of the deadweight — also in a storm, the ballast tank was full. On these trips the sufficient stability had been obtained solely from the effect of the ballast water and of the cargo’s own bearing capacity. The deck of the fully loaded vessel became immersed already at a list of 4 1/2°. On the day of the accident the whole deck cargo was on the top of the hatches so that its centre of gravity was very high. According to his calculations the metacentric height was 0.14 m. This is 1/5 of the smallest χs G shown on the stability curve table, but it is however not absolutely dangerous nor can it be considered as being the reason for the capsize. This explains the fact that the captain judged the stability to be sufficient by feeling, but the judging of initial stability is insufficient; one must also take the range of stability into consideration and that cannot be judged by feeling. He has calculated, on the basis of curve C of the stability curve table, the stability arm curve (curve D, Fig. 23) corresponding to the disaster situation, which is so low and short that one cannot any more speak of any stability. If the deck erections had been considered,

the largest stability arm would have only been about 0.01 m, the corresponding angle of heel 12° and the range of stability less than 30°. At the strength of the gust of wind, which lasted some minutes only, had been 7 Beauford (the wind’s speed 14 m/sec, and the wind pressure 24 kg/m²), a heeling moment of approximately 10 metrotontons was caused by this; had even the deck erections been taken into consideration, the ship’s largest stability moment would have been only 6.43 mt; it is thus perceptible that the vessel had to capsize. — If the ballast tank were filled and the deck cargo decreased by 56 tons, then the metacentric height would have been 0.610 m, but the stability arm curve would have nevertheless remained below curve C. On comparing curve C with those of the capsized vessels Elbe 1, Galleon, Rau III and Flottbek the expert says that it must be considered to be insufficient.

The Seesamt agreed in general with the expert’s statement; however, in this special case, it considered possible to judge also the range of stability by feeling. The bulk’s-eyes being open has only made the capsizing quicker. Even though the captain is responsible for the loading, he was charged on this occasion for the stability curve table in no case gave him any sufficient particulars. The Seesamt considers it important that particulars about the ship’s stability properties be prepared in such a manner that they explain critical conditions, especially in regard to deck cargos. It was also remarked upon that the captains of vessels should know the rudiments of the theory of stability and its practical application.

Source: [42]

Example 34. Kavasae (formerly Westfalen), a cargo boat of quarter-deck type, built in 1926 at Lubeck. Her length between perpendiculars was 54.30 m, breadth 9.40 m, moulded depth to main deck 4.28 m, height of forecastle and bridge erections 2.15 m and height of the quarter-deck 1.35 m; the ship’s gross tonnage was 617.69 and net tonnage 315.84 reg. tons and displacement at the time of the disaster 1,006 t. At stern of the forecastle was an approximately 0.6 m long well, on both sides of which there were two freeing ports; the height of the covered gunwale was about 1 m.

The ship left Hamburg on 16—17. 11. 1933 at midnight with a wheat cargo and her destination, London. Altogether 995.68 t of wheat were on board, which quantity did not completely fill the cargo hold; empty spaces remained, especially between the two cargo hatches of the lower hold and aft of the upper hold. Free surfaces of cargo were not covered. After the loading the vessel had been somewhat listed to port. Because of this, the ship’s captain gave the order to fill a starboard ballast tank with so much water that the list would disappear. Water was taken into starboard tank IV, the total volume of which was 36 m³ (according to the ship’s drawings only 26 m³), 12—15 t, whereas the vessel got a starboard list of 3°—5°. The other ballast tanks were left empty. On November 17th at about 23 o’clock the chief engineer, who was sleeping in his berth, woke up when flung to the floor by the ship’s heavy list to starboard — he is the sole survivor of the accident. On going a moment later into the engine room he measured the list as being 30°. The list had arisen quite suddenly, and increased rapidly, the spray penetrating i. a. into the engine room by means of the starboard skylight and ash port. The engine had to be stopped and the engine room abandoned. Soon afterwards the ship capsized. With the
exception of the chief engineer all the others either drowned immediately or
succumbed in the lifeboat from cold and sufferings.

The disaster was investigated by Seeamt Hamburg, WROBBREL acting as
expert. According to his calculations the ship’s metacentric height on leaving
the harbour was 0.095 m, if one does not take into consideration the free liquid
surfaces of the fuel and ballast tanks. The corresponding stability arm curve
is shown in fig. 24, curve A (page 86). As there were free surfaces for certain,
at least in the smaller fuel tank and in starboard ballast tank IV, then the actual
metacentric height was only — 0.042 m, i. e. negative. Curve B corresponds
to this value. A negative metacentric height is by no means always dangerous
to a ship. Such vessels have a list and their sea-keeping qualities thus listed
are the best. However, the list of ships carrying a bulk wheat cargo should be
considered as being a signal of warning, for on these vessels special caution
should be exercised. The list should not be removed by flooding the ballast tank
on the high side for on such ships the flooding of a tank, performed to remove a
list, can affect quite contrary. — If one assumes that the captain at sea had even
floated the port side tank IV, then the metacentric height value is merely — 0.155
m. The corresponding stability arm curve shows that the ship would then
already have an initial heel of 30° (curve C), thus the same heel as that measured
by the chief engineer. At this point the cargo must be also shifted for which
there was a possibility because of the empty spaces. If one further assumes that
the swell has filled the ship’s well, the metacentric height decreases to the value
— 0.455 m and the stability arm curve obtains the shape D; the ship would
absolutely capsize. — The expert thus reached the final conclusion that the sta-
bility of the ship, which already in itself was comparatively small, the insuffici-
cy of the cargo hold, the free liquid surfaces in the vessel and the breakers that have
filled the well, have caused the capsizing of the vessel. As the reason for the
disaster must be considered the incidental, simultaneous effect of these different
factors.

In the expert’s opinion the disaster could have been very probably averted
if, instead of the starboard tank IV, the starboard as well as port tanks III had
been fully flooded. The tanks’ aggregate capacity was 27 t and after their flooding
the metacentric height would have been, if the free liquid surface of the fuel
tank were not considered, 0.11 m and even though this were taken into con-
sideration in the calculations the $\Delta G$ would have been 0.074 m, if the fuel had
been in the big tank, and 0.086 m if it had been in the small one. In the ballast
tanks there would not have then been any free water surfaces.

As regards the disaster the expert remarks i. a. on the great effect of the free
liquid surfaces on vessels transporting shifting cargo and that one should abso-
lutely avoid removing a list by a flooding on the high side.

The Seeamt concurred with the expert in regard to the reasons for the disaster
and also with his foregoing remarks. According to the decision the ship’s owners,
officers and stevedores were responsible that the list, that arose during the
loading, had not been removed by trimming the cargo but by taking water into
the tank and further that, though the cargo did not fill the ship, the careful
trimming of the vessel and sufficient covering were left undone.

During the night of the accident the wind was east-south-easterly and its
strength 6—7 Beaufort, high swell.
Appendix 2.

List of Sources.

This list contains all sources consulted for this investigation, irrespective of whether they have been directly used or not. The publication of this list may be of benefit to other investigators of the minimum stability problem.

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