Visualization and modelling of rock fractures and rock quality parameters in 1-3 dimensions in crystalline bedrock

Mira Markovaara-Koivisto
Visualization and modelling of rock fractures and rock quality parameters in 1-3 dimensions in crystalline bedrock

Mira Markovaara-Koivisto

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Aalto University
School of Engineering
Department of Civil Engineering
Supervising professor
Prof. Jussi Leveinen

Thesis advisor
Ph.D. (Tech.) Evaliisa Laine, Geological Survey of Finland

Preliminary examiners
Dr. Helen Reeves, British Geological Survey, United Kingdom
Professor Luís Sousa, Universidade de Trás-os-Montes e Alto Douro, Portugal

Opponent
Ph.D. Pietari Skyttä, University of Turku, Finland

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Abstract

Building underground facilities in bedrock is increasing in the modern world. The brokenness and quality of bedrock can have a negative effect on underground construction and effect the costs. One has to be able to describe and measure the brokenness and quality to be able to take it into account in construction and excavation planning. Different mapping methods give direct information and geophysical methods indirect information about the brokenness and quality to support its modeling task.

This thesis describes new methods developed to study, visualize and analyze brokenness and quality of the bedrock. The results of the development work were tested on mapping and measurement data gathered from a Palin Granit Oy owned dimension stone quarry situated in Mäntsälä, southern Finland. Observations of the rock discontinuities were gathered by several methods: by mapping and scanline measurements; by ground penetrating radar; and by stereophotogrammetry. The discontinuity data was utilized in developing methods:

1) to calculate fracture density in a rock volume;
2) to write computer scripts, which clusters fracture sets semi-automatically, calculates mean orientation and density of the fracture sets;
3) presents the connection between fracture properties and dip direction;
4) visualizes fractures and their properties in 3D and makes a stereographic projection of the fracture density and rock quality designation revealing their orientation dependency.

In addition, development work in the branch of determining fracture filling material based on the polarity change of ground penetrating radar signal was made.

The results indicated confidence in determining and modeling the brokenness of the bedrock increases by exploiting several study methods. Gathering abundant observation data enabled statistical analysis of the data and allowed realistic discrete fracture network models to be generated.

Keywords  rock fracture, rock quality, fracture density, rock quality designation, scanline survey, oriented data, ground penetrating radar, stereophotogrammetry, MATLAB, Mäntsälä

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Väitöskirjan nimi
Kiteisen kallioperän rakojen ja laututekijöiden visualisointi ja mallintaminen 1-3 ulottuvuudessa

Julkaisija
Insinööriyhteiden korkeakoulu

Yksikkö
Rakennustekniikan laitos

Sarja
Aalto University publication series DOCTORAL DISSERTATIONS 240/2017

Tutkimusala
Teknillinen geologia

Käsikirjoituksen pvm
15.08.2016

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18.09.2017

Kieli
Englanti

Monografia

Artikkeliväitöskirja

Esseeväitöskirja

Tiivistelmä


1) laskea rakotiheys tutkitun kiven tilavuudessa;
2) tietokoneohjelma rakoisuuntien puoli-automaaattiseen ryhmittelyyn, ryhmien keskisuunnan ja rakotiheyden laskemiseen;
3) rakojen ominaisuuksien ja kaateen suuntien välisen yhteyden esittämiseen;
4) rakojen ja niiden ominaisuuksien esittämiseen avaruudessa ja rakotiheyden sekä kallion eheyden suuntariippuvuuden esittämiseen stereograafisella projektioilla.

Liiaske kehitettiin rakotäytteen määrittämistä maatutkaheijasteen perusteella perustuen heijastuvan maatutkasignaalin polariteetin muuttumiseen rakopinnoilla.

Tulokset osoittivat, että kallion rikkonaisuuden tutkiminen monipuolisina menetelmin lisää rikkonaisuuden määrittelyn ja mallintamisen varmuutta. Laajan havaintoaineiston kerääminen mahdollistaa myös aineiston tilastollisen analyysin ja käyttämisen realisissassa rakoverkkomallinnuksessa.

Avainsanat
kalliokerä, kalliolaatu, rakotiheys, RQD-luku, linjamittaus, suuntaa, maatutka, stereofotogrammetria, MATLAB, Mäntsälä

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In 2010, I attended a MATLAB course given by Mr. Håkan Träff from MathWorks in order to develop the skills I utilized in making the scanline visualization and analysis tools presented in Paper I and the stereographic visualization of fracture density and Rock Quality Designation presented in Paper III. In 2011 I participated in a GOCAD course given by Mrs. Jennifer Levett from Mira Geosciences, at the Pyhäsalmi Mine, to improve my skills in GOCAD modelling. I thank the Inmet Mining Corporation for their hospitality during my stay.

This thesis was funded by the Finnish Doctoral Programme in Geology and Aalto Doctoral Programme in Engineering. In addition the K.H. Renlund Foundation, the Oskar Öflund Foundation, The Finnish Foundation for Technology Promotion, and the Finnish Research Programme on Nuclear Waste Management are gratefully acknowledged for making this research possible. I would like to give thanks to Dr. Olavi Selonen and Palin Granit Oy for his kind help, and
allowing the use of a dimension stone quarry for the studies and for providing rock blocks for ground penetrating radar studies.

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Espoo, 15 November 2017
Mira Markovaara-Koivisto
Acknowledgements .......................................................................................... 1
List of Abbreviations and Symbols .................................................................. 5
List of Publications ......................................................................................... 7
Author’s Contribution .................................................................................... 8
1. Introduction ..................................................................................................... 9
  1.1 Background and research environment ..................................................... 10
  1.2 Objectives and scope ................................................................................. 11
  1.3 Research approach .................................................................................... 12
  1.4 Research process and dissertation structure .............................................. 12
2. Theoretical framework .................................................................................. 15
  2.1 Combined Navier-Coulomb-Griffith failure criteria .................................. 15
  2.2 Effect of ductile structures on fracturing ..................................................... 17
  2.3 Generation of fracture networks ................................................................. 18
  2.4 Fractures in perspective of rock engineering .............................................. 18
  2.5 Engineering geology ................................................................................... 19
3. Materials and methods .................................................................................. 22
  3.1 Site description .......................................................................................... 22
  3.2 Approaches to study fracturing ................................................................. 31
    3.2.1 Surface mapping .................................................................................. 31
    3.2.2 Scanline mapping ................................................................................ 33
    3.2.3 Ground penetrating radar .................................................................... 34
    3.2.4 Stereophotogrammetry ........................................................................ 36
4. Review of the original publications and 3D Q’ modelling ......................... 38
  4.1 Publication 1: MATLAB script for analyzing and visualizing scanline data 38
  4.2 Publication 2: The effect of fracture aperture and filling material on GPR signal ........................................................................................................... 39
  4.3 Publication 3: MATLAB scripts for stereographic projection of fracture density and RQD ................................................................. 39
### List of Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Cohesion</td>
</tr>
<tr>
<td>DFN</td>
<td>Discrete fracture network</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>Relative permittivity</td>
</tr>
<tr>
<td>Ga</td>
<td>Billion years, $10^9$</td>
</tr>
<tr>
<td>GTK</td>
<td>Geological Survey of Finland</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetrating Radar</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HRC</td>
<td>Host Rock Classification</td>
</tr>
<tr>
<td>$J_a$</td>
<td>Parameter for fracture surface alteration in Q system</td>
</tr>
<tr>
<td>$J_n$</td>
<td>Parameter for number of fracture sets in Q system</td>
</tr>
<tr>
<td>$J_r$</td>
<td>Parameter for fracture surface roughness in Q system</td>
</tr>
<tr>
<td>$J_V$</td>
<td>Number of fractures in $m^3$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Linear rock fracture density ($1/m$)</td>
</tr>
<tr>
<td>Ma</td>
<td>Million years, $10^6$</td>
</tr>
<tr>
<td>MRMR</td>
<td>Rock Mass Rating for Mining</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Friction coefficient</td>
</tr>
<tr>
<td>N</td>
<td>Rock Mass Number</td>
</tr>
<tr>
<td>NATM</td>
<td>New Austrian Tunneling Method</td>
</tr>
<tr>
<td>$\varnothing$</td>
<td>Internal friction angle</td>
</tr>
<tr>
<td>Q</td>
<td>Rock Tunnelling Quality Index, Rock Mass Quality system</td>
</tr>
<tr>
<td>Q'</td>
<td>Modified Rock Tunnelling Quality Index</td>
</tr>
<tr>
<td>RQD</td>
<td>Rock Quality Designation</td>
</tr>
<tr>
<td>RG</td>
<td>Finnish Engineering Geological System</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>RMi</td>
<td>Rock Mass index</td>
</tr>
<tr>
<td>RMR89</td>
<td>Rock Mass Rating</td>
</tr>
<tr>
<td>RMS</td>
<td>Rock Mass Strength</td>
</tr>
<tr>
<td>RSR</td>
<td>Rock Structure Rating</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>Major principal stress component</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>Intermediate principal stress component</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>Minor principal stress component</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>Normal stress on a surface</td>
</tr>
<tr>
<td>T</td>
<td>Tension strength</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear stress</td>
</tr>
</tbody>
</table>
List of Publications

This doctoral dissertation consists of a summary and of the following publications:


Author’s Contribution

Publication 1: MATLAB script for analyzing and visualizing scanline data

M. Markovaara-Koivisto participated in the fieldwork, and geological and scanline mapping. She participated in developing the scanline mapping form to collect required data for later 3D visualizations and analysis. M. Markovaara-Koivisto wrote the MATLAB™ script to visualize and analyse scanline data and demonstrated its use with a dataset from the scanline surveys. Her responsibility was also to write the most part of the manuscript.

Publication 2: The effect of fracture aperture and filling material on GPR signal

M. Markovaara-Koivisto participated in the planning and execution of the laboratory measurements. She analysed the results of the laboratory tests and ground penetrating radar profiles from the quarry with Reflexw software. Her contribution was also to write the most part of the manuscript.

Publication 3: MATLAB script for stereographic projection of fracture density and RQD

M. Markovaara-Koivisto wrote the MATLAB™ script to visualize fracture density and Rock Quality Designation on a stereographic projection. She participated in scanline mapping to recover the data used in the examples. She was responsible for writing most part of the manuscript.
Building underground facilities in bedrock is increasing in the modern world. In large cities underground alternatives are taken into account due to the lack of space above ground, to ease traffic and parking in city centres, to guarantee stable environment for super computers, electrical lines etc. (de Mulder and Pereira 2009). Bedrock can be utilised also for safe isolation of toxic wastes (Posiva 2012, SKB 2013). The planning of the layout, reinforcement and the execution of the excavation are based on town planning, the future usage of the underground space, the related safety regulations and the geological conditions. Description of the geological conditions describes information about the rock type, its mineralogy, rock mechanical properties, geological structures causing heterogeneity, hydrogeological properties and stress state. In rock engineering, geological conditions are taken into account with the help of rock quality systems (eg. RQD, RMR) developed during the past decades based on executed rock engineering projects (among others Goel et al. 1995, Barton 2002). The properties of the bedrock, the description of rock quality, are distributed to all of the parties involved in a project.

Rock quality can be estimated in 3D with the modern modelling software with information collected from rock at the surface and drill cores at depths. Major weakness zones can be identified with non-invasive geophysical methods, which provide indirect information of the rock mass (near-surface refraction seismic studies and electrical resistivity tomography for example). Some geophysical methods can also be used to even identify individual rock fractures (Porsani et al. 2006, Pujari et al. 2014). In large tunnelling projects the cross sections gathered for the tunnel designs usually contain geological features such as the zones of weakness and the estimated rock. In addition, the rock quality parameters are marked onto the cross sections. As part of the tunnel design reinforcing plans take into account the rock quality with separate factors for the roof and the walls. Considering the vast need for information of the rock quality, a 3D model can improve cost effectiveness and safety in the planning and construction of underground facilities.

A 3D model can be used to plan advantageous layouts and the rock quality would be estimated along the length of excavation. Therefore the main target of this thesis was to build a 3D rock quality model with the modern 3D modelling tools at hand by utilizing structural geological mapping, scanline mapping, ground penetrating radar survey and stereophotogrammetry to gather information about the discontinuities. The fieldworks in Mäntsälä, southern Finland,
was carried out during the summers 2006-2009. The results are based on 7 scanlines, 22 ground penetrating radar profiles, 6 stereophotographs and numerous GPS points to tie the model into global coordinates. To assist utilization of the vast datasets gathered during scanline mapping, a computer program was developed. The orientation dependency was studied with developed computer program which presents the rock brokenness parameters on a stereographic projection.

1.1 Background and research environment

Rock quality is commonly determined and expressed by different rock quality classification systems. Several of them have been developed around the world to suit the local geotechnical environment and reinforcement methods:

- The Rock Tunnelling Quality Index, also known as Rock Mass Quality system (Q, Barton et al. 1974, Barton 2002) was developed in Norway,
- The Rock Mass Rating, also called the Geomechanics Classification (RMR, Bieniawski originally 1973, modified 1975, 1976, 1979 and 1989) was developed in South Africa for civil engineering purposes,
- The Modified Rock Mass Rating for mining (MRMR, Laubscher 1977, 1984, Laubscher and Taylor 1976, Laubscher and Page 1990) was developed for the special needs in mine environment, but was later completed with other cases as well,
- The Rock Mass index (RMi, Palmström 1996a,b) was developed in Norway to characterise rock mass strength,
- The New Austrian Tunneling Method (NATM, Rabcewicz 1964, Steiner and Einstein 1980) was developed in the Alpine environment,
- The Rock Mass Strength value (RMS, Stille et al. 1982) was a Swedish modification of Bieniawski’s RMR, Rock Mass Number (N, Goel et al. 1995) is a modification of Barton’s Q value, and Rock Structure Rating classification (RSR, Wickham et al. 1972) was developed for smallish tunnels with steel set reinforcement.
- The geological strength index (GSI, Marinos et al. 2005) was developed to apply also in poor and heterogenous rock masses and to estimate their rock-mass properties.

These are used for calculating a value or gathering a description of the rock quality based on the distinct rock quality parameter defined in the field and laboratory (Table 1).
Table 1. Rock quality classification systems and parameters which they take into account.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rock quality classification system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q</td>
</tr>
<tr>
<td>RQD</td>
<td>x</td>
</tr>
<tr>
<td>Type of fracturing</td>
<td></td>
</tr>
<tr>
<td>Joint spacing</td>
<td></td>
</tr>
<tr>
<td>Joint roughness</td>
<td></td>
</tr>
<tr>
<td>Fracture aperture</td>
<td></td>
</tr>
<tr>
<td>Fracture trace length</td>
<td></td>
</tr>
<tr>
<td>Joint orientation</td>
<td></td>
</tr>
<tr>
<td>Groundwater conditions</td>
<td></td>
</tr>
<tr>
<td>Stress</td>
<td></td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td></td>
</tr>
<tr>
<td>Alteration of fracture surfaces</td>
<td></td>
</tr>
<tr>
<td>Joint strength</td>
<td></td>
</tr>
<tr>
<td>Joint condition</td>
<td></td>
</tr>
<tr>
<td>Number of joint sets</td>
<td></td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td></td>
</tr>
<tr>
<td>Excavation damage zone</td>
<td></td>
</tr>
<tr>
<td>Rock type</td>
<td></td>
</tr>
<tr>
<td>Rock hardness</td>
<td></td>
</tr>
<tr>
<td>Geologic structure</td>
<td></td>
</tr>
<tr>
<td>Fracture zone properties (length, thickness, transmissivity and Q')</td>
<td></td>
</tr>
<tr>
<td>Main minerals</td>
<td></td>
</tr>
<tr>
<td>Grain size</td>
<td></td>
</tr>
<tr>
<td>Degree of particle organisation</td>
<td></td>
</tr>
</tbody>
</table>

According to the results of the interviews in Markovaara-Koivisto (2010), two rock quality classifications have taken root in Finland in civil engineering purposes: Rock Tunnelling Quality Index (Q, Barton et al. 1974, Barton 2002), which uses Rock Quality Designation (RQD) value (Deere 1963), and the Finnish engineering geological system (RG, Korhonen et al. 1974). In addition, some companies use Rock Mass Rating classification (RMR, Bieniawski 1974), which has a modification for mining; Mining Rock Mass Rating (MRMR) value (Laubscher 1977, 1984, Laubscher and Jakubec 2000). In addition to these, two classification systems have been developed for more limited use: the Construction Potential Model of Bedrock for Urban Areas made by GTK (Pajunen et al. 2008) introduced a classification method, which is possible to use as basic information for regional and local planning in the capital area of Finland, and the Host Rock Classification, which was developed for classifying the rock at the nuclear waste repository site in Olkiluoto area (Hagros 2006).

Because of the numerical nature of RQD and Q system, their suitability for hard crystalline rock conditions such as in Finland, and that they are widely used in Finland, they were chosen for the numerical modelling task in this thesis.

1.2 Objectives and scope

The aim of this thesis was to develop utilization of geological and geophysical methods, more precisely ground penetrating radar, in defining rock fracturing and rock quality in 3D. The idea was to collect the direct observations of rock...
fractures in the field from geological mapping and scanline surveys. These observations were then utilized in interpreting fracturing in 3D from ground penetrating radar (GPR) radargrams and in statistical analysis for later fracture network simulation. According to the field observations and the type of the GPR reflections, the simulated fractures were given surface properties to calculate the modified Rock Tunnelling Quality Index (Q’) for the rock mass.

The thesis elaborates on the aforementioned study process, and the papers, the additional modelling conducted in this synopsis and discussion aim to answer the following questions raised during the studies:

1. How can reflections in ground penetrating radargrams be combined into horizontal and nearly horizontal fracture surfaces? What information is needed?
2. How can the rock quality parameters fracture density and RQD be computed within a 3D fracture model?
3. How can the detailed fracture data collected with scanline method be visualized and analysed?
4. How can orientation dependency of fracture/fracturing properties be visualized?
5. How can scanline data be used to simulate a 3D fracture network?
6. How can rock quality be calculated in 3D?
7. What are the sources of inaccuracy in the models?

1.3 Research approach

The modified Rock Tunnelling Quality Index (Q’, Hoek et al. 1995) utilised in this study is based on numerical parameters, which describe the properties of the block size and shear strength of the fracture surfaces. The numerical rock quality parameters were of significant use in the modelling task as the thesis emphasises was a mathematical approach. The numerical rock quality parameters were defined in the field from the rock faces of the quarry. Because the observations are bound to the location, the rock quality was simulated in 3D volume based on statistical analysis of the fracture observations.

The thesis utilizes several research methodologies. The fracture modelling part is descriptive, as the modelling procedure is described, stages are documented and the most interesting features are elaborated. In addition, explanations for the problems faced in the modelling work are given and causal relationships are discussed. Furthermore, developing new computer programs to visualise and analyse the gathered data gives another dimension for the thesis.

1.4 Research process and dissertation structure

The Mäntsälä dimension stone quarry in southern Finland was chosen for the research environment because there were rock walls in two nearly orthogonal orientations and it had several excavation levels which were easily accessed. The rock mass is relatively fractured, so that material for fracture and rock quality
studies were available. The fracturing pattern was also systematic, which was taken into account in the quarry planning.

Figure 1 illustrates the three types of information concerning the rock quality collected with different methods, and in which modelling task the information was utilized. The three types of information are direct and indirect observations and simulations.

![Figure 1. Illustration of gathered 3 types of information and the fracture density and rock quality modelling tasks it was utilized at.](image)

The research started by making the direct observations of the fracturing by geological mapping. Geological surface mapping provided direct information about the fracture sets and their properties. Information of the orientations of the fracture sets was utilized in user-friendly construction of fracture surfaces by coupling reflections from adjacent ground penetrating radar (GPR) survey lines to form a fracture network (Markovaara-Koivisto et al. 2009a,b). The GPR provided indirect information about the fracture pervasiveness and fracture straightness. Due to methodological and site specific limitations, the 3D fracture model needed to be combined from GPR surveys and scanline measurements (Markovaara-Koivisto et al. 2010). GPR soundings were not able to detect vertical discontinuities. The fracture observations were made on a near horizontal scanlines, along the rock walls, which are ideal for sampling vertical fractures, but miss easily horizontal fractures parallel to the scanline. These and similar limitations to be taken into account are rather a rule than an exception in engineering geological investigations.

At the time the author was not aware or any free of charge/open access software available to visualize and analyse the results of the scanline mapping. Conclusions of the fracture sets properties had to be made in the field, and the gathered data could not be visualized in any other way than with drawings, tables and charts. This had to be overcome, as 3D surfaces presenting the mapped fractures were needed for the 3D fracture model. The developed MATLAB script takes into account the observed trace length of the fracture, the waviness of the surface, and calculates point sets for the fracture surfaces for later 3D visualization with commercial programs (Markovaara-Koivisto and Laine, 2012).
After the 3D fracture model was completed with the results of the scanline survey, more broken areas could be detected (Markovaara-Koivisto et al. 2010). Nevertheless the model still lacked nearly vertical discontinuities inside the rock mass, except for those which cropped out at the scanline.

As the next step, the fracturing data gathered by scanline mapping, was used for simulating the nearly vertical fractures into the 3D space. This was carried out with Gocad FractCar plug-in developed by Henrion and Bonneau in 2011 (Bonneau et al. 2013, 2016). The program calculated fracture locations with Monte Carlo simulation and generated the fractures stochastically based on their length and orientation distributions. The fracture model was created by combining the simulated nearly vertical fractures, horizontal fractures based on the GPR survey. The horizontal fractures were supplemented with the fractures which were observable in the stereophotographs, but not in the GPR radarograms.

The aim was to calculate the Q’ value in the modelled space. Therefore the Q’ parameters \( J_{r} \) and \( J_{n} \) had to be given to the fracture surfaces based on the observations made in the scanline mapping, and straightness of the GPR reflections. Other Q’ parameters, RQD and \( J_{a} \), were calculated in the model based on the fracture network. The number of fracture sets was defined by excluding fracture sets which are further than a certain distance from the determination point. After calculating all of the parameters needed to determine rock quality value (Q’), the final round of computing was executed, and the rock quality could be visualized in 3D.
2. Theoretical framework

The studies concentrated on brittle fracturing present at the Mäntsälä quarry. The framework of this thesis is therefore limited by

- the explanation of the brittle failure by combined Navier-Coulomb-Griffith failure criteria,
- the role of ductile structures in steering the later fracturing,
- the formation of fracture networks,
- the variety of fractures’ roles in rock engineering and how they are dealt by the means of engineering geology.

2.1 Combined Navier-Coulomb-Griffith failure criteria

The brittle fracturing of rock can be described with the combined Navier-Coulomb-Griffith failure criteria shown in Figure 2. The diameter of the Mohr’s circle of biaxial stress state is the difference between \( \sigma_1 \), the major principal stress component, and \( \sigma_3 \), the minor principal stress component. The failure envelope following the combined Coulomb-Griffith criteria is defined with cohesion \( c \), normal stress \( \sigma_n \) and friction coefficient of the rock \( \mu \), when \( \sigma_n \) is positive, and with tension strength \( T \), shear stress \( \tau \) and \( \sigma_n \), when the \( \sigma_n \) is negative. \( T \) is half of the cohesive strength \( c \).

![Figure 2. Combined Navier-Coulomb-Griffith failure theory. Tension failure occurs when the Mohr’s circle touches the failure envelope when \( \sigma_3'=0 \) and \( (\sigma_1'-\sigma_3')<4T \) (small Mohr’s circle), and shear failure when \( \sigma_3\neq0 \) and \( (\sigma_1-\sigma_3)>4T \) (large Mohr’s circle).](image-url)
Rock fractures can be divided into four modes: mode I tension, mode II sliding, mode III tearing and mode IV closing (stylolites) (Fossen 2010). The combined Navier-Coulomb-Griffith failure theory describes the conditions needed to produce tension and sliding fractures. Hydraulic fracturing is used to describe the tensile or shear fracturing, which is caused by the fluid pressure. Fluid pressure decreases the effective stresses, and therefore moves the Mohr’s circle left by the quantity of the fluid pressure. This may cause the circle to touch the failure envelope, and failure of the rock. Because stress is usually compressive in the Earth’s crust, tensile failure is driven by the effect of fluid pressure.

According to the combined Navier-Coulomb-Griffith failure theory, the conditions when tension failure occurs have been achieved when the Mohr’s circle touches the failure envelope (Figure 2), \( \sigma_3 \) is tensile and exceeds the tensional strength of the rock (T) and (Cosgrove 1995)

\[
(\sigma_1-\sigma_3)<4T. \tag{1}
\]

The point at which the Mohr-circle touches the failure envelope represents both the shear and the normal stresses on the failure plane at the moment of the failure as well as the orientation the failure plane defined by \( 2\theta \).

The orientation of the tensional failure surfaces are defined in respective to \( \sigma_1 \) and \( \sigma_3 \). Tension failure occurs parallel to \( \sigma_1 \), but the order of the fractures or parallelism becomes poorer as \( \sigma_1 \) approaches \( \sigma_3 \) as shown in Figure 3. In hydrostatic pressure, for example, tension failure occurs at any direction (Figure 3 d). This is because \( \sigma_2 \) defines the dip direction of a fracture plane, and when it becomes equal to \( \sigma_3 \), the planes can dip in any direction.

![Figure 3. Patterns of tensile fracturing by the four stress states a-c (After Cosgrove 1995).](image)
Shear failure occurs when the Mohr’s circle touches the failure envelope, $\sigma_3$ is greater than 0, and (Cosgrove 1995)

$$ (\sigma_1-\sigma_3)>4T. \quad (2) $$

Shear failure (Figure 4) takes place on the surface, which is at $\theta$ angle to $\sigma_1$. The angle between the possible conjugate fractures $2\theta=90^\circ-\phi$, where $\phi$ is the angle of sliding friction on the fracture surface. $\sigma_2$ acts on the fracture surface and at right angle to the direction of the shear, or more precisely the intersection of the conjugate fractures. Lineation on the shear surface is caused by the movement of the generated rock block past by each other.

![Figure 4](image)

When the intermediate principal stress component $\sigma_2$ equals $\sigma_3$, the orientation of the shear or tension failure surface becomes less defined. Only the angle between the failure surface and $\sigma_1$ is determined.

In addition to pure tensile and shear failure, they can also occur at the same time. This happens when the Mohr’s circle touches the failure envelope, when $0.8T<\sigma_3<T$ and $4T<|\sigma_1-\sigma_3|<5.5T$. The resultant fractures show the characters of both tension and shear failure, and the angle between the possible conjugate surfaces is $<45^\circ$ (Price and Cosgrove 2010).

2.2 Effect of ductile structures on fracturing

Ductile shearing and folding cause the rock forming minerals to rearrange and to generate foliation. As a result, the rock has a preferred orientation of brittle failure, the orientation of the foliation. Uniaxial compressive tests (Hakala et al. 2007, Hudson and Harrison 2000) of foliated rock show that the rock strength is the highest perpendicular and parallel to the foliation. When the angle between the compressive stress and the foliation increase, the strength of the rock
starts to decrease and reaches its minimum close to $45^\circ + (\varnothing/2)$, where $\varnothing$ is the friction angle of the rock. As the angle increases, the rock strength increases steeply to its maximum. The rock is therefore weaker at small angles between the compressive stress and the foliation surface, than with larger angles. As a consequence, usually one fracture set follows the foliation.

### 2.3 Generation of fracture networks

Fractures are generated at different times at different events characterized by unique stress fields. A general rule is that younger tension fractures end or curve to the older ones. If the younger fracture ends to an older one perpendicularly, the older fracture has been open, if at an acute angle, the fracture has been closed enough to have and effective shear stress on the surfaces. In the case of shear fractures, the younger ones cut the older ones or their propagation stops at them are.

Fractures, which are generated under the same stress regime, are generated subsequently and under the influence of the fractures generated earlier. First, the fractures generate at random locations, but as their number increases, they start to affect each other, and eventually saturate at a rather even density. The state of saturation can be studied with the fracture spacing distributions (Figure 5). The saturation increases from negatively exponential distribution to lognormal and finally to Gaussian distribution (Rives et al. 1992).

![Figure 5. Effect of fracture set maturing on fracture spacing. Saturation of fractures increases from A to C. (After Rives et al. 1992)](image)

The mineralogy of the fracture filling material can also give an indication of the circumstances the fracture was generated.

### 2.4 Fractures in perspective of rock engineering

Fractures in the rock mass have several functions in the perspective of rock engineering. Taking into account the fracture zones and orientations of the densest fracturing in planning the location of an underground facility can ease construction actions and lower the maintenance costs. In blasting, fractures comprise possible gateways for the explosion gasses to escape that can cause rock fragments to fly into the surroundings and the power of the expanding gas to escape from where it was needed, and cause an unsatisfactory release of the blasted rock. In drilling, the drill bit can get stuck into a drill hole if the rock is severely fractured and then could cause the hole to collapse. Fractures can also redirect the drill bit and cause bending of the drill hole. In road cuts and underground
facilities fractures can form blocks and wedges that cause stability issues, which have to be secured. They can also be the reason of over break of the rock when blasting. They can cause inflow of water in underground facilities and are therefore taken into account in pre-grouting plans and in maintenance schedules. They can act as flow channels of harmful materials such as liquid wastes from underground storage facilities, airports or dumping grounds. In dimension stone quarrying, intact rocks are preferred due to the possibility of recovering large valuable rock blocks. Long continuous fractures can also be utilized in quarrying to help the blocks to break loose from the bedrock.

2.5 Engineering geology

The role of engineering geology is to provide information about the characteristics of the rock, the fractures, their properties, their interdependencies and dependency on rock structures, and taking into account their possible effects on the rock engineering projects and quarrying. Rock fractures are usually described as part of rock quality classification studies as described in Table 1. In this thesis, the rock quality is expressed with RQD and Q values, which are presented in the following.

Rock Quality Designation (RQD) has been developed to make a semi-quantitative description of the amount of good rock recovered from a core run (Deere 1963). RQD is a percentage of the sum of the lengths of the sound pieces of the core, divided with the total length of the core run (equation 3 by Deere, 1963).

\[
RQD = \frac{\sum \text{Length of core pieces } > 10 \text{cm}}{\text{Total core run length}} \times 100\%
\] (3)

The length of the sound core pieces is governed by the natural fractures in the rock, but also by the degree of weathering. If the rock is altered or weakened by surface weathering or hydrothermal activity, it should be excluded from the RQD. If the RQD value does contain altered rocks, it should be indicated with an asterisk (Deere and Deere 1988). The rock quality is appointed into the categories according to the RQD value as presented in Table 2.

<table>
<thead>
<tr>
<th>RQD (Rock Quality Designation)</th>
<th>Description of Rock Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25 %</td>
<td>Very Poor</td>
</tr>
<tr>
<td>25-50 %</td>
<td>Poor</td>
</tr>
<tr>
<td>50-75 %</td>
<td>Fair</td>
</tr>
<tr>
<td>75-90 %</td>
<td>Good</td>
</tr>
<tr>
<td>90-100 %</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

The Rock Tunnelling Quality Index (Q) is widely used in Finland. It was developed in Norway (Barton et al. 1974, Barton 2002) and is very suitable for Finland because the properties of bedrock are rather similar. Q values can be used for determining the need for reinforcement in a tunnel or any excavated space.
The Q system has become popular, because the reinforcement methods in Norway apply also in Finland.

The Q system is a quantitative system, which gives values for different rock properties. Q value is calculated as (Barton et al. 1974)

$$Q = \frac{RQD}{J_n} \frac{J_r}{J_a} \frac{J_w}{SRF},$$

where RQD is the rock quality designation (Equation 3, Table 2), $J_n$ is the rating for the number of fracture sets, $J_r$ is the rating for the roughness of the least favourable of these fracture sets or filled discontinuities, $J_a$ is the rating for the degree of alteration or clay filling of the least favourable fracture set or filled fracture, $J_w$ is the rating for the water inflow and SRF is the rating for faulting, squeezing or swelling type. Q value defines in which category the rock mass belongs to as shown in Table 3. Q value is determined for the most unfavourable fracture set according to the orientation or the friction properties of the fracture surface. Q value can be used for defining reinforcement in a tunnel of a certain span and purpose of use. Length of rock bolts depends on the excavation width and the purpose of use. After the invention of iron fibre reinforced schotcrete, the reinforcement categories were updated in 1986 (Grimstad et al.) to match better the methods available.

Table 3. Description of rock quality after Q value (Barton et al. 1974).

<table>
<thead>
<tr>
<th>Q (Rock Tunnelling Quality Index)</th>
<th>Description of Rock Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001-0.01</td>
<td>Exceptionally poor</td>
</tr>
<tr>
<td>0.01-0.1</td>
<td>Extremely poor</td>
</tr>
<tr>
<td>0.1-1</td>
<td>Very poor</td>
</tr>
<tr>
<td>1-4</td>
<td>Poor</td>
</tr>
<tr>
<td>4-10</td>
<td>Fair</td>
</tr>
<tr>
<td>10-40</td>
<td>Good</td>
</tr>
<tr>
<td>40-100</td>
<td>Very good</td>
</tr>
<tr>
<td>100-400</td>
<td>Extremely good</td>
</tr>
<tr>
<td>400-10000</td>
<td>Exceptionally good</td>
</tr>
</tbody>
</table>

Also the modified Rock Tunnelling Quality Index (Q’) is very commonly used. Q’ is calculated as (Hoek et al. 1995)

$$Q' = \frac{RQD}{J_n} \frac{J_r}{J_a} .$$

Q’ does not take into account the stress factors ($J_w$ and SRF) in the rock. The Q’ system is easier and faster to use than Q system, because it does not demand in situ stress measurements, information about the rock strength or water inflow measurements.

In addition to defining the rock quality, engineering geologist can use the gathered information about the fracturing properties and age dependencies to simulate realistic fracture network models. This requires more detailed analysis
of the data, but definition of the fracture sets, orientations and surface properties are also utilized.

In addition to the analysis of single fractures and fracture sets, ductile and brittle deformation zones are studied. They are treated as features which have a core and a damage zones with different properties (Milnes et al. 2007). In data collection and fracture modelling they are treated separately from the other fracturing, which is considered stochastic.

Statistical fracture network simulations can be carried out based on several methods. The methods can be divided into object based methods and grid block methods. Object based or Boolean methods model individual objects (Discrete Fracture Networks), to which properties are addressed to. The fracture planes can be created by Poisson process (statistical) (Leckenby et al. 2007) or Boolean models (statistical and conditional). Conditional simulations can take into account location of the direct observations and honour them while simulation (Tran et al. 2006). Some can be partly controlled by observations, like fracture spacing to avoid unnatural close occurrence of fractures (Niven and Deutsch 2012).

Grid block models (Finite Element Models) are commonly used in rock mechanics, groundwater flow and contaminant transport studies to model the conductivity of geological strata. The models can contain both primary porosity and secondary porosity i.e. rock fractures. The properties in the grid can be designated with two-point statistics i.e. variograms and cross-variograms (Viruete et al. 2003), multiple-point statistics simulation by using training images (Liu et al. 2009), pluriGaussian structural simulation, where spatial distributions of two or more observed structures are united (Dowd et al. 2007), and Markov Chain Monte Carlo simulation, which could be used when only drill core data is available, because it does not need input of fracture length or orientation (Mardia et al. 2007).
3. Materials and methods

3.1 Site description

The bedrock in Finland can be divided into the Archean rocks (>2.5 Ga) in the east and the north of Finland, and to Svecofennian rocks (2.5-1.80 Ga) in the south and the west. The Archean bedrock consists of metamorphosed volcanic and sedimentary rocks, gneisses, granodiorite, gneissose tonalite, amphibolites, and migmatites. The Svecofennian bedrock consists metamorphosed volcanic and sedimentary rocks such as schists and quartzites, layered mafic intrusions, diabase dikes, migmatites, volcanics and granitoid complexes. A small proportion of younger rocks exists in Finnish bedrock; rapakivi intrusions (1650-1200 Ma) in the southern parts of Finland, diabase dikes (1.26 Ma), limestone in the south-western parts (490-443 Ma), and clay- and sandstone in the western parts (543-490 Ma). (Vaasjoki et al. 2005)

Crustal scale faulting started soon after the Archean crust had formed and began to ease only about 2.4 Ga ago. Then 2.2-1.97 Ga ago numerous diabase dikes penetrated the Archean bedrock. Another phase of faulting occurred ca. 1.83 Ga ago with incipient extentional collapse of Svecofennian orogen and transpressional faulting. The movements decreased ca. 1.8 Ga ago when the modern erosion level was still buried some 15 km deep. After the bedrock cooled, post-orogenic granites were able to push through the opened fissures. In the cooling environments, the faults remained active for hundreds of millions of years, and some of them are weakly active even today. (Vaasjoki et al. 2005)

The complex strain history of the Finnish bedrock has caused anisotropy in great part of the rocks. Orientation of the schistosity of the rocks is a sum of the stress field created by the orogeny or shear, and the local heterogeneity. In the perspective of engineering geology, the schistocity is taken into account as a possible weakness plane and a possible orientation of one of the fracture sets.

The dimension stone quarry in Mäntsälä is located at the edge of one of the round shaped granodiorite massifs located in the area. Origin of the granodiorite has been explained to be magmatic plumose intrusion, which forced the older schists to move aside (Härme 1978). The dome and basin structure is caused by sequential folding in two rather orthogonal stress regimes (Pajunen et al. 2008).

The quarry is orderly cut, and has several excavation levels in three different directions, forming a U shaped pot (Figure 6). Extraction started at the end of
the 1980’s. Annual production is approximately 3 000 m³ for monuments, interior stone, and environmental stone with the trade name of Aurora. The leftover material is for aggregate production. The quarry was chosen for the studies because the rock type resembles the rock in Helsinki, Finland. The planarity of the rock walls in the quarry also enhances the study. The geological mapping of the rock walls and 18 GPR survey lines have been possible to execute consistently. This enables us to see directly which fracture has caused the radar signal to reflect.

All together seven approximately horizontal scanlines were placed on three different levels and on different sides of the quarry (Figure 7). The numbering of the scanlines in Figure 6 may differ from the ones presented in the publications. Two of the scanlines (3 and 5) were approximately in perpendicular orientation to the other ones.
Materials and methods

Figure 7. Scanlines on the rock faces of the Mäntsälä dimension stone quarry.

The fracturing at the Mäntsälä quarry was studied with the 7 scanlines. Their length, the number of observed fractures and orientation are presented in Table 4. Note that negative dip intends descending and positive dip rising scanline on contrary to general practice in geoscience.

Table 4. Length, number of fractures, and orientation of the scanlines.

<table>
<thead>
<tr>
<th></th>
<th>SL1</th>
<th>SL2</th>
<th>SL3</th>
<th>SL4</th>
<th>SL5</th>
<th>SL6</th>
<th>SL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>33</td>
<td>23</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Number of fractures</td>
<td>62</td>
<td>61</td>
<td>44</td>
<td>22</td>
<td>57</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>Dip [°]</td>
<td>4.4</td>
<td>-1.6</td>
<td>-1.7</td>
<td>ca. 0</td>
<td>ca. 0</td>
<td>-1.8</td>
<td>-3.9</td>
</tr>
<tr>
<td>Strike [°]</td>
<td>230</td>
<td>238</td>
<td>328</td>
<td>040</td>
<td>333</td>
<td>052</td>
<td>054</td>
</tr>
</tbody>
</table>

Figure 8 presents the fracture orientations on a stereogram. Six fracture sets and random fracturing were found. Properties of the fracture sets are presented in Table 5-Table 9.

Figure 8. Fracture sets in the Mäntsälä quarry. Set 1 purple squares, set 2 red asterix, set 3 yellow circle, set 4 blue cross, set 5 cyan triangle, set 6 green diamonds, and set 7 (randoms) black triangles.

In short, set 1 contains straight or stepped, slightly rough fractures in mean orientation 83/217. The fractures are hematite filled. Average trace length is 1.9 m. Set 2 contains undulating slightly rough fractures in mean orientation 83/325. The undulation might be the cause of the wide scale of dip directions. The fractures have hematite and palgorskite filling. Set 2 has the densest fracturing.
Average trace length is 1.6 m. Set 3 contains undulating, slightly rough fractures in mean orientation 81/283. The fractures are commonly hematite filled. Average trace length is 1.5 m. Set 4 contains undulating slightly rough or rough fractures in mean orientation 41/212. They are nearly perpendicular to the schistosity. Fractures are commonly hematite filled. Average trace length is 1.9 m. Set 5 contains undulating smooth fractures in mean orientation 41/040. They follow the schistosity. Chlorite, biotite and epidote are common filling minerals. Average trace length is 2.5 m. Set 6 contains undulating or tortuous slightly rough or rough fractures in mean orientation 14/080. Fractures are either tight or open and have no fracture fillings. Average trace length is 4 m. Random fractures are commonly slightly rough and have a mineral filling.

Table 5. Mean pole orientations of the fracture set and the number of observations at the Mäntsälä quarry.

<table>
<thead>
<tr>
<th></th>
<th>Dip [°]</th>
<th>Dip direction [°]</th>
<th>Number of fractures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>83</td>
<td>217</td>
<td>73</td>
</tr>
<tr>
<td>Set 2</td>
<td>83</td>
<td>325</td>
<td>107</td>
</tr>
<tr>
<td>Set 3</td>
<td>81</td>
<td>283</td>
<td>27</td>
</tr>
<tr>
<td>Set 4</td>
<td>41</td>
<td>212</td>
<td>12</td>
</tr>
<tr>
<td>Set 5</td>
<td>41</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>Set 6</td>
<td>14</td>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td>Set 7</td>
<td>51</td>
<td>257</td>
<td>29</td>
</tr>
</tbody>
</table>

The fracture densities of the sets along the scanlines were calculated with StereogramRQD MATLAB multiple script (Markovaara-Koivisto and Laine 2013). The fracture densities were calculated by dividing the number of fractures in a set with the length of the scanline perpendicular to the fracture set.

Table 6. Orientation corrected fracture densities along the scanline.

<table>
<thead>
<tr>
<th>Orientation corrected fracture density along the scanline (1/m)</th>
<th>SL 1</th>
<th>SL 2</th>
<th>SL 3</th>
<th>SL 4</th>
<th>SL 5</th>
<th>SL 6</th>
<th>SL 7</th>
<th>Mean density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1 (83/217)</td>
<td>0.63</td>
<td>0.41</td>
<td>0.33</td>
<td>0.69</td>
<td>2.25</td>
<td>0.92</td>
<td>0.21</td>
<td>0.85</td>
</tr>
<tr>
<td>Set 2 (83/325)</td>
<td>2.12</td>
<td>0.93</td>
<td>1.68</td>
<td>1.67</td>
<td>2.16</td>
<td>1.63</td>
<td>6</td>
<td>2.31</td>
</tr>
<tr>
<td>Set 3 (81/283)</td>
<td>0.11</td>
<td>1.32</td>
<td>0.35</td>
<td>0.46</td>
<td>0.26</td>
<td>0.12</td>
<td>-</td>
<td>0.44</td>
</tr>
<tr>
<td>Set 4 (41/212)</td>
<td>0.08</td>
<td>0.19</td>
<td>1.33</td>
<td>-</td>
<td>0.25</td>
<td>0.24</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td>Set 5 (41/40)</td>
<td>0.17</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.23</td>
</tr>
<tr>
<td>Set 6 (14/80)</td>
<td>0.48</td>
<td>0.33</td>
<td>0.26</td>
<td>0.39</td>
<td>0.39</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Set 7 (randoms)</td>
<td>0.51</td>
<td>0.2</td>
<td>0.37</td>
<td>0.21</td>
<td>0.36</td>
<td>0.32</td>
<td>0.13</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Table 7. Trace length [m] of fractures in the sets.

<table>
<thead>
<tr>
<th>Length</th>
<th>Mean</th>
<th>STD</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>1.96</td>
<td>1.59</td>
<td>6.01</td>
<td>0.12</td>
</tr>
<tr>
<td>Set 2</td>
<td>1.62</td>
<td>1.75</td>
<td>7.40</td>
<td>0.09</td>
</tr>
<tr>
<td>Set 3</td>
<td>1.51</td>
<td>1.72</td>
<td>12.65</td>
<td>0.20</td>
</tr>
<tr>
<td>Set 4</td>
<td>1.90</td>
<td>2.04</td>
<td>6.00</td>
<td>0.17</td>
</tr>
<tr>
<td>Set 5</td>
<td>2.45</td>
<td>1.94</td>
<td>6.00</td>
<td>0.23</td>
</tr>
<tr>
<td>Set 6</td>
<td>4.00</td>
<td>3.99</td>
<td>11.81</td>
<td>0.98</td>
</tr>
<tr>
<td>Set 7</td>
<td>1.55</td>
<td>2.28</td>
<td>12.65</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 8. Fracture properties as per cents [%] in sets.

<table>
<thead>
<tr>
<th>Straightness</th>
<th>Openness</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorenite/biotite/epidote</td>
<td>Hematite</td>
<td>Light clay</td>
</tr>
<tr>
<td>Set 1</td>
<td>51</td>
<td>23</td>
</tr>
<tr>
<td>Set 2</td>
<td>35</td>
<td>49</td>
</tr>
<tr>
<td>Set 3</td>
<td>23</td>
<td>62</td>
</tr>
<tr>
<td>Set 4</td>
<td>15</td>
<td>79</td>
</tr>
<tr>
<td>Set 5</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Set 6</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>Set 7 (randoms)</td>
<td>45</td>
<td>41</td>
</tr>
</tbody>
</table>

Per cent of the fracture filling minerals were calculated as the number of observations on all of the fractures in the set. Some of the fractures had several fracture filling materials due to the complex history of brittle fracturing and faulting.

Table 9. Per cent [%] of the fractures in sets containing the filling mineral.

| Chlorenite/biotite/epidote | Hematite | Light clay | Staining | Black filling | Yellow filling | Dark green filling | Carbonate | Green filling | Yellowish green filling |
| Set 1                      | 14       | 60        | 3        | 3           | 1           | 0           | 0           | 14         | 1          |
| Set 2                      | 9        | 39        | 11       | 13          | 0           | 1           | 4           | 14         | 1          |
| Set 3                      | 15       | 44        | 26       | 19          | 4           | 0           | 0           | 4          | 0          |
| Set 4                      | 8        | 33        | 17       | 0           | 0           | 0           | 0           | 0          | 8          |
| Set 5                      | 25       | 0         | 0        | 13          | 0           | 0           | 0           | 0          | 0          |
| Set 6 (randoms)            | 0        | 0         | 0        | 0           | 0           | 0           | 0           | 0          | 0          |

Fracture set 1 is likely to be the older than set 2, because the fractures are longer and fractures of set 2 terminate to fractures of set 1. Sets 1 and 2 are also older than the fractures of the set 6, because they continue through the open fractures of set 6. In addition, the fractures of set 6 sometimes terminate to fractures of set 1.

Schistosity observed in the migmatitic structure had two different orientations due to the basing structure. One schistosity was observed in orientation 22/115 and the other in 32/052. The basin structure caused also folding, which could be measured from the amphibolite veins cutting the quarry. The fold axis was in orientation 08/327, nearly perpendicular to the latter orientation of schistosity.
Paleostress analysis was carried out using 5 fault/striation observations made in the scanline studies. The scientific results were obtained using (Win)TENSOR, software developed by Dr. Damien Delvaux of the Royal Museum for Central Africa, Tervuren, Belgium (Delvaux and Sparner 2003, Delvaux et al. 2012). Two separate stress regimes were recognised. Orientation of the resultant strike-slip faults and striations are shown in Table 10. Fault group 1 is in the same orientation as fracture set 1, and fault group 2 in the same as fracture set 2. According to Pajunen et al. 2008, brittle faults at the area tend to follow the ductile shear zones, which follow the NW-SE trending edge of the dome structure at the quarry. This coincides well with the orientation of fracture set 1. Fracture orientation of set 2 is recognised as a fracture interpreted from airborne magnetic map in the Digital geological map of Finland (DigiKP, Geological Survey of Finland).

Table 10. Orientations of the fault and striations, direction of movement, and the analysed orientation of the stress field.

<table>
<thead>
<tr>
<th>Group</th>
<th>SL</th>
<th>Fault</th>
<th>Striation</th>
<th>Type</th>
<th>Stress field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SL1</td>
<td>66</td>
<td>220</td>
<td>22</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>SL6</td>
<td>73</td>
<td>208</td>
<td>5</td>
<td>118</td>
</tr>
<tr>
<td>2</td>
<td>SL7</td>
<td>84</td>
<td>124</td>
<td>2</td>
<td>221</td>
</tr>
<tr>
<td></td>
<td>SL7</td>
<td>84</td>
<td>114</td>
<td>9</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>SL1</td>
<td>88</td>
<td>309</td>
<td>6</td>
<td>219</td>
</tr>
</tbody>
</table>

When the fault group 1 occurred, the main principal stress component $\sigma_1$ was nearly horizontal in E-W orientation as shown in Figure 9. The minor stress component $\sigma_3$ was also nearly horizontal, in N-S orientation. When the fault group 2 formed, the $\sigma_1$ had turned at N-S orientation, but still remained horizontal as illustrated in Figure 10. The $\sigma_3$ was also horizontal, but in E-W orientation. Stereograms are presented with Schmidt lower hemisphere projections. Stress ratio $R (\sigma_2 - \sigma_3)/ (\sigma_1 - \sigma_3)$ is not reliable due to the small data set.
Materials and methods

Figure 9. Results of stress regime analysis of fault group 1. Only the fault with known direction of movement is shown. Red and blue arrows show orientation of the main and minor principal stresses. Directions of the arrows show compressional or tensional nature of the stress component. Blue dots represent tension quadrants. $R:0.5 =$ stress ratio infers tensile stress, $QRw:E =$ World Stress Map rank is very poor, and $QRt:E =$ tensor quality rank is very poor.

Figure 10. Results of stress regime analysis of fault group 2. Only faults with known direction of movement are shown. Red and blue arrows show orientation of the main and minor principal stresses. Directions of the arrows show compressional or tensional nature of the stress component. Blue dots represent tension quadrants. $R:0.75 =$ stress ratio infers tensile stress, $CD:5.7 =$ counting deviation, $QRw:E =$ World Stress Map rank is very poor, and $QRt:E =$ tensor quality rank is very poor.
A fault with associated tension fractures was observed on the southern wall of the quarry (Figure 11). The fractures are in an acute angle with the fault. The fault has a nearly vertical striation, which does not coincide with the formation of the tension fractures. Therefore the fault must have been reactivated later.

Figure 11. A) A fault crosscutting SL1 at 28.68 m, and associated tension fractures (joints) on the southern wall of the quarry. B) Schematic illustration of the fault and joints. Thick arrows illustrate $\sigma_1$ and $\sigma_3$ (tension). View is from north-west.

At the time the fault and the tension fractures were formed, the major principal stress component operated nearly vertical, along the tension fractures. This caused the tension fractures to open, and the fault plane to develop at an acute angle to $\sigma_1$. A paleostress analysis on the fault data is shown in Figure 12.
Figure 12. SL1 26.68 m fault, associated tension fractures shown as great circles and the principal stress components. Red and green arrows show orientation of the main and minor principal stresses. Directions of the arrows show compressional or tensional nature of the stress component. Blue dots represent tension quadrants. R:0.88 = stress ratio infers tensile stress, CD:13.5 = counting deviation, Q Rw:E = World Stress Map rank is very poor, and Q Rt:E = tensor quality rank is very poor.

The rotation optimization minimized the misfit of tensors to the fault plane and gave different orientations for the two greatest principal stress components (Figure 13).

Figure 13. Rotation optimised tensors of the SL1 28.68 m fault forming stress field. R:0.5 = stress ratio infers tensile stress, F5:0.7 = rotation optimization function, Q Rw:E = World Stress Map rank is very poor, and Q Rt:E = tensor quality rank is very poor.
The reactivation of the fault surface, which caused a dextral strike slip on the fault surface, and the 149/22 striation, was caused by a nearly horizontal $\sigma_1$. The results of paleostress analysis are presented in Figure 14. The orientation of striation was changed from 149/22 to 142/25 to better fit the shear plane.

![Figure 14](image)

**Figure 14.** Reactivation on the SL1 28.68 m fault plane. R:0.5 = stress ratio infers tensile stress, F5:0 = rotation optimization function value, QRw:E = World Stress Map rank is very poor, and QRt:E = tensor quality rank is very poor.

To conclude the paleostress analysis, the fault sets observed at the quarry are recognised also in the earlier studies by Pajunen et al. 2008 and the Geological Map of Finland (DigiKP). Brittle deformation follows the ductile shear zones, which conform the edges of the dome structure. Some faults have been reactivated during their history, which can be seen on the fracture surface as an unfitting striation.

### 3.2 Approaches to study fracturing

The following describes the methods used in this thesis to study rock fracturing in the dimension stone quarry. The methods were complementary and the results were used in subsequent stages of the 3D fracture modelling.

#### 3.2.1 Surface mapping

The mapping was carried out based on a form developed in the Construction Potential Model of Bedrock for Urban Areas (Pajunen et al. 2008) project at GTK. The main idea in the project was that during the long geological history rocks have deformed and it has been produced different tectonic structures,
which control the later fracturing. Therefore the structures indicate the technical properties of rock mass, which were separately defined for the zones of weakness and the intact blocks.

The rock fracturing properties were studied along the rock walls on different levels of the quarry. The following parameters were determined: rock types, tectonic parameters, fault orientations and inner properties, number of fracture sets, their orientations, type, trace length, fracture density, straightness, surface roughness, mineral filling, alteration, water leakage, and relation to other tectonic structures. Orientations of fracture sets were measured as dip and dip direction. The type of fracturing was divided into three groups; tight, open and filled. The aperture was measured across the widest part of the fracture. Slickensides were also noted. The longest and average fracture length was measured and possible continuation outside the mapping area was estimated. Fracture density in fracture sets was measured perpendicular to the strike of the fractures. Proportion of fractures that cut the whole mapping area was calculated, and fracture density inside the fracture zones was measured. Mapping was carried out at three levels of the quarry: each covered 15 to 25 metres wide area of the ca. 6 meters high walls (Figure 7). The walls were photographed and georeferenced with GPS survey.

It is worth noticing that the measured fracture properties were not exactly the same as in Barton’s Q system (Barton et al. 1974, Barton 2002), but they were categorised differently according to the needs of the project (Pajunen et al. 2008): i) J_n was divided into four classes: 1-2 sets, 2 and random or 3 sets, 3 and random and 4 or more sets. ii) J_w was divided into three classes: small, moderate or high water conductivity. iii) J_a was described with four properties (alteration or weathering on the fracture surface, filling material, fracture type, and presence of slickensides. iv) J_r was described with surface geometry (straight, wavy or stepped) and roughness (smooth, slightly rough or rough).

RQD could be estimated by first calculating the volumetric fracture count J_V, with the following equation (Palmström 1982)

\[ J_V = \frac{1}{s_1} + \frac{1}{s_2} + \ldots + \frac{1}{s_n} + \left( \frac{Nr}{5\sqrt{A}} \right), \quad (6) \]

where s_1-n are the average spacings of the fracture sets 1...n and Nr is the number of possible random fractures and A is the area (m²) of the mapping window. And then by calculating the RQD with the following equation given by Palmström (2005)

\[ RQD = 110 - 2.5J_V. \quad (7) \]

After the surface mapping, more information was needed of the fracture persistence into the rock mass and statistics of the fracture properties. These were gathered by ground penetrating radar survey and scanline mapping. Scanline mapping also provided more alternatives to define RQD.
3.2.2 Scanline mapping

Scanline survey is an effective way to collect information about rock fracturing for statistical analysis. This is because it provides abundant information about many different properties. Scanline logging is a technique in which a measuring line is drawn over an outcropped rock surface and all the discontinuities intersecting it are measured and described (Priest and Hudson 1981, ISRM 1987).

The scanline technique is also a tool to define the fracture sets and their properties, because all the discontinuities are observed and measured in the field, and only later divided into the fracture sets during data analysis. The geologist makes an interpretation about the fracturing separately during geological mapping, which supports the information from scanline survey.

Here a new scanline survey logging form was created based on the forms published by Priest (1993a) and Georgia State University (2009). The new form is redeveloped based on a form, produced by GTK in cooperation with rock engineers in 1997-1998, for assessing constructability of urban areas (Pajunen et al. 2008). The new logging form contains the conventional parameters of a scanline survey, but it is more detailed than its precursors, concerning the parameters used for visualizing the fractures. It was designed especially for later 2D or 3D visualization of the fracturing, which was not fully taken into account in the preceding forms. The Matlab (The MathWorksTM) m-file scripts for 2D and 3D fracture visualization from scanline data were created and published in this project (Markovaara-Koivisto and Laine 2012). The 2D visualization can be used to reproduce a scene of the fracture traces intersecting the scanline. The 3D visualization enhances the conception of the interrelations of the fracture sets and the persistence of the fractures.

Parameters of the discontinuities which are usually measured or described in scanline survey are: orientation, dip angle, type of infilling materials, spacing, aperture, water condition, roughness, waviness, fracture length, fracture compressive strength (JRC), number of fracture sets and spacing. In the studies by El-Naqa (2001) and Khanlari and Mohammadi (2005), the parameters were usually determined according to the norms given by the ISRM in 1978 or 1981. The new logging form was planned to take into account most of the above mentioned common parameters and the parameters used for 2D and 3D visualization. The form can be found in Appendix 1 and filling instruction in Appendix 2.

Trace length is measured separately for the part above and below scanline on the rock wall. In addition, the wave length and amplitude of undulating fractures are measured, and the apparent dips of fracture traces are measured, if orientation cannot be measured otherwise.

The use of the results of a scanline survey needs to be considered when deciding how long discontinuities are taken into account. Hermanson et al. (2005) did not take into account discontinuities shorter than 0.5 m in the discrete fracture network model of Forsmark, because they were considered to represent the surface fracturing of the rock. Priest and Hudson (1981) recommend to measure and observe discontinuities even as short as 10 mm. In this thesis, Priest’s and Hudson’s recommendation was followed, because fractures caused by excavation were excluded during the mapping. The fractures caused by excavation...
were short, curved and rough, and the minerals on the fracture surface were clear and the fractures did not have any mineral coating. The interest was in the intactness of the rock and the short fractures are essential part of assessing the total brokenness.

The RQD value could be determined from the scanline measurements by three different methods:

1) Using Equation 3 by calculating the distance of adjacent fractures on the scanline, and summing all the distances over 10 cm together, and dividing the sum with the total length of the scanline (Deere 1963).

2) Making a fracture set analysis and using Equation 6 to define \( J_V \) and then Equation 7 to for RQD.

3) Calculating fracture density \((\lambda)\) on the scanline and using the following equation by Priest (1993)

\[
RQD = 100(0.1 \times \lambda_{scanline} + 1)^{0.1 \times \lambda_{random}}
\]

Table 11 presents RQD values calculated with the different methods from the scanline data. In method 2 (Equation 6) the effect of random fractures was taken into account and the area (m²) of mapping window was defined as 1 m height x the length of the scanline. Furthermore, the fractures which orientation could not be determined in the field were added to the effect of the random fractures. As expected, the rock material is very intact in the quarry, which has been used for quarrying dimension stone.

<table>
<thead>
<tr>
<th>Method</th>
<th>SL1</th>
<th>SL2</th>
<th>SL3</th>
<th>SL4</th>
<th>SL5</th>
<th>SL6</th>
<th>SL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>98.3</td>
<td>96.1</td>
<td>94.6</td>
<td>97.3</td>
<td>96.1</td>
<td>94.3</td>
<td>94.0</td>
</tr>
<tr>
<td>Method 2</td>
<td>99.9</td>
<td>99.7</td>
<td>100</td>
<td>100</td>
<td>96.2</td>
<td>100</td>
<td>93.3</td>
</tr>
<tr>
<td>Method 3</td>
<td>98.4</td>
<td>97.0</td>
<td>96.5</td>
<td>99.0</td>
<td>96.6</td>
<td>99.0</td>
<td>99.0</td>
</tr>
</tbody>
</table>

### 3.2.3 Ground penetrating radar

Ground penetrating radar (GPR) is an electromagnetic survey method, which is used to study the structures of soil or as in this thesis, the bedrock. The GPR device, illustrated in Figure 15, consists of: the antenna unit, which consists of:

- a transmitter, which sends the waveform electromagnetic signal into the bedrock;
- a receiver, which records the signals returning back to the rock surface after being reflected from the structures;
- a trigger wheel, which measures the travelled distance and gives the transmitter a sign to send the next signal; and
- a computer generates a radargram, which shows the subsequent signals side by side as a function of time on y-axis and surveyed distance on x-axis.
Materials and methods

Transmitters can send signals which have different frequencies. The lower frequency signals can be used to receive reflections deeper from the bedrock than the higher frequency signals. This is because the signal attenuates in the bedrock in proportion to the frequency. On the other hand, lower frequency also means lower resolution, as the wavelength of the signal is longer.

After being sent into the bedrock, the electromagnetic signal is reflected from interfaces with different electrical properties. A rock type interface, for instance, which has high enough difference in relative permittivity $\varepsilon_r$, can cause a reflection which can be seen in the signal. Other common interfaces are rock fractures, which can be filled with air, water or mineral substance, and fracture zones, which contain crushed rock material and possibly flowing water. It should be noticed that the GPR method cannot detect steep fracture surfaces, because of lack of reflecting surface.

The reflectors location in depth is solved by utilising the known GPR signal velocity in the bedrock, and the two way travel time the signal took to travel from the transmitter down to the reflecting interface, and then up to the receiver.

In this thesis, the persistency of the fractures deeper into the rock mass was studied with the GPR method on three excavation levels of the quarry. GPR profiles were measured on each level with 2-3 metres intervals parallel to the walls of the quarry as shown in Figure 6. The equipment used for the GPR survey consists of a laptop PC; RAMAC/GPR CUII control unit with 500 and 800 MHz shielded RAMAC/GPR surface antennas; and a trigger wheel. The reflection data was interpreted with Reflexw 4.5 (Sandmeier Scientific Software).

The collected GPR raw data was first processed with a sequence of filters. The first filter removed the DC component from each trace along a section. After that
a gain function filter was applied to the data to strengthen the deeper weak signals. In some cases also a filter removing background noise was utilized. The travelling speed of the signal in rock was postulated to be $0.13 \text{ m/s}$, which is a common value for granitic rock.

In the processed radargrams, the open fractures were seen as strong reflections. Reflections were recorded as deep as 6 meters, corresponding approximately to the wall height. The data collected with the two antennas was complementary as some of the reflections were weak with one and well observable with the other. Because GPR cannot detect vertical surfaces, the modelled fracture surfaces contain only gently dipping fractures. These orientations, for example the orientation of the schistosity, were observed also in the geological mapping.

The reflections seen in the radargrams were interpreted as fractures, not as rock type contacts. This was concluded comparing of the reflections seen on a radargram of the survey line closest to the rock walls and photographs of the rock wall, the rock type or melanosome/leucosome interfaces could not be found. From the GPR results the global coordinates were calculated for later use in producing the 3D fracture model. The reflections were classified based on their straightness, strength and orientation, and colour coded for the visualization. On parallel GPR survey lines, the reflections with similar characteristics were combined with GOCADTM software to form a surface.

### 3.2.4 Stereophotogrammetry

Stereophotogrammetry can be used for creating a 3D model of the walls of a quarry, and to map fractures which are too high to reach. Stereophotography is generated by two points being marked to the wall and their locations determined with GPS, known here after as the “common known points” (Figure 16). Then two digital photographs covering the same area of the wall from two different points are taken. The distance between the cameras is approximately $1/8 - 1/6$ of the distance to the rock wall. Location of these points is determined with a GPS, the tilt and photographing direction are measured with a compass. Then the two photographs are processed into 3D photographs with software such as SiroVision by CSIRO. The common GPSed known points are marked to the photographs, then the program uses there to compare the disparity between the image points within a number of pixels given by the user, and finally generates a 3D image.

![Figure 16. Stereophotogrammetry with two cameras L and R. The two common known points in the photographs are marked with x1 and x2.](image)
Fracture orientation analysis could be carried out with SiroJoint (CSIRO). SiroJoint fits 3D planes to the marked fractures and cleavages and gives orientations to the created planes.

In this thesis, the stereophotographs were used for creating fracture surfaces of the nearly horizontal fractures, which could not be reconstructed with the GPR survey. Traces of the fractures were digitized from the 3D stereophotographs with SurpacTM by Gemcom. The digitized horizontal fracture traces were then used to create the horizontal fractures by extrapolating horizontal surfaces into the rock mass.
4. Review of the original publications and 3D Q’ modelling

This thesis consists of three original papers, which present methods developed and utilized in the work. First paper presents the MATLAB scripts developed in the need of presenting the scanline measurements carried out in the rock quarry’s walls. The second paper presents a method to interpret fracture filling material of the ground penetrating radar surveys carried out in the rock quarry. The third paper presents also MATLAB scripts developed to calculate rock fracture density from scanline surveys and presenting the outcomes on a stereographic projection. In addition to the papers, the data gathered by ground penetrating radar, stereophotogrammetry and scanline surveys are put together to produce a 3D rock quality model according to modified Rock Tunnelling Quality Index (Q’).

4.1 Publication 1: MATLAB script for analyzing and visualizing scanline data

This paper provides tools for visualizing and analyzing data gathered during the scanline survey. The tools that have been developed can be used for making 2D and 3D visualizations of the discontinuities along the scanline, and show fractures’ surface properties as colour codes. In 2D, the fractures are shown as traces on a vertical wall. Undulating fractures are reproduced as wavy traces. Advantage of this 2D visualization is that it can visualize also fractures, which orientation could not be determined in the field. In addition the 2D visualizations include bar illustrations of RQD and fracture density along the scanline. In 3D visualizations, the fractures are shown as round thin discs with the same orientation as recorded in the field. Undulating fractures are shown as round wavy surfaces if their wavelength and amplitude were determined in the field. The x, y, and z coordinates of these discs and wavy surfaces are exported as ASCII files for further use in other software, such as GOCADTM. Furthermore, the fractures can be divided into sets according to their orientation, and parameters such as mean orientation, fracture spacing and density are calculated within the sets.
4.2 Publication 2: The effect of fracture aperture and filling material on GPR signal

Possibilities of GPR to determine the fracture aperture and to see if the fractures are dry or water-filled were studied in this paper. According to the laboratory measurements, the aperture could be determined if it was greater than 1/4 of the GPR signal’s wavelength. The wavelength is dependent on the fracture filling material, as the signal has different velocity in different materials, and change in velocity causes change in the wavelength; the faster the signal is, the longer the wavelength. The fracture filling material could be determined by studying the shape of the reflecting signal. The signal goes through a 180° phase shift, when it is reflected from material which has higher relative permittivity than the material it has come from. Because the relative permittivity of rock, air and water are known, and the phase of a signal reflecting from a metal plate held in the air is the same as the one of a signal reflecting from a water-filled fracture, the filling type of an unknown fracture can be determined.

The fractures at the Mäntsälä quarry were air-filled at the upper excavation levels. Only the fractures interpreted from radargrams measured from the lowest excavation level were water-filled as they were below the ground water level.

4.3 Publication 3: MATLAB scripts for stereographic projection of fracture density and RQD

A MATLAB script was developed for stereographic projection of fracture density and RQD calculated from fracturing data collected by one or several scanline survey lines. The input data can also be collected from drill core, or any other linear method. The stereographic projection can be used in tunnelling or underground facility design to find the most advantageous orientations. It can also be used for evaluating the range of RQD, caused by its orientation dependency.

4.4 3D Q’-model

As the target of this study was to model rock quality in 3D, the methods utilized in the previous studies were combined to make such a model (Markovaara-Koivisto et al. 2009a, 2009b, 2010). Figure 17 presents the workflow of the Q’ modelling of the northern part of the dimension stone quarry in Mäntsälä.

Then the Q’ modelling task was carried out in a 46*10*8m³ grid with 1 m³ cell size. Q’ is a modification of Q, and it is used for characterizing the rock, not for tunnel support studies. The basic idea was to calculate all of the parameters affecting the Q’ value separately, and then to calculate the Q’ value based on them.

In short the work started by gathering all of the fracture surfaces based on different modelling methods. Then the fracture surfaces were given surface properties Jᵢ and Jᵢ, their average values (which were calculated from the observations made during the scanline and geological mapping), number of fracture sets (Jₙ), fracture density (RQD) was computed in the modelling grid, and Q’ could be computed. The following describes the modelling task in more detail.
in the northern wall in a grid located in the rock mass behind scanline number 6.

**4.4.1 Fracture surfaces**

Traces of sub-horizontal fractures seen in the GPR radargrams were digitised and the traces were combined into fracture surfaces according to the most expected fracture set orientations and their appearance. Undulating traces were combined together, and straight ones together.

Some nearly horizontal fractures seen on the rock walls could not be restored with the reflection from parallel GPR profiles. These fractures were constructed by digitizing their traces from 3D stereophotographs, and generating horizontal surfaces, which continue into the rock mass in the same persistence as the fracture traces were long on the rock wall.

Sub-vertical fractures were well represented in the scanline mapping, and the mapping data from SL6 was used as input for discrete fracture network (DFN) simulation. The DFN simulation was carried out with Gocad FractCar plug-in developed by Henrion and Bonneau in 2011. One fracture network realization within the modelling grid was simulated using discrete distributions for dip,
strike and length of the fracture sets. Before the simulation could start, the number of fractures in a cubic metre of rock, or in other words, the volumetric frequency of the ith joint set \((\lambda_v)_i\) had to be calculated with the following equation,

\[
(\lambda_v)_i = \frac{4(\lambda_l)_i}{\pi E(D^2)E(|n_i|)},
\]

where \((\lambda_l)_i\) is the linear frequency of the ith joint set along the mean vector direction, \(E(D^2)\) is the expected value of the squared diameter, and \(E(|n_i|)\) is the expected value of \(|n_i|\). \(E(|n_i|)\) can be expressed as

\[
E(|n_i|)=E(|n\cdot i|),
\]

where \(n\) is the unit normal vector of a joint in the joint set and \(i\) is the normal vector along the mean vector of joint set \(i\).

Before the fracture density could be calculated, the distributions of the squared fracture diameter, \(D^2\), and \(|n_i|\) had to be defined. MATLAB Statistics Toolbox was used in this task. The distributions were then tested with the Kolmogorov-Smirnov (K-S) test to find the distribution that best fitted the data, the \(E(D^2)\) and \(E(|n_i|)\) were resolved and \((\lambda_v)_i\) could then be calculated.

Normal, log-normal, exponential and gamma distributions were tested for both \(D^2\) (Table 12) and \(|n_i|\) (Table 13). The distribution with highest \(P\)-value and smallest \(k\)-value were chosen. Expected values of the chosen distributions are written in bold italic font.

**Table 12.** Distribution tests for squared fracture lengths of the sets.

<table>
<thead>
<tr>
<th></th>
<th>Distribution</th>
<th>K-S test</th>
<th>P-value (maximum significance level)</th>
<th>(k)</th>
<th>Parameters</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1 (82/220)</td>
<td>Exponential</td>
<td>0</td>
<td>0.2168</td>
<td>0.2638</td>
<td>(mu=10.1922)</td>
<td>10.1922</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.9212</td>
<td>0.1381</td>
<td>(a=0.587194) (b=17.3574)</td>
<td>10.1922</td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.3854</td>
<td>0.2267</td>
<td>(mu=1.266) (sigma=1.85738)</td>
<td>19.9043</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0</td>
<td>0.2168</td>
<td>0.2638</td>
<td>(mu=10.1922) (sigma=11.5254)</td>
<td>10.1922</td>
</tr>
<tr>
<td>Set 2 (81/331)</td>
<td>Exponential</td>
<td>0</td>
<td>0.7162</td>
<td>0.2500</td>
<td>(mu=23.3075)</td>
<td>23.3075</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.6225</td>
<td>0.2700</td>
<td>(a=0.603736) (b=38.6054)</td>
<td>23.3075</td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.3657</td>
<td>0.3300</td>
<td>(mu=2.12629) (sigma=2.87193)</td>
<td>518.165</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0</td>
<td>0.9948</td>
<td>0.1500</td>
<td>(mu=23.3075) (sigma=16.989)</td>
<td>23.3075</td>
</tr>
<tr>
<td>Randoms</td>
<td>Exponential</td>
<td>0</td>
<td>0.0049</td>
<td>0.5791</td>
<td>(mu=16.7211)</td>
<td>16.7211</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.7384</td>
<td>0.2164</td>
<td>(a=0.278249) (b=60.0941)</td>
<td>16.7211</td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.6714</td>
<td>0.2291</td>
<td>(mu=0.307853) (sigma=2.46525)</td>
<td>28.4052</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>1</td>
<td>0.0201</td>
<td>0.4800</td>
<td>(mu=16.7211) (sigma=47.5875)</td>
<td>16.7211</td>
</tr>
</tbody>
</table>
Table 13. Distribution tests for angle between fracture surface normal and mean orientation of fracture set of the sets.

<table>
<thead>
<tr>
<th>Set</th>
<th>Distribution</th>
<th>K-S test</th>
<th>P-value (maximum significance level)</th>
<th>k</th>
<th>Parameters</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>Exponential</td>
<td>1</td>
<td>7.8241e-07</td>
<td>0.6800</td>
<td>mu= 0.957315</td>
<td>0.957315</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.3600</td>
<td>0.2314</td>
<td>a= 861.063</td>
<td>0.957315</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b= 0.00111178</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.4737</td>
<td>0.2114</td>
<td>mu= -0.0442035</td>
<td>0.957347</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.0350386</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0</td>
<td>0.2655</td>
<td>0.2514</td>
<td>mu= 0.957315</td>
<td>0.957315</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.0332148</td>
<td></td>
</tr>
<tr>
<td>Set 2</td>
<td>Exponential</td>
<td>1</td>
<td>0.0215</td>
<td>0.5400</td>
<td>mu= 0.788266</td>
<td>0.788266</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.7618</td>
<td>0.2400</td>
<td>a=416.517</td>
<td>0.788267</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b=0.00189252</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.8461</td>
<td>0.2200</td>
<td>mu= -0.239121</td>
<td>0.788390</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.0521273</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0</td>
<td>0.8461</td>
<td>0.2200</td>
<td>mu= 0.788266</td>
<td>0.788266</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.0417202</td>
<td></td>
</tr>
<tr>
<td>Randoms</td>
<td>Exponential</td>
<td>0</td>
<td>0.1119</td>
<td>0.3800</td>
<td>mu= 0.691104</td>
<td>0.691104</td>
</tr>
<tr>
<td></td>
<td>Gamma</td>
<td>0</td>
<td>0.5097</td>
<td>0.2600</td>
<td>a=4.2177</td>
<td>0.691104</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>b=0.163858</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lognormal</td>
<td>0</td>
<td>0.4827</td>
<td>0.2655</td>
<td>mu= -0.492671</td>
<td>0.732231</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.601684</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0</td>
<td>0.5373</td>
<td>0.2545</td>
<td>mu= 0.691104</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sigma= 0.281442</td>
<td></td>
</tr>
</tbody>
</table>

The volumetric fracture densities (Table 14) were calculated for the sub-vertical fracture sets with equation 9 using expected values of the chosen distributions (Table 12 and 13). Because nearly vertical fractures dipping to opposite directions have to be simulated separately in the FractCar plug-in, fractures in set 1 had to be simulated in two parts. Their densities were defined by first calculating the combined density with equation 9, and then calculating the number of fractures in the sets based on the volume of the DFN model. Then the number was divided into the subsets based on the percentage of observations belonging to the subsets in the scanline mapping.

Table 14. Volumetric fracture density of the sets.

<table>
<thead>
<tr>
<th>Set</th>
<th>λv</th>
<th>p32</th>
<th>Number of fractures in /46<em>10</em>8m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td></td>
<td></td>
<td>403 fractures:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>96 dip towards NE, 307 dip towards SW</td>
</tr>
<tr>
<td>Set 2</td>
<td></td>
<td></td>
<td>409</td>
</tr>
<tr>
<td>Randoms</td>
<td></td>
<td></td>
<td>259</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1204</td>
</tr>
</tbody>
</table>

The 3D fracture model was compiled by combining the sub-horizontal fractures from the GPR and stereophotogrammetric studies, and the nearly vertical fractures from the discrete fracture network (DFN) simulation, based on the results of scanline mapping of SL6. Figure 18 illustrates the fractures which were considered in the Q’ modelling task.
Figure 18. The fracture network model used in the Q’ calculations. A) Simulated fractures (Set 1NE as peach, Set1SW as blue, Set 2 as cyan and randoms as purple), B) horizontal fractures observed in GPR studies (red surfaces) and horizontal fractures extrapolated from the traces seen on the quarry walls (blue surfaces).

4.4.2 Fracture surface properties \( J_r \) and \( J_a \)

The Q system’s fracture roughness and alteration parameters were given to the simulated fracture sets according to the most common or disadvantageous properties of the fractures observed in scanline mapping of SL6 (Table 16) to avoid having too optimistic results. Many of the fractures had for example multiple mineral fillings: 72 \% of the fractures dipping to the south-west in set 1 had hematite filling, 39 \% had carbonate filling and 11 \% had chlorite/biotite filling. Because chlorite/biotite and carbonate filling is more disadvantageous for fracture surface strength and stability than hematite, and they are commonly present in the fracture set, the \( J_a \) value was set to 4.

Table 15. Fracture sets and their surface properties, \( J_a \) and \( J_r \).

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Dip</th>
<th>Dip direction</th>
<th>Mean length [m]</th>
<th>Most common ( J_r )</th>
<th>Most common ( J_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1 SW dipping</td>
<td>81</td>
<td>218</td>
<td>2.82</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>Set 1 NE dipping</td>
<td>86</td>
<td>039</td>
<td>1.99</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Set 2</td>
<td>81</td>
<td>331</td>
<td>4.36</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Randoms</td>
<td>-</td>
<td>-</td>
<td>2.32</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>Horizontal</td>
<td>0</td>
<td>-</td>
<td>12.20</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>GPR (straight)</td>
<td>08</td>
<td>070</td>
<td>6.85</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>GPR (undulating)</td>
<td>34</td>
<td>057</td>
<td>3.63</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Values representing the fracture surface roughness \( J_r \) and alteration \( J_a \) were calculated as an average of these parameters intersecting the cell. \( J_r \) and \( J_a \) shown as partially transparent points in Figure 19 and 20. A continuous average value represents certain properties on the fracture surface even if \( J_r \) and \( J_a \) values are originally defined on a stepped scale. Furthermore, the average value was considered a good representation, because of the continuous nature of Q’ value. The proportional effect of the different fracture alteration values of each set, given
Review of the original publications and 3D Q’ modelling

in Table 15, was considered an advantage, because in large simulated fracture models the interest is on the stochastic distribution of fracture properties and characteristics. Continuous rating in rock quality systems is not a new idea. Earlier Şen and Sadagah (2003) have presented continuous ratings for the parameters of RMR system. There the parameters, such as RQD, fracture spacing, the uniaxial compressive strength of the rock and span of the underground space, are continuous by nature.

4.4.3 RQD

The number of fractures cross cutting each of the 1 m³ unit cells was calculated to receive the Jv value. The GOCAD mining utility tool by Mira Geoscience eases this task. In the earlier work (Markovaara-Koivisto et al. 2009a,b) the same calculation had to be carried out by calculating the distance to the fracture surfaces and summing all the fractures, which distance was less than 0.62 m, which is the radius of a cubic metre sphere. Then RQD was calculated from Jv value by using equation 7 (Palmström 2005). Figure 21 presents the RQD values as partially transparent points in the modelling grid. The RQD varied between 38 and 100, and mean value was 83.
4.4.4 \( J_n \)

The number of fracture sets was calculated so that if the closest fracture in a set was more than 3 m away from the cell, it was excluded from the total number of fracture sets. The \( J_n \) value was given according to the number of the remaining fracture sets. \( J_n \) values are shown in Figure 22. \( J_n \) value 6 corresponds to 2 fracture sets and random fracturing, and value 12 three fracture sets and random fracturing. The third fracture set in this case is the horizontal fractures modelled based on GPR reflections and fractures seen in the stereophotographs.

4.4.5 Resulting \( Q' \)-model

The \( Q' \) was calculated with equation 5 using the parameters calculated in the modelling grid as shown above. The \( Q' \) values varied from 1.9 to 12.5. This corresponds to poor or good rock quality. The calculated \( Q' \) values are shown as partially transparent points in Figure 23. The parts of highest rock quality are located in the right bottom corner, where the horizontal fractures area scarcest.
The user may study the produced 3D rock quality model with vertical and horizontal 2D cross sections, or with 3D contour lines or as partially transparent point model. These alternatives help for example in assessing effects of rock quality in tunnel cross sections and maps, intersection surveys of poor rock quality and the planned underground spaces and volume calculations of poor rock mass in a quarry. Parameters affecting the Q’ value can also be seen in tabulated form for each cell and thus be transported to any other software.

The resulted rock quality model consists of the Q’ value and its parameters: RQD, Jₘ, Jᵣ and Jₜ. This helps the user of the model to see which the reasons behind a low Q’ value are in different parts of the model.
5. Discussion and conclusions

5.1 Implications for rock engineering

The conclusions answering the original research questions presented in this thesis are as follows:

How can reflections in ground penetrating radargrams be combined into horizontal and nearly horizontal fracture surfaces? What information is needed?

(1) Coupling features seen on separate geophysical survey lines (ground penetrating radar in this survey) should be done with caution. Information about the possible orientations of the features, their similarity and consistency from survey line to another should be utilized.

(2) Geophysical methods can be used to provide information inside the rock. The physical limitations of the methods should be kept in mind and supplementary methods should be used whenever needed.

How can the rock quality parameters fracture density and RQD be computed within a 3D fracture model.

(3) The number of discontinuities in a cubic meter of rock (J_V) is commonly defined from the fracture spacing, but it can also be computed from a 3D fracture network model.

(4) A 3D fracture model has to be comprehensive when calculating RQD from the number of fractures in a cubic meter of rock (J_V) with Palmström’s equation, because J_V needs to be at least 5 to have an effect on the RQD value.

(5) Using equation especially designed for 3D (Palmström’s equation) for delivering rock quality parameters from 1D data (scanline) causes bias. The model should be completed with DFN modelling based on the results of the scanline survey.

How can the detailed fracture data collected with scanline method be visualized and analysed?

(6) The undulating nature of some fracture surfaces should be taken into account in the visualizations and models because it has a direct effect on the rock mechanical behaviour of the surface.

(7) Fractures which orientation could not be measured can still be visualized in 2D as traces if their apparent dip is measured during scanline survey.
(8) Fractures’ real dimensions are often not known. In these cases, a round thin disc which diameter equals to the observed trace length can be used to represent such a fracture surface in 3D modelling.

**How can orientation dependency of fracture/fracturing properties be visualized?**

(9) The orientation dependency of fractures’ properties can be studies with 3D visual illustration of fracture surfaces with colour codes representing the properties or with intensity rose diagrams.

(10) In scanline or window mapping, the discontinuities which are nearly parallel with the rock wall or comprise parts of it can be visualized the easiest with a 3D drawing.

(11) A bar or line diagram showing the RQD value or number of fractures per metre located above the scanline 2D visualization helps locating the broken parts.

(12) Range of orientation dependent parameters such as fracture density and RQD can be visualized on stereographic projection to get a better conception of the orientations of the densest and sparsest fracturing.

(13) Georeferenced stereophotographs can be used for digitizing discontinuities and measuring orientations for making 3D representations.

**How can scanline data be used to simulate a 3D fracture network?**

(14) Scanline method can provide information about fracture orientation and length, which is needed as an input when determining distributions in statistical simulation of fracture networks.

(15) Fracture density in the 3D fracture simulations can be calculated from fracture observations made by scanline method.

**How can rock quality be calculated in 3D?**

(16) Rock quality consists of several individual parameters (RQD, Jn, Jr, Jn), and they ought to be modelled separately to ease later explanation of the reasons behind the rock quality.

(17) 3D modelling makes enables later 2D section studies, volumetric calculations, and intersection assessment of planned underground structures or quarry plans.

**What are the sources of inaccuracy in the models?**

This question is discussed in the following chapter.

### 5.2 Reliability and validity

Reliability in the 3D rock quality model depends on several uncertainties along the whole process from data collection, analysis, fracture surface production, to the modelling task. Figure 24 shows a compilation of the possible sources of uncertainties through the process to generate the Q’ value model. The data collection with geological mapping, stereophotogrammetry, ground penetrating radar, scanline methods were prone to uncertainties. For example in GPR survey choosing a suitable signal velocity in rock has an effect on the depth the reflections are interpreted to come from. In addition, the data analysis and utili-
Discussion and conclusions

zation can be carried out with many different principles. In the ground penetrating radar survey the reflections were categorized and only reflections with similar appearance were coupled to form a fracture surface.

Figure 24. Uncertainty in the 3D rock quality model created in this thesis.

The rock quality parameter themselves can be sums of several properties of a fracture, a fracture set, or fractures, which belong to separate sets but are in the same space. Therefore, parametrisation is carried out on different scales and at different accuracies based on direct observations and generalized properties in simulated models. For example defining the fracture filling on a fracture surface is unambiguous. Giving the $J_a$ value for the fracture is straightforward, but evaluation of the thicknesses of the fillings can be affected by the judgement of the observer. When the fractures are grouped into sets to be later used in fracture simulations, the sets are given parameters based on the single observations. Due to the heterogeneity within a set, only the most common or relatively common disadvantageous properties are taken into account. When modelling the parameter in 3D space, the cells are given a value for the parameters based on the simulated fractures in the cells. An easy way is to calculate an average value of the parameter and point that value to the cell. This way the effect of the different properties is taken into account. A conservative way could be to give the most disadvantageous value to the cell. This way the user would know what the threats to be prepared for are.

When the amount of uncertainty is defined and can be expressed numerically, it can be visualized in a 3D model with several ways. Viard et al. (2011) presented uncertainty as a partly transparent grid, which intensity grew with the uncertainty. Knowing the uncertainty of certain parameters in a model supports decision making and directs additional investigations to the less defined areas.
5.3 Limitations

The study contained several limitations in different scales, methods, and computing.

5.3.1 Methods

The surface mapping methodology used was designed for a slightly different application, and therefore the definitions of parameters were not coherent with Q system. Nevertheless, the Q value could be determined based on the gathered data. Surface mapping is also dependent on the mapper, and the precision of the mapping. Long and prominent fractures in a set are more likely to be observed and the fracture density calculated along a line perpendicular to the fracture surfaces can be biased.

At the quarry, most of the ground penetrating radar surveys consisted of several parallel survey lines. In addition, also perpendicular lines should have been made to the present GPR profiles to make better and more reliable fracture models based on the reflections.

5.3.2 Scales

The major limitation in scanline fracture mapping was the intact nature of the dimension stone quarry chosen for the studies. The scanlines should have been several tens of meters long to be able to record enough fractures to be statistically representative. Horizontal fracturing was especially difficult to capture when using horizontal scanlines.

5.3.3 Computing

Fracture length and density analysis required several corrections to be made to the raw data. In this thesis the orientation correction of fracture spacing and density was carried out as suggested by Terzahgi (1965) and Hofrichter and Winkler (2006).

Fracture length bias caused by censoring should be taken into account. This is dependent on the length distribution (Priest and Hudson 1981), and cannot therefore be carried out automatically to the collected data and was not implemented in the MATLAB script.

In this thesis truncation bias was managed by measuring even the shortest fractures. If only fractures longer than say 25 cm are taken into account, the truncation bias can be corrected as explained in Priest 2004, but this also requires information about the length distribution.

In addition, the length of the scanline has an effect on the fracture spacing, because fracture spacing longer than the length of the scanline cannot be measured. When the scanline is longer than $20/\lambda$, the correction is not necessary. As explained in Sen and Kazi (1984), negatively exponential distribution satisfactorily represents fracture spacing when fractures are not evenly spaced. The expected value of fracture spacing on a scanline is calculated with the following equation (Sen and Kazi 1984, Kulatilake 1993)
Discussion and conclusions

where λ is the fracture density and L length of the scanline. In this thesis, the scanlines were longer than 20/λ, which made the density correction unnecessary.

5.4 Future challenges

Future challenges in 3D fracture modelling lie in evaluating the reliability of a 3D fracture model and the obtained rock quality values or dealing with the uncertainty in how it is modelled/presented to users/in results. The reliability of the model should be a sum of its parameters as they all have inherent uncertainty. The parameter's reliability in a point should depend on its distance to the nearest direct or indirect observation and the continuous nature of the defined property.

In defining the reliability of a fracture model, the next natural step would be to define rock mechanical parameters for the fracture surfaces for later stress-strain modelling of behaviour of the rock mass in case of tunnelling or excavating road cuts.
6. Summary

In this doctoral dissertation, rock quality and brokenness of rock mass was studied and modelled by applying several mapping methods, stereophotogrammetry and ground penetrating radar survey in a dimension stone quarry in Mäntsälä, southern Finland. New methods to analyze and visualize the gathered discontinuity data were developed and published.

A combination of several direct and indirect methods was utilized to gather information of the location and properties of the discontinuities. Ground penetrating radar was utilized to gather indirect fracture observations inside the rock and to study the continuity of the fractures observed on the quarry walls. The application of ground penetrating radar over a fracture to determine the filling material and its thickness was studied in laboratory and verified in the field. Some horizontal fractures seen on the quarry’s walls could not be reconstructed based on the ground penetrating radar survey, and were thus only extrapolated deeper into the rock mass based on the traces seen on the stereophotographs. A geological description of the rock mass was based on geological mapping of the quarry walls. The rock type, schistosity, folding, striation on slickensides, main fracture sets and their average properties were mapped. A detailed fracture mapping was carried out with scanline method. From the scanlines the following parameters were recorded: their orientation, trace lengths above and below the scanline, straightness, roughness, wavelength and amplitude of undulation, aperture, mineral coatings and striations on slickensides. In addition to the vast information about the fracture surfaces, the location of the fractures were recorded. This enabled the main work carried out in this thesis; realistic 2- and 3D visualization of the mapping results and analyzing for example the fracture density and RQD in 2- and 3D. Furthermore, the abundant dataset enabled DFN simulation based on property distributions, and modeling Q’ in 3D.

In the DFN modeling task, a simulation was ran to generate the sub-vertical fractures which could not been detected with ground penetrating radar, but were well represented in the scanline measurements. Q’-properties of the modeled discontinuities were based on the observation made in geological mapping, scanline mapping and the undulating or straight style of the ground penetrating radar reflection from the fracture surfaces. The modeled fractures and their properties were wrapped up in a Q’-model to visualize the rock material at hand.

For the modeling of the rock quality in 3D, two sets of MATLAB scripts were created to visualize and analyze the gathered scanline data due lack of access to software capable to undertaking the task. The first set of scripts was able to
make realistic 2- and 3D visualizations of the mapped fractures and fracture density and calculate RQD value along the scanlines; to group the observed fractures semi-automatically and analyze fracture density and mean orientation of each set. In addition, it can present fracture properties on a rose-diagram. The second set of scripts enables stereographic presentation of fracture density and RQD to study the inherent orientation dependency and variation range of these two parameters.

To conclude, the work presented in this thesis combined information from several survey methods, which all had their pros and cons. Along the way tools to analyze, visualize and utilize this information were provided. As an outcome a 3D model of rock fractures with information about the surface conditions, a grid holding information about rock quality model and the parameters it is based on were received, hoping to take also engineering geology one step closer to BIM modelling.
References


Appendices

Appendix 1 Scanline mapping form
Appendix 2 Explanations for scanline mapping form
## Appendix 1

**Scanline mapping form**

<table>
<thead>
<tr>
<th>Code</th>
<th>Line</th>
<th>Location</th>
<th>Mapper ID</th>
<th>Notes</th>
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<tbody>
<tr>
<td></td>
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</table>

**Starting point**
- $x^o$  
- $y^o$  
- $z^o$  

**Ending point**
- $x^e$  
- $y^e$  
- $z^e$  

**Scanline direction (dip/dipdir):**
- Dip
- Dip direction

**Tectonics**
- Sliceline

**Order of fracturing (dip/dipdir):**
- Flex
- Fracture width
- Fracture length

**Additional information:**
- Amplitude
- Wave length
- Roughness
- Slickness
- Straightness
- Aperture width
- Aperture length

**Meanders**
- Meander type

**Frac.**
- Fracture zone
- Fracture type

**Zone width**
- Zone width

**Length**
- Zone length

**Additional lines:**

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Appendix 2

Explanations for scanline mapping form

**Code:** Individual code for the observation

**Line:** Name or number of the scanline

**Location:** Name of the area, quarry, tunnel etc.

**Mapper ID:** Name of the mapper

**Starting/ending point \((x,y,z)\):** Measure the coordinates of the starting and ending point with a GPS.

**Notes:** e.g. additional notes about the specific location of the scanline.

**Scanline direction \((\text{dip/dipdir})\):** Measure the orientation of the scanline with a compass and inclinometer.

**Length:** Scanline length along the measuring tape.

**Additional lines:** Codes of the other lines in the same orientation.

**Tectonics:** S schistosity \((\text{dip/dipdir})\), L lineation\((\text{dip/dipdir})\), F folding\((\text{dip/dipdir})\) of fold axis and fold plane

**Order of fracturing \((\text{dip/dipdir})\):** When choosing a representative location for the scanline, make interpretation of the fracture sets (name then according to their dip/dipdir), and their age order.

**Meters \([m]\):**
Meters from the starting point.

**Dip direction:**
Accuracy in one degree.

**Dip:**
Accuracy in one degree.

**Alfa:**
If it is impossible to measure other directions, measure the angle the fracture cuts the scanline.

**Fracture zone:**
Mark observations from one fracture zone with a, the next zone set with b and so on.

**Zone width \([cm]\):**
Measure width of the fracture zone perpendicular to the mean orientation.

**Length \([cm]\):**
Measurable length of the fracture. Mark to the left cell the fracture length above the scanline, and to the right cell the fracture length below the scanline.

**Ending type:**
1= though going
2= fading
3= ends to another fracture
4= ends to a rock type contact
5= end not observable
Mark to the left cell the ending type above the scanline, and to the right cell the ending type below the scanline.

**Type:**
1= open  
2= tight  
3= filled  
4= narrow shear zone  
5= vein

**Straightness:**
1= straight, undulation <1cm/m  
2= wavy, undulation >1cm/m  
3= stepped  
4= tortuous - measure general direction

**Aperture [mm]:**
Describes the aperture of the whole fracture. Observations like water leakage to additional information.

**Roughness:**
1= smooth, f.e.g. slickenside  
2= slightly coarse, like sandpaper  
3= coarse, >3mm roughness

**Alteration, width [mm]:**
Total width of the altered zone in millimetres, “―” if not altered. 
Description of the alteration into additional information (slightly altered strongly altered, observable alteration minerals)

**Wavelength [cm]:**
Wave length of a wavy fracture, which is the distance of the peaks from each other's.

**Amplitude [cm]:**
Amplitude of a wavy fracture, which is the height of the peak.

**Slickenside:**
Mark slickenside with “x”.

**Additional information:**
Info about:  
Shape of the fractures:  
en-echelon, hook, feather, H (II or -), I, K (I or <),  
T (I or -), V, X, Y(I or V)  
Measure the angle between fractures constituting a V or X shape.  
Surface morphology:  
step (arrest line), en echelon, planar, slickenside, feather
About slickensides:
Striation: dip and dip direction
Sense of movement: sinistral, dextral, hanging wall up/down
Drift (cm) on a horizontal surface or more exact description.
Mineral filling:
Hard minerals: anhydride, quartz, epidote, feldspar
Soft/low friction minerals: chlorite, micas, calcite, gypsum, talc, graphite, kaoline
Structure of the filling: fresh surface, staining/overlay, thickness, breccia, welded