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ONKALO POSE Experiment — FRACOD2D Back-Analyses

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ABSTRACT

The POSE experiment was conducted in ONKALO® underground research laboratory as an in situ rock mass strength test that revealed the rock mass failure in Olkiluoto being governed by fracture growth at lithological borders. In this study, the experiment outcomes were back-analyzed with FRACOD2D code which is based on principles of fracture mechanics, capable of modelling explicit fracture initiation and growth in continuous medium.

The FRACOD2D simulations were aimed to act as an extension to the conducted 3DEC back-analyses of POSE, by providing more realistic and detailed information of the observed fracturing process in specifically selected 2D cross-sections. Consequently, the methodology in the FRACOD2D approach involved elastic simulations to achieve consistent stress levels and temperatures, equivalent to the monitored or back-analysed values during the experiment, after which fracture initiation and growth was implemented within the simulations. The overall nature and extent of the simulated damage was evaluated against the POSE observations. The strength properties for the rock matrix and developing fresh fractures were adjusted, within the limit of associated uncertainties in the available data, until a sufficient match against in situ observations was achieved.

The FRACOD2D back-analysis results indicate a damage extent in the order of centimetres to decimetres. The simulated damage extent can be perceived to be in the same order of magnitude as observed during the execution of POSE. Damage depth estimation from scaling of the experimental holes indicated a damage extent of less than 100 mm, while hydraulic flow measurements indicated an average value of 118 mm.

No available means or literature estimations exist of the strength and deformation properties for freshly developing new fractures as a consequence of stress exceeding the rock strength. During the FRACOD2D back-analyses, it was discovered that the best fit between simulated results and in situ observations was obtained with conceptualizing the freshly developing fractures having 90% strength of the intact rock properties, with the logic of fresh fractures having to be weaker than the intact rock material while stronger than existing old fractures. In addition, it was discovered that the simulation results were highly sensitive on the Mode II fracture toughness ($K_{IIc}$), which in turn is dependent on the applied level of confining stress. FRACOD2D does not take into account the confinement dependency in applied fracture toughness values and it was necessary to determine appropriate confinement value for determining the $K_{IIc}$ as an input.

Although FRACOD2D suffers from the two-dimensional simplification of the back-analysis problem at hand, the methodology can capture the observed structural failure and the variability of the results depending for example on the foliation angle, such as observed in situ during the execution of POSE. Uncertainty exists in all of the parameters as majority of the parameters given did not allow taking account the changing confining pressures during the test. Also the boundary conditions brought from 3D modelling were complex and were simplified in the 2D model, rendering the comparison between methods often impractical.

Keywords: POSE, FRACOD2D, fracture mechanics, modelling, back-analysis, in situ
POSE koe suoritettiin maanalaisessa ONKALO® tutkimus laboratoriossa kalliomassan in situ lujustestinä, joka osoitti kalliomassan vaurioituvan Olkiluodossa raon kasvuna litologisilla rajapinnoilla. Tässä raportissa käsitellään POSE kokeen havaintojen takaisinlaskentaa rakomekaanisella FRACOD2D koodilla.

FRACOD2D simulaatiot tähtäisivät laajentamaan 3DEC-takaisinlaskentojen tuloksia, tuottamalla realistisempia ja yksityiskohtaisempaa tietoa havaitusta rakoiluprosessista valituissa 2D-poikkeileikkauksissa. FRACOD2D-lähestymistavassa käytettiin kimmoisia simulaatioita vertailukelpoisista monitoroinnissa ja takaisinlaskennossa havaittuihin jännitystasoihin ja lämpötiloihin pääsemiseksi, jonka jälkeen rakoilun annettiin tapahtua simulaatioissa. Simuloituja vaurioitumisen luonnetta ja laajentumista verratettiin kokonaisvaltaisesti POSE koeen havaintoihin. Riittävän vastaavuuden in situ-kokeen tulosten kanssa saavutettiin, kalliomatriisin ja syntyvien uusien rakojen lujuusominauksia muunneltiin olemassa olevan tiedon epävarmuuden rajoissa.


Uusille, jännityksen aiheuttamille raoille ei kyetty määrittämään syyvyyslujuutta- ja muodonmuutos ominaisuuksia. FRACOD2D takaisinlaskentojen aikana havaittiin, että POSE kokeen in situ havaintoja parhaiten vastaavat mallinnusten lopputulokset saavutettiin asettamalla uusien rakojen lujuu- ja muodonmuutot ominaisuuksiksi 90% ehjän kiven ominaisuuksista. Jännityksistä aiheutuvien rakojen tulisi olla vähemmän kuin kalliossa olevien vanhojen rakojen, mutta kuitenkin heikompa kuin ehjän kiven. Takaisinlaskennossa havaittiin, että mallinnusten lopputulokset olivat herkkiä leikkausvoimasta aiheutuville rakojäykkyydelle (K_jk), joka on vahvasti riippuvainen vallitsevasta jännitystilasta. FRACOD2D ei kykene ottamaan huomioon rakojäykkyyden jännitystilaa riippuvuutta, ja on tärkeää valita mallinns tilannetta vastaava rakojäykkyyksarvo takaisinlaskentoihin.

Vaikka FRACOD2D kärsii kaksidimensionaalisesta takaisinlaskentaongelmasta yksinkertaistuksesta, metodologia pystyy toistamaan havaittuja vaurioita ja vaihtelua esimerkiksi foliaatiokulman vaihtelua, jollaista havaittiin POSE-kokeessa in situ vaiheen aikana. FRACOD2D simulointiin vaadittavissa parametreissa on paljon epävarmuutta johtuen pääosin siitä, että epävarmuuden käytätyt parametrit kyenneet huomioimaan kokeen aikana vahvuus- ja syntyvien uusien rakojen lujuus- ja muodonmuutos ominaisuuksia. 2D-mallissa myös yksinkertaistettiin 3D-mallinnuksesta tuotuja monimutkaisia reuna- ja lähiksi energiamenetelmiä helpottavaksi ja moneessa tapauksessa epäkäytännöllistä.

Avainsanat: POSE, FRACOD2D, rakomekaanikka, takaisinlaskenta, mallinnus, in situ


1 INTRODUCTION

In order to provide information on the large scale rock mass behaviour at the Olkiluoto repository site, Posiva designed the *in situ* Posiva’s Olkiluoto Spalling Experiment (POSE) in 2009 to be conducted in ONKALO® research facility at the depth of -345 m, as shown in Figure 1-1. The ONKALO® research facility is located in Olkiluoto, Western Finland, embedded in complex crystalline bedrock, composed mainly of migmatitic gneiss with massive, coarse-grained pegmatoid granite (PGR) intrusions included. The ONKALO® facility is intersected by brittle deformation zones crossing the facility footprint. The rock mass in Olkiluoto is considered heterogeneous and anisotropic both in the micro and macroscale (Aaltonen *et al.*, 2016) and the prevailing rock type of Veined Gneiss (VGN) is observed to behave according to transversely isotropic material model as a result to conducted laboratory tests (Hakala *et al*. 2005; Jacobsson *et al*. 2016).

![Figure 1-1. The rock mechanics research niche in the ONKALO® facility, where POSE – experiment was conducted. Depicted within an inset that indicates the location of associated experimental holes ONK-EH1, ONK-EH2 and ONK-EH3. (Hakala *et al.*, 2017)](image)

1.1 Posiva’s Spalling Experiment (POSE)

The main objectives of the POSE experiment were to explicitly confirm the governing failure mechanism of Olkiluoto rock mass and to determine the large scale rock mass strength. Taking advantage of the previous knowledge from both the Mine-by experiment (Read, 2004) and the ÅSPÖ pillar stability experiment (Andersson, 2007), the POSE experiment was initially designed as such that spalling would be the damage mechanisms occurring in the tangential stress level of 66 MPa corresponding to 0.57 of the mean value of the conducted Uniaxial Compressive Strength tests (UCS) (Hakala & Valli, 2015). In addition, the third objective of POSE experiment was to clarify the *in situ* stress state in the proposed repository depth interval. The *in situ* POSE Experiment was divided into three distinct Phases. Within the POSE Experiment Phase 1, spalling was induced by
artificially increasing the pre-existing rock stress through excavating a pillar between two deposition holes in the tunnel floor. During the Phase 2 of the POSE Experiment, the prevailing stress state in the excavated pillar was subsequently increased by thermal loading. In the Phase 3 of the POSE experiment, single hole within isotropic PGR intrusion was heated from within for generating an experiment geometry in which the direction of the prevailing *in situ* stress tensor could be established with increased confidence.

The experiment phases were executed in the *in situ* conditions of ONKALO® facility between 2011 and 2013. The three distinct phases of the POSE Experiment were treated as Prediction–Outcome exercises, in which the rock behaviour was always predicted by throughout modelling by various alternative approaches before execution of respective experiment Phase *in situ*. The observed experiment outcome and measurements would later be compared against the predictions. 3D thermomechanical predictions were modelled for all of the three POSE Experiment phases (Hakala & Valli 2013; Hakala & Valli 2015). In addition, fracture mechanics predictions for the first and third Phases were also modelled (Siren, 2011; Siren, 2015b). The experiment layout of different Phases of the POSE experiment is illustrated in Figure 1-2.

**Figure 1-2.** Schematic representation of the POSE – experiment niche in the ONKALO underground facility with the experimental holes and the most important monitoring holes marked. (Siren et al. 2015a).
### 1.2 Back-analyses of POSE Experiment

The back-analyses of the POSE experiment is aimed at identifying a suitable approach for modelling and identifying the failure modes that dominate in the POSE niche and in the ONKALÖ® facility (for the detailed back-analysis plan see Valli et al., 2015). The back-analyses are done principally in two stages (Figure 1-3): preceding a 3-dimensional heterogeneous, anisotropic continuum approach with a few contact surfaces to attempt to replicate the behaviour observed in the experiment continued with a 2-dimensional back-analyses aimed to further investigate the processes to observed damage in more detailed manner and only for selected locations. The 2-dimensional back-analyses are conducted simultaneously using Fracture mechanics approach (FRACOD2D) and discontinuum Particle Flow Code (PFC). The whole experiment including the back-analyses campaign is summarized in the final report of the POSE.

**Figure 1-3.** Simplified back-analysis phases of the POSE experiment, this report describing the fracture mechanics approach in the 2D back-analyses.

This fracture mechanics study uses in several occasions the results of the preceding 3-dimensional back-analyses (Hakala et al., 2018) conducted using 3DEC, a three-dimensional distinct element method (DEM) computer code developed by Itasca Consulting Group (Itasca, 2016). Also the laboratory test results from Jacobsson et al. (2016a,b) and Valli & Hakala (2016) have been used when determining the rock and fracture properties in the fracture mechanics modelling.
2 EXPERIMENT AND CONDITIONS

This chapter describes the relevant outcomes and observations from the POSE Experiment execution for the purposes of back-analysis. Special attention is given for the areas that were included in the back-analyses and particular reasons why the locations were chosen for the back-analysis.

2.1 In situ stress

A thrust faulting stress regime is present at Olkiluoto and over the years it has been shown that the stress field is complex (Valli et al., 2011) and therefore two stress interpretations exist (Posiva, 2013; Hakala et al., 2017). One of the POSE experiment objectives was to confirm the in situ stress state. In this work the more general and continuous in situ stress model I is used as the far-field stress converted through a 3D model to 2D planes stresses (see Chapter 4.1 for the applied stresses). The POSE niche, located below the OL-BFZ020 (-345 m to -408 m), the major in situ stress is aligned with the regional NW–SE orientation of the major principal stress (Zoback, 1992).

2.2 Geology of the experiment niche

The vicinity of the POSE experiment is very competent rock with three main fracture sets interpreted with dip and dip direction 34/156°, 85/270° and 83/342°. The niche is largely composed of veined gneiss (VGN) and pegmatoid granite (PGR), with small inclusions of quartz gneiss (QGN). The border between the two dominant rock types VGN and PGR sometimes consist of mica rich gneiss (MGN) bands. The foliation is oriented on average to 45/163° when measured from combined tunnel and hole mapping data. For illustration of the lithology of the niche, see Figure 2-1.

Figure 2-1. The lithology of the POSE–niche. Mapped fractures are marked in black, veined gneiss in grey in tunnel and in cyan in the experiment holes, while PGR is marked in red in tunnel and in grey in experiment holes. (Valli et al., 2014).
2.3 Experiment Phases 1 & 2 execution

In the first Phase of the POSE Experiment, two experiment holes (ONK-EH1 & ONK-EH2) with a diameter of \( \varnothing 1.524 \) m were bored in succession close to each other, thus forming a pillar in between the two holes. Before the boring of the second experiment hole ONK-EH2, monitoring equipment was installed within the first experiment hole ONK-EH1. The emerging pillar between two experimental holes had a thickness of \( \sim 0.87 \) m and it was monitored during the boring of the experiment hole ONK-EH2 from the adjacent experiment hole ONK-EH1. The pillar in between the two experiment holes was designed to form a local concentration in the secondary stress state, thus inducing failure in the rock mass by the stress concentration exceeding the predicted rock mass strength. In the design of the experiment, the presumption of the stress state was used.

During the second Phase of the POSE Experiment, the stress state in the pillar was further increased by thermal loading. In total, four heaters were installed on the opposite sides of the pillar between the two experiment holes (ONK-EH1 & ONK-EH2). Heating was applied for two months, while the damaging process in the pillar was monitored. In addition to the instrumentation installed during the first Phase, the second experiment hole ONK-EH2 was instrumented with a pressure meter and filled with sand to create a minor support pressure on the pillar.

![Figure 2-2. On left cross-section of the tunnel and experiment hole heater and on right visualization of the microseismic monitoring setup around experiment holes in Phases 1 & 2.](image-url)
The use of filling in the second phase of the POSE Experiment for preventing spalling was based on observations obtained from similar tests conducted at the Atomic Energy of Canada Limited (AECL) Underground Research Laboratory (URL) and at the Äspö Hard Rock Laboratory (HRL), where confinement was used in differing forms (Andersson, 2007; Glamheden et al., 2010; Read et al., 1998). The first and second experiment phases are documented in detail for the fracture mechanics prediction in Siren (2011), for the 3DEC predictions in Hakala & Valli (2014), for the execution of the experiment in Johansson et al. (2014), for the proceeding laboratory testing in Jacobsson et al. (2016a,b), in Behrestaghi et al. (2016, 2018) and in Valli & Hakala (2016), and for the 3DEC back-analysis in Hakala et al. (2018).
2.4 Experiment Phase 3 execution

The third Phase (Single hole heating damage test) of the POSE experiment was conducted in the third experimental hole (ONK-EH3), located at the northern end of the niche. A thermomechanical increase in the local stress state was caused by heating the hole internally, using 8 heaters situated vertically and concentrically within the hole. The third Phase of the POSE experiment, mainly located in pegmatoid granite, aimed to study the damage behaviour, and to confirm the state of in situ stress at the -345 m depth level, and to act as a Prediction–Outcome (P–O) exercise. The third experiment phase, with no preconditions of the direction of the major horizontal stress (opposite to Phases 1 & 2 where pillar was aligned to maximize the stresses), the experiment design was considered especially robust to confirm the state of in situ stress by observing the direction of the failure. See Figure 2-4 for visualization of the experiment setup in POSE niche.

Figure 2-4. Visualization of the heater, temperature monitoring holes and AE monitoring setup around the experiment hole in Phase 3.

In the experiment the hole was instrumented, filled with aluminium oxide to provide good thermal conductivity (see Figure 2-5) and heated for three months from the inside. The experiment hole was instrumented with strain gauges and temperature sensors at several levels and locations, however strain gauges were damaged during the heating. The rock mass around the experimental hole was instrumented by means of five small boreholes with temperature sensors and four boreholes with a 24 channel acoustic emission (AE) system. The acoustic emission system constantly monitored the experiment with ultrasonic velocity surveys conducted each night.
The third experiment phase are documented in detail for the fracture mechanics prediction in Siren (2015b), 3DEC predictions in Hakala & Valli (2013), for the execution of the experiment in Valli et al. (2014), for the acoustic emission monitoring in Reyes-Montes et al. (2014), for the proceeding laboratory testing in Jacobsson et al. (2016a,b), in Behrestaghi et al. (2016, 2018) and in Valli & Hakala (2016), and for the 3DEC-back-analysis in Hakala et al. (2018).

2.5 Experiment observations and models

Phase 1 resulted in minimal damage with two sub-vertical fractures initiating in ONK-EH1 within the first four weeks of boring and one in ONK-EH2 after boring observed after four months. The first fractures were localized in mica rich layers and rock type contacts which were known to be relatively weak. The fracture growth was followed while the boring of the second experiment hole (ONK-EH2) progressed (see Figure 2-6). The third, sub-vertical fracture was observed in the wall of ONK-EH2 after boring had been completed.

Figure 2-5. Heating elements, aluminum oxide, partly visible temperature gauge wires and insulation material in ONK-EH3 at the beginning of heating (Valli et al., 2014).
In Phase 2 initiated fractures propagated further following near the rock type contacts and several new were initiated. The damage occurs from a depth of 1 meter to below 6 meters, and to conclude the damage was largely controlled by lithological features such as VGN foliation and rock type contacts. Most of the damage was localized in the northern and southern sides of the holes. In the pegmatoid granite also a region of visually observable micro-fracturing (whiter areas near shear failure) can be observed in Figure 2-7 thus indicating partial stress relaxation due to the shearing of the second fracture.

The caused damage extended maximum to ca. 100 mm depth (in radial direction) from the hole surface based on limited scaling and pointwise measurements of water intake in small drillholes (Johansson et al., 2014). A presentative depth (~4.5 m) with failure in both holes and generally representative failure directions for the experiment phase was selected as the modelling plane used in the fracture mechanics back-analysis. See Figure 2-8 for the observed damage and the selected modelling plane.
Figure 2-7. Observations from the POSE experiment Phases 1 & 2 from experimental hole ONK-EH1. A structurally controlled crack growth was detected as presented with red dashed line, occurring sometime after the boring of the hole, but before boring of the secondary experimental hole ONK-EH2. Increased initiation of micro-fracturing was detected from the nearby pegmatoid granite after the pillar stability experiment e.g. Phase 2.

Figure 2-8. Damage after scaling that occurred after Phase 2 of the POSE experiment in ONK-EH1 and ONK-EH2, viewed roughly from the south. Damage is coloured according to depth, measured from the top of the concrete slab. Crack damage is illustrated as black lines. The selected modelling plane is illustrated with red colour. (modified Valli & Hakala, 2018)
Phase 3 damage was minimal and concentrating at the bottom of the experiment hole in a contact between mica-rich gneiss and pegmatoid granite (Figure 2-9). In the damage location, the foliation is pronounced, and first observation of the damage was observed already after 18 months after boring, further increasing during the heating. Four fractures near the top of the hole were mapped after boring ONK-EH3. The acoustic emission monitoring showed higher event density in the upper parts of the experiment hole, namely in the pegmatoid granite, with no clear clustering of the events aligned with the direction of the horizontal stresses (Figure 2-10).

As in previous phases instead of spalling type damage, the shear and dilation of mica rich layers was evident. In conclusion the failure type is structurally controlled. As the pegmatoid granite suffered minimum damage, a -4.0 m level in pegmatoid granite was selected as a modelling plane together with the plane at the depth of -5.5 m, where fracturing initiated after boring of the hole and further continued during the experiment. See Figure 2-11 for the observed damage and the selected modelling plane.

*Figure 2-9. Lithology at the damage location in ONK-EH3 at -5.0 to -5.5 m depth to North.*
Figure 2-10. On left the side view looking east and on right the plan view of the acoustic emission event density grid spacing around ONK-EH3 hole. Event density for the complete monitoring period calculated as the number of AE events per 0.25m x 0.25m x 10m cell. (modified from Valli et al., 2014)

Figure 2-11. The damage traces after heating mapped on hole surface (on left) with color indicators of the vertical depth on right with selected modelling planes illustrated in red (modified after Valli & Hakala, 2018).
3 MODELLING METHODOLOGY

FRACOD2D is a two-dimensional code for the modelling of brittle failure in rocks based on the principles of the Boundary Element Method (BEM), utilizing the Displacement Discontinuity Method (DDM) developed by Crouch (1976) for the mathematical expression of discontinuity with opposing surfaces in two-dimensional plane of infinite elastic medium. The DDM allows discontinuities with opposing surfaces being expressed as one element, thus behaviour such as sliding and opening of the discontinuity can be explicitly expressed by one single DDM element. The development and capabilities of the code, including verification cases, are well documented in the literature such as Shen et al. (2014).

The FRACOD2D simulations were aimed to act as an extension to the conducted 3DEC back-analyses, by providing more realistic and detailed information of the observed fracturing process in the selected 2D cross-sections with an alternative fracture mechanics approach in contrast to 3DEC. In order to achieve this, the same exact stress path in the selected cross-sections between the different simulation tools had to be preserved while the material model, and the corresponding material response against increases in the stress was different. Consequently, the methodology in the FRACOD2D approach involved elastic simulations to achieve consistent stress levels and temperatures equivalent to the monitored or back-analysed (3DEC) values, after which fracture initiation and growth was implemented within the simulations. The overall nature and extent of the simulated damage around the experimental holes was evaluated against the observed location and extent of accumulated damage observed during POSE execution. The strength properties for the rock matrix and developing fresh fractures were adjusted, within the limit of associated uncertainties in the properties given the available data, until a sufficient match against in situ observations was achieved.
3.1 Geometrical representation

The cross-section locations for back-analyses were selected primarily based on damage observations, and secondarily on the results of the 3DEC back-analyses: Depth of -4.5 m (see Figure 2-8) for Phases 1 & 2 corresponding to the maximum achieved tangential stresses, while in Phase 3 practically no damage was observed at depth level of -4.0 m but level -5.5 m (see Figure 2-11) developed damage already prior to heating. These depth levels were also contrasting in nature: 3DEC results either indicated deformation in locations where damage was observed during the POSE execution in situ, or 3DEC simulation results did not indicate failure while failure was observed during the POSE execution.
Figure 3-2. Geological cross-sections from 3DEC for selected modelling planes.

Due to the numerical modelling restrictions in FRACOD2D, the analysed cross-sections had to be simplified to consist solely of single material. As the hole filling did not have any significant effect or impose any significant support pressure on the hole wall in Phase 2 of the POSE experiment, it was excluded from the simulation for simplicity. The selection of material for each cross-section was based on the prevailing rock type obtained from the geological model applied in 3DEC (see Figure 3-2), such that the cross-section associated with Phase 1 & 2 and the -5.5 m cross-section associated with Phase 3 were chosen to be represented by VGN, while the cross-section of -4.0 m associated with Phase 3 was chosen to be represented by PGR.

VGN was perceived as an anisotropic rock material, presented in the FRACOD2D simulations in the form of directional anisotropy. Anisotropy consisted of an implicit systematic angle of weakness that was based on the generally interpreted dip and dip direction (46°/164°) of foliation obtained from geological mapping. PGR on the contrary was perceived as an isotropic material and presented as such in the simulations, as interpreted from the available laboratory testing data (Behrestaghi et al., 2016). The cross-
section for the experiment phases 1 & 2 is presented in Figure 3-3 and the cross-sections for the experiment phase 3 in Figure 3-4.

**Figure 3-3.** FRACOD2D model geometry, consisting of single anisotropic VGN rock type for back calculation of POSE Experiment phases 1 & 2. Gray lines in the material VGN illustrate the direction of foliation in the models, acting as an implicit directional weakness in the anisotropic material presentation.

**Figure 3-4.** FRACOD2D model geometry, consisting of isotropic PGR at -4.0 m depth (on left) and anisotropic VGN at -5.5 m depth (on right) for back calculation of POSE Experiment phase 3. Gray lines in the material VGN illustrate the direction of foliation in the models, acting as an implicit directional weakness in the anisotropic material presentation.
3.2 Stress state representation

Besides the geological model, the stress state in the 2D models was compared against equivalent cross-sections in 3D models, in order to confirm that the models do model the same stress path as implemented in the 3D models, so that the interface between 3D and 2D models is as small as meaningfully possible. The 2D-sections of a 3D-model are plotted from 3D-elements of the model as shown in Figure 3-6 and Figure 3-5 for each level back-analysed using 2D-model.

![ONK-EH1&2 -4.5 m](image)

**Figure 3-5.** 2D-section from a 3D-model created using 3DEC (Itasca, 2013) plotted from 3D-elements for -4.5 m level in ONK-EH1 & ONK-EH2. Red colour indicates the elements from 3D-model. (From model by Valli & Hakala, 2018).

a) ONK-EH3 -4.0 m  
b) ONK-EH3 -5.5 m

![2D-sections](image)

**Figure 3-6.** 2D-sections from a 3D-model created using 3DEC (Itasca, 2013) plotted from 3D-elements for a) -4 m level and b) -5.5 m level in ONK-EH3. Blue colour indicates the elements from 3D-model and red colour the extraction plane. (From models by Valli & Hakala, 2018).

3.3 Elastic anisotropy

Anisotropy in rock material is composed of both deformation- and strength anisotropy. However, the handling of anisotropy in FRACOD2D can be divided into three distinct parts, as the strength anisotropy consists of two different parts itself in addition to deformation anisotropy. The deformation anisotropy is considered as anisotropy in the elastic properties, while the strength anisotropy is divided into anisotropy in fracture initiation and fracture propagation separately.
The consideration of deformation anisotropy required modification on the fundamentals of how stress and displacement calculation were conducted in the DDM solution applied in FRACOD2D, as the calculation procedure was developed for isotropic medium. The analytical expression of the anisotropy solution, along with the development and verification cases of the deformation anisotropy in FRACOD2D is described in the article of Shen et al. (2016). However, no thermo-elastic solution for stress and displacement of a discontinuity displacement in an anisotropic medium could be obtained from existing literature, and the derivation was found difficult. Hence the thermal stress in FRACOD2D is handled through isotropic solution while the mechanical stresses can be calculated through anisotropic solution.

3.4 Fracture initiation

It is important to distinguish between the terminology on fracture initiation and propagation in the context of this report before advancing on presenting the modelling approach of the corresponding processes for anisotropic medium. In literature, such as Bieniawski (1967), the term crack initiation is often used to describe the process in which one or more cracks are formed in a material free from any other flaws. In this report, the same process is referred as fracture initiation describing the process when new DDM fracture elements are introduced into the intact flawless rock mass after the material strength has been exceeded locally.

When modelling FRACOD2D, after the material strength is reached in either tension or shear new DDM fracture elements are added to the corresponding location with orientation in relation to the prevailing stress component exceeding the strength criteria (Shen, 2017). After the material strength is exceeded and fracture elements have been added in the corresponding locations, the deformation and propagation of these DDM fracture elements will cause the relaxation of the stress field until a new equilibrium or collapse of the material is reached.

3.4.1 Fracture initiation in isotropic rock

FRACOD2D considers the rock mass as flawless medium, without any pre-existing flaws if not explicitly implemented within the model before the material strength has been exceeded. Fracture initiation, as introduction of new DDM fracture elements, occurs when the 2D stress state reaches its critical value in either compression or tension, and the introduced fractures represent a localized failure of the otherwise flawless rock. Within FRACOD2D, the Mohr–Coulomb failure criteria is applied to determine the compressive strength of the rock as follows:

\[ \sigma_1 = \frac{2c \cos \phi + \sigma_3 (1 + \sin \phi)}{1 - \sin \phi} \]  

(1)

where \( \sigma_1 \) is the maximum principal stress, \( \sigma_3 \) is the minimum principal stress, \( \phi \) is the friction angle and \( c \) is the cohesion.

Similarly, the tensile strength of the rock is determined as follows
\[ \sigma_1 = \sigma_t \]  

(2)

where \( \sigma_t \) is the tensile strength of the rock. The direction of the tensile failure occurs perpendicular to the direction \( \sigma_1 \) e.g. in the plane of \( \sigma_3 \).

**3.4.2 Fracture initiation in anisotropic rock**

The abovementioned approach is suitable for isotropic rock conditions, in which no directional dependency on the rock strength exists. However, for anisotropic rock the strength is direction dependent and has to be presented as a function of the orientation angle \( \beta \), thus the compressive and tensile strength parameters are presented as following (Shen et al., 2015).

\[
\varphi = \varphi(\beta) \tag{3}
\]

\[
c = c(\beta) \tag{4}
\]

\[
\sigma_t = \sigma_t(\beta) \tag{5}
\]

For determining the direction of failure plane for anisotropic rock, the stress and strength relation of an arbitrary plane A-B with an angle \( \beta \) needs to be considered as shown in Figure 3-7 below.

![Figure 3-7. Illustration of arbitrary plane A-B for determining the shear failure plane in anisotropic rock. Reproduced and modified from Shen et al. (2015).](image-url)
For determining compressional failure, the normal and shear stresses on an arbitrary plane A-B with an angle $\beta$ can be calculated as following.

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos(2\beta)$$

$$\sigma_s = \frac{\sigma_1 - \sigma_3}{2} \sin(2\beta)$$

The shear strength of the corresponding plane A-B with an angle $\beta$ can be assessed through the conventional Mohr–Coulomb envelope, combining the directional dependent strength properties as follows:

$$S = c(\beta) + \sigma_n \tan \varphi(\beta) = \left[\frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\beta\right] \tan \varphi(\beta) + c(\beta)$$

The indicator of failure can be determined by shear failure indicator $F_s$ determined for the corresponding plane A-B as follow:

$$F_s = \frac{\sigma_s}{S} = \frac{(\sigma_1 - \sigma_3) \sin 2\beta}{[\sigma_1 + \sigma_3 + (\sigma_1 - \sigma_3) \cos 2\beta] \tan \varphi(\beta) + 2c(\beta)}$$

The shear failure will occur in the plane where $F_s$ obtains its maximum value, however reaching at least the value of 1.0 thus representing a scenario where shear stress exceeds the directional shear strength.

However, $F_s$ has often four peak values in four different directions depending on the anisotropic rock strength properties (Shen et al. 2015). To be able to determine the actual plane of shear failure, the shear failure indicator $F_s$ must satisfy the following rules so that only the maximum $F_s$ are selected as the planes of shear failure.

$$\frac{dF_s}{d\beta} = 0$$

$$\frac{d^2F_s}{d\beta^2} < 0$$

$$F_s \geq 1.0$$

Similar approach can be applied for determining the direction of tensile failure, through introducing tensile failure indicator $F_t$. For the assessment of tensile failure, the ratio of tensile strength and tensile stress in a principal stress state can be presented as follows:

$$F_t = \frac{\sigma_n}{\sigma_t} + \frac{(\sigma_1 + \sigma_3) + (\sigma_1 - \sigma_3) \cos 2\beta}{2\sigma_t}$$
It should be noted that the development of modelling approach for determining the fracture initiation and propagation in anisotropic medium is described more in detail in the works of Shen et al. (2014) and Shen et al. (2015), including verification cases.

3.5 Fracture propagation

Fracture propagation is defined by Bieniawski (1967) as failure process during which the pre-existing cracks start to extend or grow subsequent to “crack initiation”. In this report, fracture propagation represents the process of fracture growth from existing fracture tip to a new position, irrespective of the loading configuration (Shen et al. 2014). The process of fracture propagation is confined to the tips of pre-existing fractures, formed during fracture initiation. Consequently, fracture propagation can only occur subsequent to fracture initiation. The combined process of fracture initiation and subsequent propagation may ultimately lead to the rupture of the material, when for example a rock specimen disintegrates into two or more pieces (Rinne, 2008).

3.5.1 Fracture propagation in isotropic rock

Within Fracod2D, the fracture propagation is determined by using a modified version of the original G-criterion based on the work of Griffith (1921). The modified G-criterion, named as the F-criterion, was proposed by Shen and Stephansson (1993) as it can consider the Mode I and Mode II fracture propagation simultaneously. In the F-criterion, the total strain energy release rate (G) of the material is divided into pure Mode I (tension) and Mode II (shear) components as follows:

\[ F(\theta) = \frac{G_I(\theta)}{G_{Ic}} + \frac{G_{II}(\theta)}{G_{IIc}} \]

where \( G_I \) and \( G_{II} \) are the strain energy release rates in Mode I and II, correspondingly. The F-criterion is used to assess the likelihood and direction of possible fracture growth. Fracture element tip within the FRACOD2D model is determined to propagate when the F-value exceeds the limiting value of 1.0, thus sufficient total amount of strain energy within the fracture tip is released for fracture growth to occur, as follows:

\[ F(\theta)|_{\theta=\theta_o} = 1.0 \]

During the fracture propagation process, after the F-value has reached the limiting value of 1.0, fractures exceeding the F-criterion are considered to propagate towards the direction \( \theta \) where the maximum amount of strain energy is released as follows:

\[ F(\theta)|_{\theta=\theta_o} = max \]

As the individual strain energy components \( G_I \) and \( G_{II} \) of the F-criterion are normalized by their critical limits, the critical strain energy release rate \( G_{Ic} \) for tension and \( G_{IIc} \) for pure shear, the overall limiting value of 1.0 for fracture growth threshold can be achieved with lower strain energy release than either pure Mode I (tension) or Mode II (shear)
would allow. In nature, where complex loading scenarios consisting of both tension and shear simultaneously prevail, the fracture growth process alters between Modes I and II during ongoing fracture propagation. Consequently, the normalization of the F-criterion is used to capture this change in the fracture growth process during complex mixed-mode loading scenarios.

The strain energy release rates for pure Mode I and Mode II, noted as \( G_I \) and \( G_{II} \) respectively, can be presented as stress intensity factors \( K_I \) and \( K_{II} \) through the work of Irwin (1957). The relation between the strain energy release rates \( G_I \), \( G_{II} \) and the stress intensity factors \( K_I \), \( K_{II} \) for the Modes I and II are presented as follows:

\[
K_I = \frac{G_I}{E'} \tag{17}
\]

\[
K_{II} = \frac{G_{II}}{E'} \tag{18}
\]

where \( E' \) is the effective Young’s Modulus for either plane stress or plane strain conditions.

The critical values of the corresponding Mode I & II stress intensity factors, called the fracture toughness and noted as \( K_{Ic} \) and \( K_{IIc} \) for the respective modes of loading, can be considered as material parameters. Thus the F-criterion can be described in terms of fracture toughness \( (K_{Ic}, K_{IIc}) \) instead of strain energy release parameters \( (G_{Ic}, G_{IIc}) \), if necessary. The fracture toughness of Modes I and II are measurable by laboratory testing means such as the ISRM suggested chevron bend testing for determining \( K_{Ic} \), and punch-through shear test for determining \( K_{IIc} \) (Backers et al. 2002; Ulusay & Hudson 2007).

### 3.5.2 Fracture propagation in anisotropic medium

FRACOD2D applies the F-criterion, presented in Equation (14), for determining the likelihood and the direction of fracture propagation. Anisotropy of fracture propagation can be taken into account by applying a directional dependent variable \( \beta \), as in the case for determining fracture initiation, for the fracture toughness \( (K_{Ic}, K_{IIc}) \) as following.

\[
K_{Ic} = K_{Ic}(\beta) \tag{19}
\]

\[
K_{IIc} = K_{IIc}(\beta) \tag{20}
\]

When considering anisotropic material, the F-criterion needs to be assessed with the directional dependency \( \beta \) to reflect the directional preference of fracture propagation in anisotropic medium. Consequently, the F-criterion is re-written, in terms of fracture toughness \( (K_{Ic}, K_{IIc}) \) using the relation of Irwin (1957) instead of strain energy release rates \( (G_{Ic}, G_{IIc}) \), as following:
The direction where the F-value obtains its maximum value is considered as the potential direction for fracture propagation. During the iteration process of determining fracture propagation, all directions with the angle interval of 1° with its respective fracture toughness are examined in order to define the direction of possible fracture growth. An example of rock strength anisotropy for a synthetic rock specimen from Shen et al. (2015) is illustrated in Figure 3-8 and Figure 3-9.
3.6 Thermo-mechanical coupling

The constitutive thermo-elastic equations to which FRACOD2D is based on can be found for example in Timoshenko & Goodier (1970). The thermo-elasticity is divided in to constitutive equations of deviatoric and volumetric responses of which latter contains the thermal coupling terms. The thermal coupling is implemented using indirect method which uses fictitious heat sources. The indirect method suites well the Displacement Discontinuity (DD) method used in FRACOD2D.

The coupling is implemented so that the thermal solution is calculated before the mechanical equations. The thermal stresses are calculated for each boundary element and added into boundary stresses. Finally the stresses and displacements are calculated for the internal points with added thermal stresses and displacements.

The diffusivity is calculated in FRACOD2D from the thermal conductivity ($\lambda$), density $\rho$ and specific heat capacity $c_p$ as follows:

$$\kappa = \frac{\lambda}{\rho c_p}$$  \hfill (22)

3.7 Phase 2 temperature boundary conditions

In the back-analysis models corresponding to the POSE experiment phase 2, the applied heating pattern of the in situ experiment was followed as closely as possible in the model construction. Due to the modelling simplifications related to modelling of the actual three-dimensional heater holes of line source type as point source in a 2D plane, the modelled heating power in 2D environment was needed to be decreased to a portion of the applied total heating power. As a result, the heating power used in the 2D back calculation models are approximately 9% of the applied total heating power during the three experiment phases (Table 3-1).

In the back-analysis models, the heat flux at experiment hole surface was assigned to approximately fit the measured temperatures data (Johansson et al., 2014). The average of measured temperature from depths of -3.6 m and -6.2 m and modelled temperature are shown in Figure 3-10 for the second phase of the experiment. Note that with heaters of 6 m length, the temperature decreases rapidly after -6.0 meters. During the second phase of POSE experiment one heater failed and to retain symmetry a pair of heaters were turned off and power increased in other two heaters, taken in account in the modelling (see Figure 5-8 later in the results).
Table 3-1. The recorded heating power at the experiment, calibrated heating power at 3DEC back-analysis model and effective heating power assigned in the fracture mechanics model (in 20-day interval). Note that at later stage only two heaters were used.

<table>
<thead>
<tr>
<th>Date</th>
<th>Experiment</th>
<th>3DEC heating</th>
<th>Fraco effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 March 2011</td>
<td>4 x 400 W</td>
<td>4 x 500 W</td>
<td>0 W</td>
</tr>
<tr>
<td>29 March 2011</td>
<td>4 x 1000 W</td>
<td>4 x 1000 W</td>
<td></td>
</tr>
<tr>
<td>30 March 2011</td>
<td>4 x 1500 W</td>
<td>4 x 1500 W</td>
<td></td>
</tr>
<tr>
<td>31 March 2011</td>
<td>4 x 2000 W</td>
<td>4 x 2000 W</td>
<td></td>
</tr>
<tr>
<td>19 April 2011</td>
<td></td>
<td></td>
<td>4 x 184 W</td>
</tr>
<tr>
<td>6 May 2011</td>
<td>4 x 1300 W</td>
<td>4 x 1300 W</td>
<td>4 x 204 W</td>
</tr>
<tr>
<td>9 May 2011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 May 2011</td>
<td>2 x 2600 W</td>
<td>2 x 2600 W</td>
<td>2 x 251 W</td>
</tr>
<tr>
<td>29 May 2011</td>
<td>0 W</td>
<td>0 W</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-10. Average of the measured temperature -3.6 m and -6.2 m depths in ONK-EH1 and ONK-EH2 holes during the heating experiment and the calibrated temperatures for corresponding locations. The T12 and T22 are strain gauge rosettes at pillar and T11, T13, T21 and T23 rosettes 90° from the pillar line.
3.8 Phase 3 temperature boundary conditions

The experiment phase 3 boundary conditions are assigned as temperature on the hole surface as measured from the experiment, reducing the model to exclude the hole filling material and heaters within. The temperatures of the measured and simulated are illustrated in Figure 3-11. Note that the temperatures assigned for -4.0 m level are slightly higher than measured from -4.5 m level.

![Figure 3-11. Measured temperature at different depths in ONK-EH3 during the heating experiment and the constant temperature boundary condition used for -4.0 m and -5.5 m models.](image-url)
4 FRACOD2D MODELLING PARAMETERS

In FRACOD2D the modelling process differentiates from conventional approach. The fracturing is a two-fold process with new fractures initiating from excavation boundaries or within the rock mass (not used in the models described in this report) and fracture propagation of the initiated, or existing fractures. The chapter describes the parameters used in the modelling in the order they are in use as following:

1. *The applied stress state* prevailing in the experiment location;
2. *The thermal properties*, controlling the induced stress during the heating of the POSE Phase 2 & 3;
3. *Rock matrix properties*, controlling the deformability of the rock and followed by, if matrix strength is exceeded, initiation of fractures;
4. *Strength and deformation properties of newly initiated fresh fractures*;
5. *Fracture toughness properties*, controlling if exceeded the further propagation of the initiated fractures.

4.1 Stress state applied in the 2D back-analyses of POSE

The prevailing *in situ* stress state in the experiment location is a crucial input parameter controlling pre-existing loading of the rock mass within the model. FRACOD2D is based on the assumption of plane strain conditions, e.g. the out of plane strain $\varepsilon_z$ is assumed to be zero. The resulting stress state to be applied in the FRACOD2D models is therefore constrained to consist of the in-plane stress components, while the out-of-plane shear $\tau_{xz}$ & $\tau_{yz}$ components, in addition to out-of-plane compressive $\sigma_z$ stress, are ignored in the fracture mechanics back-analysis models.

The stress state applied in the back-analysis models of POSE was based on the *in situ* stress model I of the Olkiluodo Island (Posiva, 2013). The *in situ* stress model I of the Olkiluoto Island was used during the 3D back-analysis of the POSE by Hakala et al. (2018), from which an equivalent 2D stress state consisting of $(\sigma_x, \sigma_y, \tau_{xy})$ components was derived for the selected cross-sections associated with the back-analysis of Phases 1, 2 and 3. Keeping in mind the 2D stress state is already a crude simplification of the 3D stress state, only two different levels were enforced in the 2D models. The applied two dimensional stress state in the fracture mechanics back-analysis models is presented in Table 4-1, at which depth sections -2.2 m and -4.5 m are associated with POSE Phases 1 & 2, while -4.0 m and -5.5 m & -5.5 m are associated with Phase 3. See Figure 4-1 for an illustrative comparison of the stress states for -5.5 m model in ONK-EH3. The plane stresses for principal stress components is shown in Appendix 3.

**Table 4-1. In situ plane stress in tensor form at -345m depth based on in situ stress model I (Posiva, 2013). Direction of y-axis is towards North.**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>$\sigma_x$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\tau_{xy}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.0 m</td>
<td>22.5 MPa</td>
<td>13.5 MPa</td>
<td>-2.2 MPa</td>
</tr>
<tr>
<td>-4.5 m &amp; -5.5 m</td>
<td>21.2 MPa</td>
<td>15.7 MPa</td>
<td>-2.7 MPa</td>
</tr>
</tbody>
</table>
Figure 4-1. Comparison of major principal stress in post-exciavation state for the POSE Phase 3 back-analyses at depth level of -5.5 m in 3DEC (on left) and FRACOD2D simulations (on right). Stress concentration observed at distance from the experiment hole periphery in the 3DEC model (left) occurs to lithological contact, absent in the FRACOD2D model (right) simplification.

4.2 Thermal properties

In the heating experiments, the stress state is increased by thermally induced stresses caused by thermal expansion of the rock mass. Thermal properties for specimen obtained from POSE niche were determined by laboratory testing, and reported in Kukkonen (2015). The thermal properties applied for both the VGN and PGR rock types in the FRACOD2D back-analyses of the POSE are presented in Table 4-2. Thermal properties of the rock have been noted to be dependent on the prevailing temperature, and during the execution of the Phase 2 & 3 of the POSE experiment, the temperature field of the rock mass increased from the initial temperature of 13°C to up to 70 °C as a part of the experiment execution. However, FRACOD2D is not able to take into account the temperature dependency on the thermal properties. Consequently, the measured properties at the temperature of 25 °C were used as a part of the POSE back calculation, while data exists for 12°C, 25°C, 60 °C and 100 °C in Kukkonen (2015).

Table 4-2. Thermal properties used in modelling. Diffusivity given for reference only.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VGN Thermal properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, $\lambda$ (W/m·K)</td>
<td>2.74</td>
<td>Kukkonen (2015)</td>
</tr>
<tr>
<td>Specific heat capacity, $c_p$ (J/kg·K)</td>
<td>732</td>
<td></td>
</tr>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>2740</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivity, $\kappa$ (m$^2$/s)</td>
<td>(1.31E-06)</td>
<td></td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion, $\alpha$ (K$^{-1}$)</td>
<td>1.06E-05</td>
<td></td>
</tr>
<tr>
<td><strong>PGR Thermal properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, $\lambda$ (W/m·K)</td>
<td>3.00</td>
<td>Kukkonen (2015)</td>
</tr>
<tr>
<td>Specific heat capacity, $c_p$ (J/kg·K)</td>
<td>691</td>
<td></td>
</tr>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>2635</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivity, $\kappa$ (m$^2$/s)</td>
<td>(1.62E-06)</td>
<td></td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion, $\alpha$ (K$^{-1}$)</td>
<td>7.2E-06</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Rock matrix properties

The in situ stress state and induced stresses cause the deformation of the intact rock medium (intact rock matrix) and fracture initiation process after the applied level of stress at the excavation boundary exceeds the rock matrix strength.

Deformation properties of the rock matrix

The set of parametrization describing the deformability and strength of the intact rock matrix in the FRACOD2D back-analyses of POSE was based on the laboratory testing results of intact rock samples by Jacobsson et al. (2016b), supplemented by the observations of the rock mass behaviour as a result of the 3DEC back-analyses by Hakala et al. (2018). The deformation properties (E, ν) for the anisotropic description of VGN, both in the direction of plane of foliation and perpendicular to the plane of foliation, as illustrated in Figure 4-2. The deformation properties for isotropic description of PGR were based on the laboratory test results of Jacobsson et al. (2016b). The derived properties for the rock matrix deformability for both VGN and PGR are described in Table 4-3 and in Table 4-4.

![Figure 4-2. Definition for the dip of foliation angle β for determination of rock matrix properties for the anisotropic VGN. On the left, the vertical arrows indicate the direction of plane of foliation, while on the right the vertical arrows indicate a plane parallel to the plane of foliation.](image)

Rock matrix strength

The equivalent length of initiating fractures in the models was set to the size of 10 mm. Consequently, the Mohr–Coulomb parameters were determined using normal stresses acting near the excavation surface, ranging from 0 MPa to 5 MPa, with an average value of 2.5 MPa used when determining the appropriate friction angle and cohesion.

During the 3DEC back-analyses of the POSE described by Hakala et al. (2018), it was observed that the best fit between simulated and observed damage was reached with assuming the strength VGN in to the plane of foliation being 25 % weaker than estimated from laboratory testing results (Valli & Hakala, 2016), while in the 3DEC back-analyses the VGN matrix perpendicular to the plane of foliation was assigned to be 25 % stronger than estimated. Partly similar in FRACOD2D, the plane of foliation was considered to be
being 25% weaker than estimated, while the VGN matrix was left to the estimated values. The difference of approaches is however not very significant since the failure is always initiated where the driving stress is highest compared to the rock strength. Thus, the weakest direction dominates the failure as long as there is a clear difference in strength in different directions.

FRACOD2D considers anisotropy as an implicit directional weakness, and thus by applying the analogue derived from the 3DEC back-analyses, the strength properties of the VGN were defined both, for the implicit description of the foliation planes with the friction angle of 42° and cohesion of 15.3 MPa, corresponding to a rock strength of 68.1 MPa (using Eq. 1), and for the direction parallel of the foliation planes with the same friction angle but with cohesion of 28.2 MPa, corresponding to a rock strength of 130.4 MPa. The FRACOD2D applies these strengths through elliptical variation from 0° to 90° as illustrated in Figure 4-3 (Shen et al., 2015).

PGR was considered isotropic with a friction angle of 42° and a cohesion of 22.8 MPa, corresponding to a rock strength of 102.5 MPa. The tensile strengths applied for the VGN plane, VGN matrix and PGR matrix were the estimated strengths, 7.9 MPa, 15.1 MPa and 6.5 MPa, respectively (Valli & Hakala, 2016). The Mohr—Coulomb fits, and the parameter derivation for the VGN and PGR properties are shown in detail in Appendix 1.
Table 4-3. Mechanical properties of anisotropic VGN applied in FRACOD2D back-analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Explanation and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGN Transversely isotropic elastic parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E$ (GPa)</td>
<td>68.6</td>
<td>Based on Jacobsson et al. (2016b)</td>
</tr>
<tr>
<td>$E'$ (GPa)</td>
<td>56.1</td>
<td></td>
</tr>
<tr>
<td>$\nu$ (-)</td>
<td>0.215</td>
<td></td>
</tr>
<tr>
<td>$\nu'$ (-)</td>
<td>0.240</td>
<td></td>
</tr>
<tr>
<td>$G$ (GPa)</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>VGN Mechanical parameters parallel to plane of anisotropy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction angle, $\phi$ (deg)</td>
<td>42</td>
<td>-25 % from Hoek–Brown VGN plane properties by Valli &amp; Hakala (2016). See Appendix 1 for Mohr–Coulomb fit.</td>
</tr>
<tr>
<td>Cohesion, $c$ (MPa)</td>
<td>15.3</td>
<td>Lab. data, Valli &amp; Hakala (2016)</td>
</tr>
<tr>
<td>Tensile strength, $\sigma_t$ (MPa)</td>
<td>7.9</td>
<td>Lab. data, Valli &amp; Hakala (2016)</td>
</tr>
<tr>
<td>VGN Mechanical Parameters perpendicular plane of anisotropy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction angle, $\phi'$ (deg)</td>
<td>42</td>
<td>From HB VGN matrix properties by Valli &amp; Hakala et al. (2016). See Appendix 1 for Mohr–Coulomb fit.</td>
</tr>
<tr>
<td>Cohesion, $c$ (MPa)</td>
<td>28.2</td>
<td></td>
</tr>
<tr>
<td>Tensile strength, $\sigma_t$ (MPa)</td>
<td>15.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-4. Mechanical properties of isotropic PGR applied in FRACOD2D back-analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$ (GPa)</td>
<td>60</td>
<td>Valli &amp; Hakala (2016)</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$ (-)</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Friction angle, $\phi$ (deg)</td>
<td>42</td>
<td>Converted after Valli &amp; Hakala (2016).</td>
</tr>
<tr>
<td>Cohesion, $c$ (MPa)</td>
<td>22.8</td>
<td>See Appendix 1 for Mohr–Coulomb fit.</td>
</tr>
<tr>
<td>Tensile strength, $\sigma_t$ (MPa)</td>
<td>6.5</td>
<td>Valli &amp; Hakala et al. (2016)</td>
</tr>
</tbody>
</table>

4.4 Strength and deformation properties of initiated fresh fractures

The fractures, initiated in the FRACOD2D back-analysis models of POSE after the level of stress has exceeded the rock strength, are each initially in the scale of a millimetres before developing into a macro scale material failure. Before propagating further, the fractures deform by shear or opening if the stresses exceed the strength properties determined for the new fractures.

At such small scales, no means of laboratory testing methodologies or reliable literature estimates exists, and uncertainties in determining the appropriate values for the shear strength and deformation properties of the freshly initiated fractures do remain in the models (Rinne, 2008). The friction angle ($\phi$) and cohesion ($c$) of the freshly initiated fractures are usually set to be equal or below the intact rock strength (Rinne, 2008). In contrast, the strength properties of the freshly initiated fractures should also be above of the properties obtained from direct shear testing of existing, old fractures in larger scales. Fracture shear test results can be expected to represent the strength of fractures that have already experienced a number of factors during their geological lifespan that are likely to have decreased their strength in contrast to freshly initiated fractures, such as shear movement, normal deformation or weathering. In the FRACOD2D back-analysis models of POSE, the strength properties of freshly initiating fractures were set to be -10% below
the strength of the implicit VGN foliation planes, following the logic that fracture strength must be below the weakest parts of the intact rock strength but above the shear testing of existing fractures (see Appendix 1).

The deformation of fracture elements in FRACOD2D is described by the normal \( k_n \) and shear stiffness \( k_s \). High stiffness values are often used for the description of new fractures in fracture mechanics modelling, due to the fractures being developed in high stress levels exceeding the rock strength, in addition to the inherently small size of the new fractures (Shen et al., 2016). FRACOD2D application examples indicate that normal and shear stiffness values up to 50 000 GPa/m and 12 550 GPa/m, respectively, have been used (Shen et al., 2016). The normal- and shear stiffness values are noted to be dependent on the fracture size scale (Bandis et al., 1981).

In addition, for freshly initiated fractures no laboratory data is available. However, Vallejos et al. (2016) has conducted a reasonable calibration of stiffnesses using Synthetic Rock Mass modelling for macro-scale quartz, anhydrite and chalcopyrite veins — used as basis for magnitudes of parameters used in this study. Vallejos et al. (2016) considered 22.6 particles across a 50-mm-diameter sample and the Mohr–Coulomb criterion to estimate the UCS of each type of vein. With these macro-scale parameters, they resulted a mean normal stiffness of 22 410 GPa/m and mean shear stiffness of 1 121 GPa/m. Their results have two implications: the strengths of 2/3 calibrated veins are higher than that of the intact rock, which is consistent with the experimental results, however the macro-parameters of veins are three orders of magnitude higher than those obtained in laboratory tests.

For the new fractures normal and shear stiffnesses of 2 2500 GPa/m and 1 500 GPa/m, respectively, were used. As a simplification, same deformation and strength properties were used, irrespective of the mode of which they were initiated e.g. either in tensile or shear, and the direction of anisotropy of the material e.g. plane or matrix properties (latter due to limitations in the code).

The resulting properties for the description of strength and deformation for the newly initiated fractures is presented in Table 4-5.

**Table 4-5.** Properties for new initiating and propagating tensile and shear fractures (applies to all new fractures as multiple parameters cannot be applied) in FRACOD2D back-analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Explanation and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fracture parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal stiffness, ( k_n ) (GPa/m)</td>
<td>22 500</td>
<td>Average value of macro-scale parameters determined for anhydrite, chalcopyrite and quartz samples by Vallejos et al. (2016)</td>
</tr>
<tr>
<td>Shear stiffness, ( k_s ) (GPa/m)</td>
<td>1 500</td>
<td></td>
</tr>
<tr>
<td>Initiating fracture aperture ( a ) (μm)</td>
<td>1</td>
<td>Assumed, negligible effect on results</td>
</tr>
<tr>
<td>Residual fracture aperture ( a_r ) (μm)</td>
<td>100</td>
<td>Assumed, negligible effect on results</td>
</tr>
<tr>
<td>Dilatation, ( \psi ) (deg)</td>
<td>5</td>
<td>Assumed, negligible effect on results</td>
</tr>
<tr>
<td>Friction angle, ( \phi' ) (deg)</td>
<td>42°</td>
<td>90 % of VGN mechanical parameters parallel to plane of anisotropy. See Appendix 1 for Mohr–Coulomb fit.</td>
</tr>
<tr>
<td>Fracture cohesion, ( c ) (MPa)</td>
<td>14.6</td>
<td></td>
</tr>
</tbody>
</table>
4.5 Fracture toughness properties

After losing their strength and deforming, the fractures may have critical stresses concentrated at the fracture tips. This leads to further propagation of the fractures, controlled by the fracture toughness properties.

These properties can be perceived to act as an extension to the strength and deformation properties of the rock matrix. The fracture mechanics properties form the basis for the description of post-peak behaviour after the rock matrix strength has been exceeded and fracture initiation has occurred. The fracture mechanics properties can be related to the fracture propagation process, as they are used to describe the necessary level of stress for causing fracture growth, e.g., propagation to occur, in addition to the strength and deformation properties of the initiated fractures.

The fracture propagation process is described by the fracture toughness for both modes I and II (\(K_{lc}, K_{Ic}\)) corresponding to tensile- and shear fracture growth. The corresponding properties can be derived from Chevron Bend (CB) for Mode I (Ouchterlony, 1988) suggested by ISRM, and Punch-Through Shear with Confining Pressure experiment laboratory testing data for the determination of Mode II fracture toughness properties, respectively (Ouchterlony, 1988; Backers & Stephansson, 2012). However, testing these properties in weaker foliation direction for the VGN rock type is a challenging task.

4.5.1 Mode I Fracture Toughness (\(K_{lc}\))

In the Chevron Bend experiment, the test specimen is subject to a three-point loading (Figure 4-4). The load is increased, controlled by constant opening rate of the notch. The axial load is aligned normal to the line drawn on the specimen (Siren, 2011). Hence, only for \(\beta = 90^\circ\) the load can be applied normal or parallel to the foliation. For all other angles of \(\beta\) the notch forms an arbitrary angle with the foliation, which is the case for all specimens. However, when coring of the holes where the specimen were obtained, it was noted to be difficult to obtain samples parallel to the plane of foliation, due to the deviation of the foliation direction along the borehole length and due to different degrees of deformation of the foliation planes.
Figure 4-4. Chevron bend test configuration for measuring Mode I fracture toughness ($K_{IC}$). Grey lines indicate the plane of anisotropy, while red lines illustrate the direction of fracture growth during testing.

Figure 4-5. Cumulative distribution Mode I fracture toughness ($K_{IC}$) results for VGN rock type, with a fitted Weibull distribution.

As the laboratory data does not directly help in determining the properties in foliation planes, the logic of the observations from the 3DEC back-analyses of POSE by Hakala et al. (2018) was used. The best fit between observed results against 3DEC simulations were obtained with foliation direction being ~25% weaker than indicated by laboratory testing results, and direction parallel to the plane of foliation being 25% stronger than indicated by laboratory testing results. Applying the same logic for determining Mode I fracture toughness ($K_{IC}$) for the plane of anisotropy in VGN, the lower 25% fractile of available laboratory CB test results, thus 2.10 MPa√m, was used. The Mode I ($K_{IC}$) fracture toughness perpendicular to the plane of anisotropy was estimated to be described by the upper 75% fractile being 2.77 MPa√m the available CB test results in absence of controlled tests perpendicular and parallel to the plane of foliation for VGN (Figure 4-5).
Figure 4-6. Cumulative distribution Mode I fracture toughness ($K_{IC}$) results for PGR rock type, with a fitted Weibull distribution.

The Mode I fracture toughness ($K_I$) for isotropic PGR 2.11 MPa\(\sqrt{m}\) was, however, based on the mean of the applicable CB test results (Figure 4-6). The Mode I Fracture Toughness ($K_{IC}$) properties used are listed in Table 4-6.

Table 4-6. Mode I Fracture toughness ($K_{IC}$) properties applied in FRACOD2D back-analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Explanation and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture toughness Mode I, $K_{IC}$ (MPa/m(^{1/2}))</td>
<td>2.10</td>
<td>25 % fractile of the CB lab. data (Siren, 2011; Meyer et al., 2015)</td>
</tr>
<tr>
<td>$VGN$ parallel to plane of anisotropy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture toughness Mode I, $K_{IC}^*$ (MPa/m(^{1/2}))</td>
<td>2.77</td>
<td>75% fractile of the CB lab. data (Siren, 2011; Meyer et al., 2015)</td>
</tr>
<tr>
<td>$VGN$ perpendicular plane of anisotropy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture toughness Mode I, $K_{IC}$ (MPa/m(^{1/2}))</td>
<td>2.11</td>
<td>Mean of CB lab. data</td>
</tr>
<tr>
<td>$PGR$</td>
<td></td>
<td>(Siren, 2011; Meyer et al., 2015)</td>
</tr>
</tbody>
</table>

4.5.2 Mode II Fracture Toughness ($K_{IIc}$)

For determining the Mode II fracture toughness ($K_{IIc}$), Punch-Through Shear with Confinement Pressure experiment (PTS-CP) was used for rock specimen obtained from the POSE niche for the purposes of providing input data for the experiment back-analyses (Meier et al., 2015). However, the PTS test is conducted on a cylindrical sample, where a shear fracture is forced to propagate through the sample length in lateral direction, as illustrated in Figure 4-7. Hence, the PTS-CP testing set up cannot accommodate fracture propagation purely in the plane of anisotropy as the fracture has to propagate also against the plane of foliation. Consequently, the Mode II fracture toughness ($K_{IIc}$) for the VGN rock, both in the direction of plane of foliation and parallel to the plane of foliation could not be directly derived from the laboratory testing data essentially providing averaged results.
In addition, the Mode II fracture toughness ($K_{IIc}$) increases with confinement (Backers et al., 2004). Backers et al. (2004) showed the influence of confining pressure for several rock types and observed that the $K_{IIc}$ fracture toughness sets after ca. 40 MPa.

The fracturing in the first centimetre from the POSE experiment hole surface towards rock mass is mostly controlled by the fracture initiation and Mohr–Coulomb parameters, thus not by Mode II fracture toughness values (see Figure 4-8 first phase for illustration). The confinement levels beyond the first centimetres can be considered to be meaningful (Figure 4-8 from second phase on). Also it should be considered that in the later stages of modelling (close to Peak of heating), the normal pressures are the highest and driving/propagating the failure further.

If the confining stress levels are set too low, the fractures can progress unrealistically deep into the rock mass in accelerating manner (see Figure 4-8 dotted fracture). Thus the confining stress determining the Mode II fracture toughness need to be sufficiently high to prevent unrealistic fracture propagation, however moderate to still allowing fracture growth to a realistic damage depth.

The confinement pressure level of the laboratory tests was chosen to represent the confined rock mass conditions of the POSE within ca. 0.5 m from the experiment hole. This was tested in unreported preliminary models by allowing fractures to grow up to 0.5 m from the experiment hole, while querying the stresses affecting to the fractures. As a result, it was estimated based on elastic models of POSE Phase 2, that ca. 30 MPa of applied confinement during the laboratory tests would reflect the in situ conditions. Therefore, the $K_{IIc}$ values 0…0.5 m from excavation surface can be considered too high, however beyond that the $K_{IIc}$ values may be considered too low, except in primary stress state far enough from the excavations, where parameters would be approximately correct.
While the existing PTS-CP testing data for Olkiluoto has been conducted at ambient conditions (Siren, 2011; Meier et al., 2015), new PTS-CP tests were conducted with 7.5 MPa, 15 MPa and 30 MPa confinement pressures during the back-analysis campaign (see Appendix 2). From these results the testing data at 30 MPa confinement was used for the description of VGN matrix being 10.67 MPa√m. See Figure 4-10 for the results and comparison with Åspö diorite data. While Olkiluoto VGN is generally weaker rock type compared to Åspö diorite, the PTS-CP results and assumption of the confined $K_{IIc}$ for VGN matrix is in line with Åspö diorite results – the Åspö diorite $K_{IIc}$ values are slightly higher throughout.

**Figure 4-8.** Illustration of the changing normal stress conditions during heating experiment while fracture propagates further away from excavation surface.

**Figure 4-9.** Mode II fracture toughness ($K_{IIc}$) for VGN matrix used in the modelling (with 30 MPa confinement), and the increase of $K_{IIc}$ with confinement for isotropic Åspö diorite (on left). (Åspö diorite data after Backers et al. 2004).
For the VGN plane of anisotropy $K_{IIc}$ value, it can be assumed that the $K_{IIc}$ value is notably lower than the VGN matrix value. This is due to the anisotropic nature of the Olkiluoto rock, observable also in the UCS testing results against foliation direction (Figure 4-10). Therefore, the assumption was made that weak anisotropic rock types such as Rüdersdorf limestone and Flechtingen sandstone (Backers et al., 2004), can provide crude assumption of the VGN plane of anisotropy $K_{IIc}$ value. The average $K_{IIc}$ value at 30 MPa confinement for Rüdersdorf limestone and Flechtingen sandstone is 5.00 MPa√m, assumed for VGN plane of anisotropy (Figure 4-11).

For PGR, only PTS-CP tests with ambient confinement has been conducted. Thus, granite literature data was used to determine the $K_{IIc}$ value 11.45 MPa√m at 30 MPa confinement used in the modelling (see Figure 4-12). See Table 4-7 for $K_{IIc}$ values used in the modelling.

**Figure 4-10.** Peak strength versus anisotropy angle for Olkiluoto gneiss (Modified after Hakala et al., 2005). The visualization of the rock type is provided for illustrative purposes only. (Siren, 2018)
Figure 4-11. Mode II fracture toughness ($K_{IIc}$) for VGN matrix (on left) and VGN plane (on right) used in the modelling (with 30 MPa confinement), and the increase of $K_{IIc}$ with confinement for isotropic Åspö diorite (on left) and for two anisotropic rock types (on right). (Rüdersdor and Flechtingen data after Backers et al. 2004)

Figure 4-12. The unconfined PGR test results, granite reference data (Mizunami and Aue granite by Backers et al. 2004 test data) and $K_{IIc}$ used in the modelling (30 MPa confinement).
Table 4-7. Mode II Fracture toughness properties ($K_{IIc}$) applied in FRACOD2D back-analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Explanation and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VGN parallel to plane of anisotropy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture toughness Mode II, $K_{IIc}$ (MPa/m$^{1/2}$) in 30 MPa confinement</td>
<td>5.00</td>
<td>Determined based on reference laboratory data (Backers et al., 2004)</td>
</tr>
<tr>
<td><strong>VGN perpendicular plane of anisotropy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture toughness Mode II, $K_{IIc}$ (MPa/m$^{1/2}$) in 30 MPa confinement</td>
<td>10.67</td>
<td>Laboratory data (see Appendix 2)</td>
</tr>
<tr>
<td><strong>PGR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture toughness Mode II, $K_{IIc}$ (MPa/m$^{1/2}$)</td>
<td>11.45</td>
<td>Determined based on reference laboratory data (Backers et al., 2004).</td>
</tr>
</tbody>
</table>
5 BACK-ANALYSES RESULTS

The results of the back-analysis models are presented for each experiment phase separately. The models are evaluated against the elastic stress state of 3DEC models and fracture initiation and propagation are evaluated against observed damage and measured strains. The results presented are for base case with strike of the foliation 74° unless stated otherwise.

5.1 Elastic stress state

The resulting 2D stress state was compared to 3DEC back-analyses results of corresponding cross-sections in order to preserve the stress path in both methodologies, as illustrated in Figure 5-1.

A comparison of the maximum and minimum principal stresses in 3D- and 2D-models at -5.5 m depth in ONK-EH3 after excavation is shown in Figure 5-1 and Figure 5-2, correspondingly. From the aforementioned figures it is evident that the stress state in the 2D models of the same depth section is not exactly identical compared to 3D-models. This is due to the fact that 2D-models cannot fully take in account 3D geometry, where the tunnel floor acts as a free surface in contrast to the plane strain assumption being applied in the FRACOD2D models. Also the element size in 3D-models is coarse causing nonlinear distribution of stresses in 3D-models.

![Figure 5-1. The maximum principal stresses in comparable range of units at -5.5 m depth before the experiment (after excavations) in ONK-EH3 for 3DEC model on left (Hakala et al., 2017) and FRACOD2D model on right.](image-url)
5.2 POSE Phase 1 back-analyses

The rock damage in the POSE experiment phase 1 was induced as a results of boring of the two holes in conjunction (Figure 5-3). However, in contrast to the POSE experiment observations, the fracture mechanics back calculation models of the corresponding experiment phase result in no fracture initiation regardless of the foliation direction. The models strains are 30 % lower than the ones measured in the experiment (Figure 5-4).

Figure 5-2. The minimum principal stress in comparable range of units at -5.5 m depth before the minimum (after excavations) in ONK-EH3 for 3DEC model on left (Hakala et al., 2017) and b) FRACOD2D model on right.

Figure 5-3. POSE phase 1 FRACOD2D modelling results of boring of the two (ONK-EH1 & ONK-EH2) experiment holes in conjunction.
Figure 5-4. Comparison of measured strains while second hole ONK-EH2 is excavated in tangential (and measured upward strain for comparison) strain gauge rosette T12 in hole ONK-EH1 at depth of -4.34 m and fracture mechanics models with different foliation directions.

5.3 POSE Phase 2 back-analyses

The back-analysis results of Phase 2 resulted in a fairly good spatial match between simulated and observed damage in ONK-EH2 periphery at the depth level of -4.5 m. More damage in the periphery of both experimental holes ONK-EH1 and ONK-EH2 was accumulated in the simulations than observed in the experiment outcome of POSE Phase 2 (Figure 5-5). Simulated strains (see Figure 5-6) were approximately 20 – 25 % of the measured strains obtained from strain gauges, which can be partly attributed to the increased effective stiffness of the 2D approach associated with the plane strain assumption vs the real 3D scenario with a free tunnel surface above. The model with -15° rotated angle of foliation (59°) exhibits significantly more fracturing than the reference case foliation (74°) as estimated from geological mapping (Figure 5-7). With a +15° rotated angle of foliation, the extent of damage was somewhat limited.

In Figure 5-8 the three critical heating phases are illustrated in three heating phases. The models achieve first symmetric heating pattern later shifted to asymmetric heating pattern after the heater failure and following changes in the heating at the northern side of the pillar.
Figure 5-5. Comparison of observed damage in POSE Phase 1 & 2 on left viewed from up (with only fractures at lower half of the holes) and South; and back-analysis on right from -4.5 m depth.

Figure 5-6. Comparison of measured strains in tangential strain gauge T12 location in hole ONK-EH1 at depth of -4.34 m and simulated strains in 3DEC (Hakala et al., 2018) and Fracod with actual heating power on right axis.
Figure 5-7. Simulated extent of fracturing of POSE Phase 2 with varying the direction of foliation ($\pm 15^\circ$).
Figure 5.8. Fracturing progress for models with temperature at critical time steps on columns and rows increasing from left to right and from up to down.

5.4 POSE Phase 3 back-analyses

Back analysis results of Phase 3 at the depth level of -4.0 m, represented by isotropic PGR, did not exhibit any fracturing at any point of the simulated stress path associated with the thermal stressing during the experiment execution. However, the back-analysis of the depth level -5.5 m of Phase 3, represented by anisotropic VGN rock type, exhibited fracturing in the N-S direction at the ONK-EH3 periphery (Figure 5-9). During Phase 3 execution, damage in the corresponding depth level was only observed in the North side of the ONK-EH3 periphery in VGN, where a contact occurs between PGR and VGN, while the South side of the hole is exhibits PGR.
During the execution of the POSE experiment phase 3, the strain gauges systematically suffered debonding damage during the heating, thus the comparison against measured strains is done against 3DEC model assumed to present the experiment behavior fairly (Figure 5-10). The modelled strains follow the measured in during the first experiment days (from 19.12.2013 to 7.1.2013) before the strain gauge readings start to be assumable unreliable, after which the strains are ca. half of the strains modelled using 3DEC.

The simulated increase in tangential stress are slightly different for two different materials (Figure 5-11 and Figure 5-12). The tangential stress increases up to 29 MPa in veined gneiss and up to 34 MPa in pegmatoid granite.

![Figure 5-9](image-url) **Figure 5-9.** Experiment damage and modelled damage during POSE Phase3, at ONK-EH3 experiment hole at depths of -4.0 m and -5.5 m.
Figure 5-10. Comparison of strains from 3DEC model and FRACOD2D models with also unreliable measured data during experiment for ONK-EH3 -5.5 m SG8 strain gauge rosette at bearing 83°.

Figure 5-11. Comparison of tangential stress increase between 3DEC and FRACOD2D models for ONK-EH3 -5.5 m.
Figure 5-12. Comparison of tangential stress increase between 3DEC and FRACOD2D models for ONK-EH3 -4.0 m.
6 DISCUSSION

The FRACOD2D simulation results were evaluated against the projected damage observations of the respective POSE phase for the depth levels under back-analysis. The damage observations from the POSE phases were obtained in a region of ± 10 cm above and below of each back-analysed cross-section, and the observations were projected onto the respective plane under scrutiny. The fracture mechanics back-analysis of Phase 1 did not result in fracture initiation or propagation in the modelled cross-cut, as the simulated stress perturbation induced by the boring of the adjacent ONK-EH2 experimental hole did not exceed the rock mass strength in the limits of parametric uncertainty, including the variation in the strike of foliation in the anisotropic VGN material (Figure 5-3). However, back-analysis results of Phase 2 at which thermal stresses were induced using the same model geometry, resulted in a fairly good spatial match between simulated and observed damage in ONK-EH2 periphery at the depth level of -4.5 m (Figure 5-5). More damage in the periphery of both experimental holes ONK-EH1 and ONK-EH2 was accumulated in the simulations than observed in the experiment outcome of POSE Phase 2. Simulated strains were approximately 20 – 25% of the measured strains obtained from strain gauges during the experiment execution (Figure 5-6). The difference between simulated and measured strains can be partly attributed to the increased effective stiffness of the 2D approach associated with the plane strain assumption vs the real 3D scenario with a free tunnel surface above.

Back-analysis results of Phase 3 at the depth level of -4.0 m, represented by isotropic PGR, did not exhibit any fracturing at any point of the simulated stress path associated with either the stresses induced by the boring of the hole or thermal stressing during the experiment execution. However, the back-analysis of the depth level -5.5 m of Phase 3, represented by anisotropic VGN rock type, exhibited fracturing in the North and South directions at the ONK-EH3 periphery (see Figure 5-9). During the Phase 3 execution, damage in the corresponding depth level was only observed in the North side of the ONK-EH3 periphery in VGN, where a contact occurs between PGR and VGN, while the South side of the hole is embedded in PGR.

As an observation from POSE execution and subsequent 3DEC back-analyses of POSE was that lithology has been found to be a direct controller for the spatial distribution and extent of the developed fracturing (Hakala et al., 2018). Due to numerical limitations associated with the fracture mechanics modelling approach with FRACOD2D, mainly the fact that the code is based on the Boundary Element Method (BEM) assuming continuous material throughout infinite space, the prevailing geological conditions in the FRACOD2D back-analyses had to be simplified to consist of a single material only. Consequently, the back-analysed cross-sections consisted either of VGN or PGR rock types. No lithological borders or contact zones between the lithological units could be taken into account in the models, where most of the fracturing was observed during POSE. Therefore an important aspect of the observed phenomena of geologically controlled failure could not be studied in detail by the FRACOD2D back-analyses.

With much of the calibration concentrated on matching of the thermal boundary conditions (with the limitation of two-dimensional modelling tool), uncertainty exists in all of the parameters. Majority of the parameters given did not allow taking account the
confining/normal pressures they were used in the model, therefore assumptions were done regarding the fixed confining/normal pressures which were used to determine the parameters were determined. Also the boundary conditions brought from 3D modelling were complex and were simplified in the 2D model, rendering the comparison between methods often impractical.

The initiating and propagating fractures are new fresh fractures (in comparison to old geological features), therefore the parameters used for them are above laboratory tested natural fractures, but below the strength of intact rock. The parameters used are in line with the ones used for example in APSE experiment (Rinne et al., 2004), ZEDEX and TSX experiments (Shen et al., 2014), where high cohesion (20 MPa, 31 MPa and 43 MPa correspondingly) and friction angle (49°, 49° and 48° correspondingly) for fresh fractures were used. This seems to be especially necessary when modelling large scale models in high stress states to retain limited damage process.

Time-dependent fracture growth was observed after the execution of POSE Phase 1 (Johansson et al., 2014), but prior to the execution of the Phase 2. Time-dependent fracture growth was not taken into account in the fracture mechanics models, due to the lack of parameters necessary for the description of time dependent fracture growth in FRACOD2D.

6.1 Limitations of the fracture mechanics modelling approach

Limitations exist between the available laboratory testing methodologies and necessary parametrisation for the material description of the fracture mechanics modelling approach associated with modelling of progressive rock fracturing process. For instance, no available means or literature estimations exist of the strength and deformation properties for freshly developing new fractures. These parameters have a significant effect on the numerical stability of the models, and as a result they had to be estimated to be between the values obtained from shear testing of existing old fractures and intact rock. For the back-analysis models, 90% of the intact rock properties for describing the strength of the newly developed fractures was found to provide numerically stable results, with the logic of fresh fractures having to be weaker than the intact rock material while stronger than existing old fractures. The applicability of this logic in other parts of the ONKALO® is uncertain.

During the course of fracture mechanics simulations when new fracture are developing, inability to define properties for the fractures regardless of them forming parallel or perpendicular to the plane of weakness/foliation was considered a limitation. Within the current version of FRACOD2D (5.3) it was not possible to assign direction dependent fracture surface properties (friction angle, fracture cohesion, fracture normal stiffness and fracture shear stiffness) for fresh, new fractures developing in the models. When anistropic rock conditions are being modelled, such as VGN encountered during the POSE, this leads to a situation where new fractures generated in the model environment in parallel to the plane of foliation or perpendicular to the plane of foliation have equal properties, although it is clear that the generated fracture surfaces can be very different.
The mode II fracture toughness $K_{IIc}$, describing the fracture propagation properties of the rock material under shear loading, could not be determined for the representation of transversely isotropic medium through the PTS-CP laboratory testing method suggested by the International Society for Rock Mechanics and Rock Engineering (Backers & Stephansson, 2012). The PTS-CP testing method is the first mode II testing method widely in use that can take in account the confining pressure. However, the test setup is such that the shear is induced in cylindrical form from which is impossible to determine the properties for planar foliation. Thus, the properties for the plane of foliation and against the plane of foliation had to be inferred to be described by the 25/75 % percentiles of the tested samples while partly relying on available literature data.

In the future laboratory test setups allowing the testing the mode II fracture toughness in the plane of foliation should be conducted, recently proposed Short Core in Compression (SCC) testing method (Jung et al., 2016) is promising in that aspect (see Figure 6-1 for comparison between PTS-CP and SCC laboratory test setups). In the SCC test setup, a planar shear is forced using two prefabricated notches, while the sample is tested in a standard triaxial compression test – thus it is possible to align the foliation in the direction of the shear. However, it has been noted in other testing campaigns that it is very hard to obtain samples parallel to the foliation.

![Figure 6-1. Comparison of the used Punch-Through Shear with Confining Pressure test setup on left and suggested Short Core in Compression test setup on right.](image)

Further, the results of the fracture mechanics models of POSE back-analyses campaign were found to be sensitive for changes in $K_{IIc}$, which is strongly dependent on the level of confinement (Backers et al., 2004). However, the current version of FRACOD2D is not able take into account the confinement dependency on fracture propagation properties. Consequently, the laboratory tests determining the $K_{IIc}$ should be conducted in a confinement level reflecting to the modelling scenario at hand.
The inability of fracture mechanics approach to capture the actual, observed 3D phenomena associated with the rock fracturing processes such as encountered during POSE execution, restricts the functionality of the fracture mechanics modelling. Complex lithology and geological features has been found to be a direct controller for the spatial distribution and extent of the developed fracturing, which could not be taken into account in the 2D cross section models (for more information see Appendix 4). Due to these simplifications associated with fracture mechanics modelling, the site specific geological conditions of Olkiluoto could not be taken fully into account restricting the predictive capability of the modelling approach in complex geological conditions. In addition, properties important for long term safety metrics, such as out of plane fracture network connectivity and fracturing extent, could not be captured with 2D simplification.

Fracture mechanics approach on modelling of rock fracturing is a recursive process, at which the result of a forward calculation step is being based on the final result of the previous calculation step. Consequently, the fracture mechanics models do contain inherent randomness and increasing amount of bias when models containing large amounts of calculation steps and fracture propagation are being analysed. When the observed fracturing process is mimicked through recursive modelling, parameters without association with physical reality are required, in order to preserve numerical stability. These parameters, such as the distance between automated interaction of adjacent fracture tips or hierarchy between the growth of independent fractures, are relying on subjective choices set by the modeller himself. The impact of such choices in the simulated end results in notable, and should be emphasized when assessing the validity of the model results against known observations.
7 CONCLUSIONS

Fracture mechanics back-analyses, by using FRACOD2D, were conducted for all phases 1, 2 and 3 of the POSE in situ experiment executed between 2011 and 2013. The back-analyses of the POSE experiment was aimed at identifying a suitable approach for modelling and identifying the failure modes for the experiment observations. The methodology in the FRACOD2D approach involved elastic simulations to achieve consistent stress levels and temperatures equivalent to the monitored or to the back-analysed with 3DEC, after which fracture initiation and propagation was implemented within the models. The overall nature and extent of the simulated damage was evaluated against the experiment observations. The strength properties for the rock matrix and developing fresh fractures were adjusted, within the limit of associated uncertainties in the available data, until a sufficient match against in situ observations was achieved.

Following the results of the 3DEC back-analyses the plane of foliation strength was considered being 25 % weaker than estimated in laboratory with friction angle of 42° and cohesion of 15.3 MPa, while the VGN matrix was left to the estimated values of friction angle of 42° and cohesion of 28.2 MPa. The strength and deformation properties of initiated fresh fractures were above laboratory tested natural fractures, but below the strength of intact rock. The properties for the plane of foliation and against the plane of foliation had to be inferred to be described by the 25/75 % percentiles of the tested samples while partly relying on available literature data. Also, the model geometries had to be simplified to consist of either of the VGN or PGR rock types.

The FRACOD2D back-analyses results of POSE indicate a damage extent in the order of centimetres to decimeters. The simulated damage extent can be perceived to be in the same order of magnitude as observed during the execution of POSE (see Figure 7-1). Damage depth estimation from scaling of the experimental holes indicated a damage extent of less than 100 mm, while hydraulic flow measurements indicated a damage extent varied from 20 to 180 mm with average value of 118 mm (Johansson et al., 2014).
Figure 7-1. FRACOD2D back-analysis results from POSE Phase 2 at -4.5 m model and all hydraulic testing results from different depths indicating interpreted damage extent during the experiment.

Although FRACOD2D suffers from the two-dimensional simplification of the back-analysis problem at hand, the methodology can capture the observed structural failure and the variability of the results depending for example on the foliation angle, such as observed in situ during the execution of POSE. A sensitivity analysis of the simulated extent of fracturing during Phase 2 back-analysis revealed the results are sensitive to the prevailing angle of anisotropy (Figure 5-7). The Phase 2 back-analysis model with -15° rotated angle of foliation (59°) exhibits significantly more fracturing than the reference case foliation (74°) as estimated from geological mapping (Figure 5-7). With a +15° rotated angle of foliation, the extent of damage was somewhat limited.

The fracture mechanics modelling was constrained on 2D and the approach cannot capture the actual 3D effects of the failure development observed during POSE execution. In addition, the modelling approach hinges on obtaining stress and temperature boundary conditions from other solutions associated with a 3D problem, such as vertical experimental hole having secondary effects from the nearby tunnel. Therefore, FRACOD2D can be considered to provide a qualitatively acceptable solution to the back-analysis of the damage extent that occurred during POSE. The results should not be extended to a quantitative nature due to the 3D requirement of the problem at hand, simplification of geological conditions of the POSE, and the ambiguity in the input parametrisation associated with the fracture mechanics modelling approach.
8 REFERENCES


Griffith A. 1921. The phenomena of rupture and flow in solids. Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character 221, 163–198.


9 APPENDIXES

Appendix 1. Mohr–Coulumb fits to Hoek–Brown data for VGN matrix and planex, PGR matrix and fresh fractures
Appendix 2. Mode II fracture toughness testing results for VGN
Appendix 3. Stress state in 3D-models
Appendix 4. Results of the multimaterial models
Appendix 1. Mohr–Coulomb fits to Hoek–Brown data for VGN matrix and planex, PGR matrix and fresh fractures

**VGN matrix**

![Mohr–Coulomb fit for VGN matrix](image)

- **σ**$_{uc}$: 130.5 MPa
- **mi**: 11.47
- **a**: 0.50
- **GSI**: 100
- **mb**: 8.53
- **s**: 1.00
- **ar**: 0.75
- **mr**: 7.00
- **sr**: 0.00
- MC tan fit: 42°, 28.9 MPa

**VGN plane**

![Mohr–Coulomb fit for VGN plane](image)

- **σ**$_{uc}$: 68.2 MPa
- **mi**: 11.47
- **a**: 0.50
- **GSI**: 100
- **mb**: 8.53
- **s**: 1.00
- **ar**: 0.75
- **mr**: 7.00
- **sr**: 0.00
- MC tan fit: 42°, 15.3 MPa
PGR matrix

\[ \sigma_{\text{ucs}} \]  
\[ \text{mi} \]  
\[ \alpha \]  
\[ \text{GSI} \]  
\[ \text{mb} \]  
\[ \text{s} \]  
\[ \alpha_{r} \]  
\[ \mu_{r} \]  
\[ \text{sr} \]  
\[ \text{MC tan fit: 42° 22.8 MPa} \]

Fresh fractures

\[ \sigma_{\text{ucs}} \]  
\[ \text{mi} \]  
\[ \alpha \]  
\[ \text{GSI} \]  
\[ \text{mb} \]  
\[ \text{s} \]  
\[ \alpha_{r} \]  
\[ \mu_{r} \]  
\[ \text{sr} \]  
\[ \text{MC tan fit: 42° 14.6 MPa} \]
Appendix 2. Mode II fracture toughness testing results for VGN

MODE II FRACTURE TOUGHNESS TESTS WITH CONFINEMENT

1. INTRODUCTION
A laboratory testing campaign on Olkiluoto veined gneiss specimens was carried out to characterize the effect of confinement on Mode II fracture toughness values determined by the Punch-Through Shear (PTS) experiment following the ISRM suggested methods (Backers & Stephansson, 2012). Tests were performed on specimens with 50 mm diameter under three confinement pressures in Stress Measurement Company's laboratory in Rauma October 2018.

1.1. Samples
The samples originated from OL-KR56 deep drillhole and are typical heterogenous Olkiluoto veined gneiss samples with visible foliation. The foliation direction to the loading direction varies from 30° to 60° and is on average 45°. The PTS test setup is incapable to test the Mode II fracture toughness values only in foliation direction, therefore the foliation direction of the samples is not considered relevant.

Figure A2-1 summarizes the experimental PTS set-up and the sample geometry. The samples were cut and grinded to parallelism of less than 10 μm. After preparation the notches were drilled using hollow drill bit. The average sample dimensions after preparation are presented in Table A2-1. Although the geometries are not exactly as suggested, the effect in results is estimated to be marginal (~1-2 %). Before testing the specimen was stored in test room in dry conditions. Appendix 1 shows photographs of the received samples before and after preparation.

![Figure A2-1. PTS method. A) Sample geometry and B) loading configuration (Backers & Stephansson, 2012).](image-url)
Table A2-1. Suggested and tested dimension of the PTS samples.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Average dimension (mm)</th>
<th>ISRM suggestion (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen height L</td>
<td>50.2</td>
<td>50</td>
</tr>
<tr>
<td>Specimen diameter D</td>
<td>49.5</td>
<td>50</td>
</tr>
<tr>
<td>Notch diameter ID</td>
<td>24.3</td>
<td>25</td>
</tr>
<tr>
<td>Upper notch depth a</td>
<td>4.9</td>
<td>5</td>
</tr>
<tr>
<td>Lower notch depth b</td>
<td>30.0</td>
<td>30</td>
</tr>
<tr>
<td>Notch tip width t</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Intact portion IP</td>
<td>15.2</td>
<td>15</td>
</tr>
</tbody>
</table>

2. Mode II fracture toughness tests

The Mode II fracture toughness was determined using the Punch-Through Shear with Confining Pressure experiment according to the ISRM suggested method (Backers & Stephansson, 2012). Pushing of the central cylinder of the specimen generates a localized shear stress between the upper and lower notch. The resulting mode II fracture toughness $K_{IIc}$ is estimated by

$$K_{IIc} = 7.74 \times 10^{-2} F_{max} - 1.80 \times 10^{-3} P_c$$

where $F_{max}$ is the maximum axial load (in kN) and $P_c$ is the applied confining pressure (in MPa). The experiments in this series were carried out at ambient conditions, i.e. $P_c = 0.1$ MPa and in high confinement conditions where $P_c = 30$ MPa.

Tests were performed using Controls MCC8 3000 kN testing system under loading rate control and automatic and adjustable force contact and failure detection logic. The loading rate was on average 0.02 mm/min. The confining pressure was applied with Hoek cell. The confinement was increased to desired level after which the test was conducted.

3. Results

In Table A2-2 the results from the tests are presented. The test results divided in the low, medium and high confinement results are presented in Table A2-3 and in Figure A2-2 with comparison to literature data in Table A2-4. The scatter of data is low (from 6 % to 14 %) and well within the literature data. Results show no apparent correlation between Mode II fracture toughness and other parameters (such as foliation direction and grain size of the specimen). The before and after testing images are presented in Figures A2-3…11 and individual results in Tables A2-5…13.
Table A2-2. Results from the determination of Mode II fracture toughness using the Punch-Through Shear (PTS) experiment.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>IP (mm)</th>
<th>Peak load (kN)</th>
<th>Displacement (mm)</th>
<th>Support pressure (MPa)</th>
<th>$K_{IC}$ (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OL-KR56_525.60</td>
<td>50.263</td>
<td>49.48</td>
<td>269.5</td>
<td>15.4</td>
<td>113.1</td>
<td>0.40</td>
<td>15.0</td>
<td>8.73</td>
</tr>
<tr>
<td>OL-KR56_526.27</td>
<td>49.93</td>
<td>49.58</td>
<td>264.4</td>
<td>15.0</td>
<td>133.2</td>
<td>0.19</td>
<td>30.0</td>
<td>10.26</td>
</tr>
<tr>
<td>OL-KR56_527.20</td>
<td>50.06</td>
<td>49.45</td>
<td>261.0</td>
<td>15.1</td>
<td>115.6</td>
<td>0.20</td>
<td>15.0</td>
<td>8.92</td>
</tr>
<tr>
<td>OL-KR56_527.64</td>
<td>50.27</td>
<td>49.45</td>
<td>262.6</td>
<td>15.3</td>
<td>155.0</td>
<td>0.21</td>
<td>30.0</td>
<td>11.94</td>
</tr>
<tr>
<td>OL-KR56_537.56</td>
<td>50.2</td>
<td>49.62</td>
<td>266.9</td>
<td>15.2</td>
<td>63.2</td>
<td>0.16</td>
<td>7.5</td>
<td>4.88</td>
</tr>
<tr>
<td>OL-KR56_540.95</td>
<td>50.11</td>
<td>49.56</td>
<td>272.6</td>
<td>15.3</td>
<td>88.7</td>
<td>0.13</td>
<td>15.0</td>
<td>6.84</td>
</tr>
<tr>
<td>OL-KR56_541.40</td>
<td>50.107</td>
<td>49.50</td>
<td>267.7</td>
<td>15.2</td>
<td>127.3</td>
<td>0.18</td>
<td>30.0</td>
<td>9.80</td>
</tr>
<tr>
<td>OL-KR56_548.75</td>
<td>50.2</td>
<td>49.65</td>
<td>268.0</td>
<td>15.3</td>
<td>64.3</td>
<td>0.16</td>
<td>7.5</td>
<td>4.96</td>
</tr>
<tr>
<td>OL-KR56_548.80</td>
<td>50.24</td>
<td>49.64</td>
<td>269.9</td>
<td>15.3</td>
<td>70.4</td>
<td>0.18</td>
<td>7.5</td>
<td>5.44</td>
</tr>
</tbody>
</table>

Table A2-3. Mean values and deviation of the test results.

<table>
<thead>
<tr>
<th>Test set</th>
<th>Mean $K_{IC}$ (MPa√m)</th>
<th>Standard deviation (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low confinement (7.5 MPa)</td>
<td>5.09</td>
<td>0.30 (6 %)</td>
</tr>
<tr>
<td>Medium confinement (15 MPa)</td>
<td>8.16</td>
<td>1.15 (14 %)</td>
</tr>
<tr>
<td>High confinement (30 MPa)</td>
<td>10.67</td>
<td>1.13 (11 %)</td>
</tr>
</tbody>
</table>

Figure A2-2. Mode II fracture toughness versus confining pressure.
Table A2-4. Values for Mode I and Mode II fracture toughness of various rocks.

<table>
<thead>
<tr>
<th>Rock</th>
<th>Country</th>
<th>$K_{IC}$ (CB)</th>
<th>$K_{IC}$ (low P)</th>
<th>$K_{IC}$ (high P)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ävrö granite</td>
<td>Sweden</td>
<td>3.8</td>
<td>4.7</td>
<td>11.5</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Aue granite</td>
<td>Germany</td>
<td>1.6</td>
<td>4.2</td>
<td>10.5</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Mizunami granite</td>
<td>Japan</td>
<td>2.4</td>
<td>4.2</td>
<td>10.9</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Seoul granite</td>
<td>Korea</td>
<td>1.6</td>
<td>4.0</td>
<td>–</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Carrara marble</td>
<td>Italy</td>
<td>2.4</td>
<td>3.1</td>
<td>6.7</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Flechtingen sandstone</td>
<td>Germany</td>
<td>1.2</td>
<td>2.1</td>
<td>5.3</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Bentheim sandstone</td>
<td>Germany</td>
<td>0.9</td>
<td>–</td>
<td>–</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Rüdersdorf limestone</td>
<td>Germany</td>
<td>1.1</td>
<td>3.1</td>
<td>4.2</td>
<td>Backers &amp; Stephansson 2012</td>
</tr>
<tr>
<td>Lac du Bonnet granite</td>
<td>Canada</td>
<td>4.9</td>
<td>–</td>
<td>–</td>
<td>Shao et al. 1999</td>
</tr>
<tr>
<td>Senones granite</td>
<td>France</td>
<td>4.3</td>
<td>–</td>
<td>–</td>
<td>Shao et al. 1999</td>
</tr>
<tr>
<td>Vienne granite</td>
<td>France</td>
<td>6.0</td>
<td>–</td>
<td>–</td>
<td>Shao et al. 1999</td>
</tr>
<tr>
<td>Åspö diorite, dry</td>
<td>Sweden</td>
<td>3.8</td>
<td>5.1</td>
<td>–</td>
<td>Backers, 2003</td>
</tr>
<tr>
<td>Åspö diorite, saturated</td>
<td>Sweden</td>
<td>2.7</td>
<td>4.5</td>
<td>13.0</td>
<td>Backers, 2006</td>
</tr>
<tr>
<td>Olkiluoto gneiss</td>
<td>Finland</td>
<td>2.5</td>
<td>3.5</td>
<td>10.7</td>
<td>Siren 2012, Meier et al. 2015, this</td>
</tr>
<tr>
<td>Olkiluoto pegmatoid</td>
<td>Finland</td>
<td>2.1</td>
<td>3.4</td>
<td>–</td>
<td>Siren 2012, Meier et al. 2015</td>
</tr>
</tbody>
</table>
Figure A2-3. Photographs of untested and tested OL-KR56_525.60_PTS_15MPa sample.
OL-KR56_526.27_PTS_30MPa

<table>
<thead>
<tr>
<th>Intact sample from top</th>
<th>Intact sample from side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested sample from top</td>
<td>Tested sample from side</td>
</tr>
</tbody>
</table>

*Figure A2-4. Photographs of untested and tested OL-KR56_526.27_PTS_30MPa sample.*
OL-KR56_527.20_PTS_15MPa

<table>
<thead>
<tr>
<th>Intact sample from top</th>
<th>Intact sample from side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested sample from top</td>
<td>Tested sample from side</td>
</tr>
</tbody>
</table>

**Figure A2-5.** Photographs of untested and tested OL-KR56_527.20_PTS_15MPa sample.
OL-KR56_527.64_PTS_30MPa

Figure A2-6. Photographs of untested and tested OL-KR56_527.64_PTS_30MPa sample.
Figure A2-7. Photographs of untested and tested OL-KR56\_537.56\_PTS\_7.5MPa sample.
Figure A2-8. Photographs of untested and tested OL-KR56_540.95_PTS_15MPa sample.
Figure A2-9. Photographs of untested and tested OL-KR56_541.40_PTS_30MPa sample.
OL-KR56_548.75_PTS_7.5MPa

Figure A2-10. Photographs of untested and tested OL-KR56_548.75_PTS_7.5MPa sample.
Figure A2-11. Photographs of untested and tested OL-KR56_548.80_PTS_7.5MPa sample.
### Table A2-5. Result sheets of OL-KR56_525.60_PTS_15MPa test.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.26</td>
<td>49.5</td>
<td>269.5</td>
<td>4.91</td>
<td>29.98</td>
<td>15.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>K_{ic} (MPa√m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2</td>
<td>113.1</td>
<td>0.40</td>
<td>8.72</td>
<td>Top of the cylinder split in the test.</td>
</tr>
</tbody>
</table>

![Graph showing axial stress and displacement over time](image1)

![Graph showing axial stress and confining pressure over time](image2)
Table A2-6. Result sheets of test OL-KR56_526.27_PTS_30 MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.93</td>
<td>49.6</td>
<td>264.4</td>
<td>4.96</td>
<td>29.96</td>
<td>15.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confine (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{IC}$ (MPa(\sqrt{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1</td>
<td>133.2</td>
<td>0.19</td>
<td>10.26</td>
</tr>
</tbody>
</table>

Notes

Top of the cylinder splitted in the test.
Table A2-7. Result sheets of test OL-KR56_527.20_PTS_15MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.06</td>
<td>49.5</td>
<td>261</td>
<td>4.95</td>
<td>29.97</td>
<td>15.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{IC}$ (MPa√m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.3</td>
<td>115.6</td>
<td>0.20</td>
<td>8.92</td>
<td>Top of the cylinder splitted in the test.</td>
</tr>
</tbody>
</table>
Table A2-8. Result sheets of test OL-KR56_527.64PTS_30MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.27</td>
<td>49.4</td>
<td>262.6</td>
<td>4.93</td>
<td>30.05</td>
<td>15.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{IC}$ (MPa/√m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.2</td>
<td>155.0</td>
<td>0.21</td>
<td>11.94</td>
<td>Top of the cylinder split in the test.</td>
</tr>
</tbody>
</table>

![Graph showing axial stress and displacement over time.](image1)

![Graph showing confining pressure and axial stress over time.](image2)
Table A2-9. Result sheets of test OL-KR56_537.56_PTS_7.5 MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.20</td>
<td>49.6</td>
<td>266.9</td>
<td>5.01</td>
<td>30.04</td>
<td>15.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>KIC (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>63.2</td>
<td>0.16</td>
<td>4.88</td>
</tr>
</tbody>
</table>

Notes:
Top of the cylinder splitted in the test.
Table A2-10. Result sheets of test OL-KR56_540.95_PTS_15MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.11</td>
<td>49.6</td>
<td>272.6</td>
<td>4.84</td>
<td>29.92</td>
<td>15.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{Ac}$ (MPa m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1</td>
<td>88.7</td>
<td>0.13</td>
<td>6.84</td>
<td>Top of the cylinder splitted in the test.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.11</td>
<td>49.5</td>
<td>267.7</td>
<td>4.92</td>
<td>29.98</td>
<td>15.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{IC}$ (MPaVm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1</td>
<td>127.3</td>
<td>0.18</td>
<td>9.80</td>
</tr>
</tbody>
</table>

Notes
Two minor axial fractures on top of the cylinder in the test.
Table A2-12. Result sheets of test OL-KR56_548.75_PTS_7.5MPa.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.20</td>
<td>49.6</td>
<td>268</td>
<td>4.98</td>
<td>29.92</td>
<td>15.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{IC}$ (MPa)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>64.3</td>
<td>0.16</td>
<td>4.97</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
Top of the cylinder disintegrated in the test.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Weight (g)</th>
<th>Notch a (mm)</th>
<th>Notch b (mm)</th>
<th>IP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.24</td>
<td>49.6</td>
<td>269.9</td>
<td>4.88</td>
<td>30.02</td>
<td>15.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Confinement (MPa)</th>
<th>Axial stress (kN)</th>
<th>Displacement (mm)</th>
<th>$K_{oc}$ (MPa/m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>70.4</td>
<td>0.18</td>
<td>5.43</td>
<td>Top of the cylinder split in the test.</td>
</tr>
</tbody>
</table>

![Graph of Axial stress vs. Time](image1)

![Graph of Displacement vs. Time](image2)

![Graph of Confining pressure vs. Time](image3)
Appendix 3. Stress state in 3D-models

**3DEC 5.00**

Maximum principal stress before experiment for the ONK-EH3 at -4 m depth

Maximum principal stress after heating experiment for the ONK-EH3 at -4 m depth

From models by Hakala *et al.* (2018).
Intermediate principal stress before experiment for the ONK-EH3 at -4 m depth

Intermediate principal stress after heating experiment for the ONK-EH3 at -4 m depth

From models by Hakala et al. (2018).
Minimum principal stress before experiment for the ONK-EH3 at -4 m depth

Minimum principal stress after heating experiment for the ONK-EH3 at -4 m depth

From models by Hakala *et al.* (2018).
Maximum principal stress before experiment for the ONK-EH3 at -5.5 m depth

Maximum principal stress after heating experiment for the ONK-EH3 at -5.5 m depth

From models by Hakala et al. (2018).
Intermediate principal stress before experiment for the ONK-EH3 at -5.5 m depth

Intermediate principal stress after heating experiment for the ONK-EH3 at -5.5 m depth

From models by Hakala et al. (2018).
Minimum principal stress before experiment for the ONK-EH3 at -5.5 m depth

Minimum principal stress after heating experiment for the ONK-EH3 at -5.5 m depth

From models by Hakala et al. (2018).
Maximum principal stress after heating experiment for the ONK-EH1 & ONK-EH2 at -4.5 m depth

Intermediate principal stress after heating experiment for the ONK-EH1 & ONK-EH2 at -4.5 m depth
Minimum principal stress after heating experiment for the ONK-EH1 & ONK-EH2 at -4.5 m depth

From models by Hakala et al. (2018).
Appendix 4. Results of the multimaterial models

RESULTS OF THE MULTIMATERIAL MODELS

The FRACOD2D back-analysis models with multiple materials in the same model were tested within the back-analyses campaign. These models consisted of two materials (transversely isotropic VGN and isotropic PGR), border between them and other components also in the single material models reported: far-field stress implemented for both materials and heating implemented with appropriate boundary conditions inside the experiment holes and with point source heaters in the rock mass. The multiregion problem in Fracod2D is solved by assigning twin elements at the lithological interface. In these elements the shear and the normal stresses at the two sides of the interface is set to be the same (Shen, 2017). The lithological units and lithological border in a Fracod2D model are illustrated in Figure A4-1.

The cross-sections from 3D-models by Hakala et al. (2018) were used as input for 2D-models, however due to numerical modelling restrictions they needed to be simplified (see Figure A4-2 and Figure A4-3). Also, the material boundaries in ONK-EH3 -5.5 m model were aligned perpendicular or parallel to principal stresses in order to reduce the shear stress concentrations at the material boundaries that would otherwise control the model outcome.

![Figure A4-1. An illustrative example of a FRACOD2D model with two different lithological units, and conceptualization of the lithological border between the units.](image-url)
Appendix 4

**Figure A4-2.** 2D-sections from a 3D-model created using 3DEC (Itasca, 2013) plotted from 3D-elements (on left) and FRACOD2D model (on right) for -4.5 m level.

**Figure A4-3.** 2D-sections from a 3D-model created using 3DEC (Itasca, 2013) plotted from 3D-elements (on left) and FRACOD2D model (on right) on upper row for -4 m level and lower row for -5.5 m level in ONK-EH3. (From models by Hakala et al., 2017).
Results and discussion of the multimaterial models

The multimaterial models result in contrasting results. Fairly simple model of Phase 3 of -5.5 m depth results in very good match with the experiment observations (see Figure A4-1). The simulation is able to catch the fracturing occurring at the North side of the experiment hole during the heating. However, is not able to model the fracture initiated already before the heating – observed approximately 18 months after boring ONK-EH3. It must be noted that time-dependent creep was not included in the simulation model.

Figure A4-1. Observed damage during execution of POSE, and simulated damage at experiment hole ONK-EH3 at depth of -5.5 m.
On the contrary the multimaterial model of the Phase 2 at depth of -4.5 m, results in unstable fracture growth. The problem lies when fractures start to grow across the lithology borders and somehow exhibit stresses some orders of magnitude higher than normally. This leads to an uncontrolled and unrealistic chain reaction of infinite fracture initiation and propagation. Due to these concerns it was decided to use only single material models in the actual back-analyses.

**Figure A4-5.** Comparison of observed damage in ONK-EH1 and ONK-EH2 during back-analysis of POSE Phase 2 on left viewed from up (with only fractures at lower half of the holes) and South; and back-analysis on right from -4.5 m depth. Unstable fracturing pointed out with red circle.