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Thermo-mechanical simulations of pillar spalling for in-situ heater test by FRACOD

Hee-Suk Lee[1], Baotang Shen[2], Rinne Mikael[3]
[1]SK Engineering & Construction, [2]CSIRO Exploration and Mining, Kenmore, Brisbane, Australia
[3]FRACOM Ltd, Farfarsbacken 14, FIN-02400 Kyrkslätt, Finland

Abstract: A two-dimensional BEM code, FRACOD^{2D}, was applied to simulate fracture initiation and propagation processes in a rock pillar during an in situ heater test of a rock pillar planned at the Äspö Underground Rock laboratory of SKB, in Southern Sweden. To take the advantage of conventional BEM for simulating fracturing processes, but without efforts for domain integral transformation, a hybrid approach is developed to simulate the fracturing processes in rock pillar under coupled thermo-mechanical loading. The code FRACOD was used for simulating the fracture initiation and propagation processes with its boundary tractions reflecting the effects of the initial and redistributed thermo-mechanical stresses in the domain of interest at multiple excavation and heating steps were produced by a special algorithm of stress inversion, based on resultant thermo-mechanical stress fields at each excavation and heat loading step by a FEM code without considering fracturing processes. This hybrid approach can take the advantages of both types of numerical methods and avoids their shortcomings for fracturing process simulation and domain effects, respectively.
In this paper, we present the hybrid approach for the stress, displacements, and fracturing processes at sequential excavation and heating steps of the in situ heater test as a predictive modelling, the formulation of the fracturing models and the predictive results. Two sections of borehole depth, 0.5 m and 1.5 m below the tunnel floor are considered. The pillar area is modelled with the FRACOD and the stress field produced by excavation and heating is transferred with corresponding boundary stresses. From the modelling results, the degree of fracturing and damage are evaluated for 120 days of heating. Dominated shear fracturing in the vicinity of the central pillar was observed from the models at both sections, but spalled area appears to be limited. Based on the modelling results, a sensitivity study for the effect of pre-existing fractures in the vicinity of the holes is also conducted, and the initiation and evolution of EDZ around the deposition holes are investigated using this particular numerical technique.

1. Introduction

An in-situ experiment is planned at Äspö Hard Rock Laboratory (URL) in Sweden to investigate the stability of a pillar between two adjacent deposition holes under combined in situ stresses and heating (Andersson, 2003). One of the holes will be pressurized with 1 MPa water pressure to simulate the effect of backfill. The heating will be applied in the pillar by use of electric heaters to simulate anticipated nuclear waste decay. To predict the fracturing process in the pillar, these loading effects should be considered properly during the modeling works. A boundary element code, FRACOD was applied for this purpose. The code is based on the principles of displacement discontinuity method (DDM), together with a fracture mechanics criterion for fracture propagation (Shen, 2002). To extend the FRACOD's capacity for coupled thermo-mechanical loading conditions, substantial development is needed to consider domain effects caused by the transient heating effects and sequential stress redistributions caused by the excavation steps of test tunnel and the deposition holes. Such development involves evaluations of the domain integrals, using traditional internal cell mapping approaches that may not be numerically efficient, and demands considerable code development. Another technique is to apply inverse solutions to generate boundary tractions based on other domain-type numerical models that are efficient to consider domain effects like heating and non-linear deformation, such as FEM or FDM. The generated equivalent boundary tractions can then be used as boundary conditions for fracturing simulations using the FRACOD. This hybrid approach is adopted for this study (Rinne et al., 2003).

In this paper, we present the hybrid approach applied for the pillar modelling as shown in Fig. 1, and the methodology for initiation and propagation of discrete fractures using the FRACOD. Outcomes from the application of the approach and the FRACOD for fracturing process development in the pillar are presented as predictive results in terms of stress, displacements and fracture initiation and growth, under the multiple steps of excavation and heating of the in situ heater tests, whose effects is reflected in the derived equivalent boundary tractions used by the FRACOD. The basic assumption is that the problem is two-dimensional, the rock material is homogeneous,

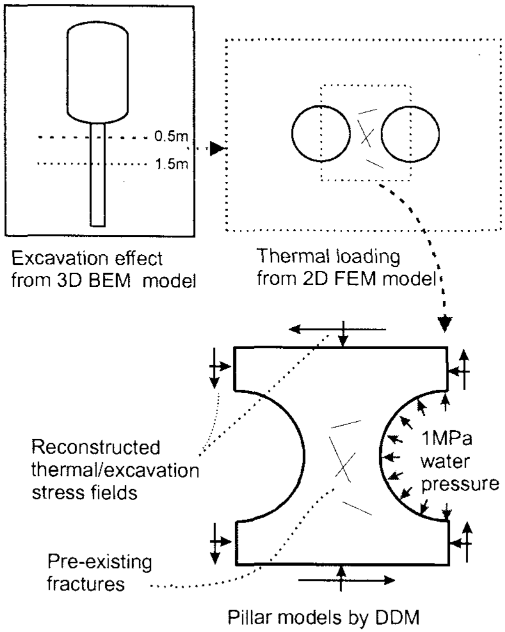


Fig. 1. Numerical methods used for the modelling.

isotropic and linearly elastic, and the linear elastic fracture mechanics (LEFM) principles govern the fracturing processes with a specially fracture initiation and propagation criterion for rock fractures.

2. Hybrid modelling approach

The principles of the inverse stress reconstruction

There are two kinds of inverse problems in the solid mechanics. One is the source reconstruction problem and the other is the parameter identification problem (Bezerra and Saigal, 1995). In the case of source reconstruction, usually unknown boundary conditions are determined using observed field quantities inside the domain of interest or over-prescribed boundary conditions. Parameter identification is the matter of characterization of unknown material parameters such as elastic modulus, Poisson's ratio, cohesion etc. with the knowledge of field quantities along the boundaries or inside domains. In this study we use only on source reconstruction technique for our application. On the other hand, if on some portion of the boundaries both displacements and tractions are unknown, it cannot be solved directly in a forward boundary value problem senses because the number of unknowns is larger than number of equations. However, if some quantities say stresses for our problem at hand, are known at some points inside the domain, the number of the equations can be increased to obtain a solution. Usually the solution of an inverse problem does not always satisfy stability and uniqueness requirements in itself, so it is generally an ill-posed problem. Therefore, special iterative or non-iterative numerical techniques should be applied to get a meaningful solution.

Based on the above concepts, stress distributions from other numerical modelling can be reconstructed after solving unknown boundary tractions with known stress distribution at some points inside the model. The reconstructed tractions along unknown boundaries can be used again to calculate stresses at all other points inside the domain using a conventional BEM code with the calculated boundary tractions directly used as prescribed boundary conditions in a BEM model, without the BEM code to have special functions for domain integral evaluations. A special BEM code was therefore developed to perform just such inversion tasks for this project and the details of the theory and verifications can be seen in Lee and Jing (2003) due to the limit of space for this paper.

Fracture modelling

Using the FRACOD, a rock fracture (crack, joint, etc.) can be simulated using DDM elements, including the opposite surfaces of the fracture. For *n* elements of fractures, a total of *2n* governing equations can be established, where the displacement discontinuities of the fracture elements are unknowns, which are obtained by solving the system of governing equations.

A rock fracture has three states: open, in elastic contact or sliding. The system of governing equations, developed for an open crack, can be easily extended for cracks in contact and sliding. The state of each crack (joint) element can be determined using the Mohr-Coulomb failure criterion:

$$\begin{aligned}&\text{- Open joint:}\ \sigma_n > 0\\&\text{- Elastic joint:}\ \sigma_n < 0,\ |\sigma_s| < c + |\sigma_n|\tan\phi\\&\text{- Sliding joint:}\ \sigma_n < 0,\ |\sigma_s| \geq c + |\sigma_n|\tan\phi\end{aligned} \tag{1}$$

where a compressive stress is taken to be negative and *c* is the cohesion. If the fracture experiences sliding, $c = 0$.

Both tensile and shear failure are common in rock masses. Therefore, to predict rock fracture propagation, a fracture criterion for both mode I and mode II fracturing is needed. In the FRACOD code, a modified G-criterion, namely the F-criterion, was proposed (Shen and Stephansson, 1994), by which the resultant strain energy release rate (G) at a fracture tip is divided into two parts, one due to mode I deformation (G_I) and one due to mode II deformation (G_{II}). The sum of their normalized values is used to determine the failure load and its direction. In an arbitrary direction (θ) at a fracture tip there exists a F-value (Fig. 2a)., which is expressed as the normalized sum of the two energy release rates

$$F(\theta) = \frac{G_I(\theta)}{G_{Ic}} + \frac{G_{II}(\theta)}{G_{IIc}} \tag{2}$$

where G_{IC} and G_{IIC} are the strain energy release rate (G) at a fracture tips for tensile and shear mode, respectively. The possible direction of propagation of the fracture tip is the direction ($\theta=\theta_0$) at which the F-value reaches its maximum value.

$$F(\theta)\big|_{\theta=\theta_0} = \max. \tag{3}$$

When the maximum F-value reaches 1.0, the fracture tip will propagate, i.e.

$$F(\theta)\big|_{\theta=\theta_0} = 1.0 \tag{4}$$

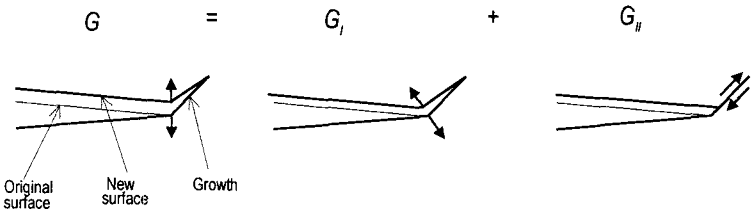
The F-criterion is actually a more general form of the G-criterion and it allows us to predict fracture propagation in both tension (mode I) and shear (mode II) modes.

In addition to the propagation of existing fractures, new fractures (cracks) may initiate at the boundaries excavations or inside the rock. Fracture initiation often starts from micro-cracks at a stress level of 0.3-0.6 of the rock strength. The micro-cracks may coalesce and finally form clusters of macro-fractures which may pose stability problems of the structure. To effectively consider the early fracture initiation at a microscopic scale before any final macro-scale failure, we assume that when the stress reaches 50% of the rock strength at a given location, a macroscopic crack will form, according to some experimental findings (Martin and Maybee, 2000). The crack surface however is assigned the strength of the intact rock. The crack may propagate only when the strength of the crack surface is exceeded during the subsequent change in stress. Using this treatment, we are able to predict that the fracture initiation starts when stress=0.5×strength but the failure occurs when stress=1.0×strength.

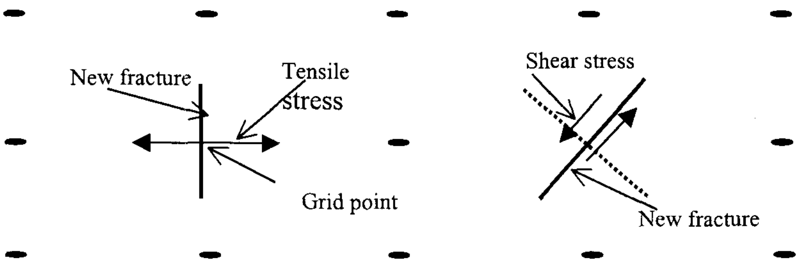
The Mohr-Coulomb criterion is used to estimate the strength of intact rock. A new rock fracture will be generated in the direction perpendicular to the tensile stress (Fig. 2b) when the relation below

$$\sigma_{tensile} \geq 0.5\sigma_t \tag{5}$$

is satisfied with the direction of the new tensile fracture given by



(a) Definition of G_I and G_{II} for fracture growth.



(b) fracture initiation in tension or shear in intact rock.
Fig.2. Modelling approach for fracture propagation and initiation.

$$\theta_{it} = \theta(\sigma_{tensile}) + \pi / 2 \tag{6}$$

where $\sigma_{tensile}$ is the principal tensile stress at a given point and σ_t is the tensile strength of the intact rock, respectively. The length of the newly generated fracture is determined by the size of the boundary elements in the model. It is currently set to be equal to the length of the smallest element.

Similarly, a shear fracture initiates when the shear stress at a given point of the intact rock exceeds 50% of the shear strength of the intact rock, a new rock fracture will be generated (Fig. 2b). The critical stress of fracture initiation in shear is given by

$$\sigma_{shear} \geq 0.5(\sigma_n \tan(\phi) + c) \tag{7}$$

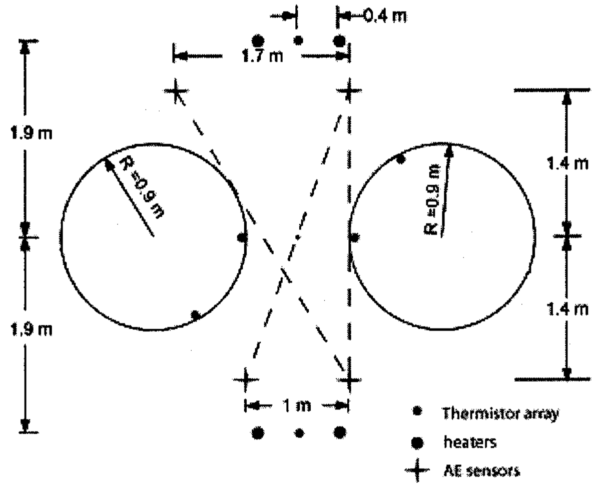
and the direction of the new shear fracture in calculated as

$$\theta_{is} = \phi/2 + \pi/4 \tag{8}$$

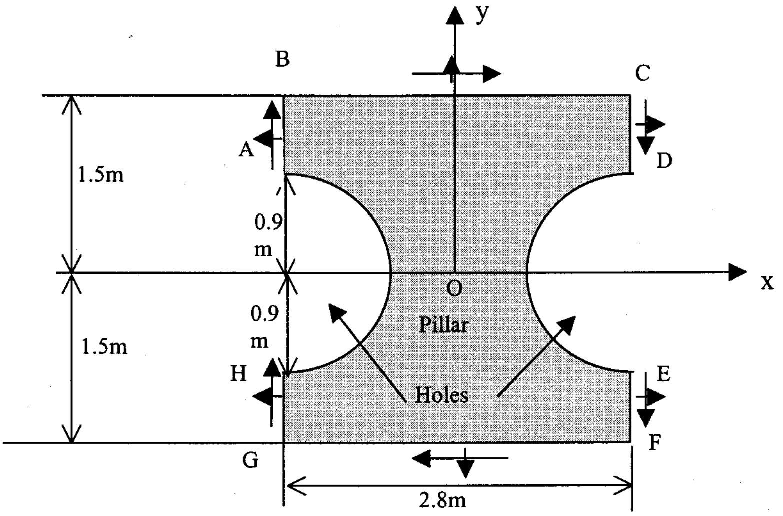
where σ_{shear} is the shear stress in the direction of θ_{is}, σ_n is the normal stress on the shear failure plane, ϕ is the internal friction angle of intact rock, c is the cohesion, respectively. The shear direction θ_{is} is measured from the direction of the minimum principal stress.

The modelling scheme using the hybrid approach

The developed hybrid approach and the FRACOD is applied to predict the fracturing process in the pillar of the planned in situ heater test at the Äspö URL, Southern Sweden. The whole test program is planned to have multiple step excavation of testing drift, two adjacent deposition holes, internal pressure of 1 MPa in one of the holes and heating of the rock pillar between the two holes. Fig. 3 shows planned experimental setup and the FRACOD model geometry. Since most stress concentration is anticipated inside pillar region, only pillar region is considered to reduce numerical efforts. Two 2D sections have been modeled at 1.5 m and 0.5 m below the tunnel floor. Different numerical modelling approaches, including FEM, BEM, and discrete particle methods will be applied to simulate the measured temperature, stress, displacement and Acoustic Emission data signaling the fracturing process inside the pillar. To test the newly developed stress reconstruction algorithm, the equivalent boundary tractions of a 2D



(a) Planned borehole geometry and instrumentations (After Fredriksson, 2003)



(b) Pillar model

Fig. 3. Experimental setup and specification for the pillar model.

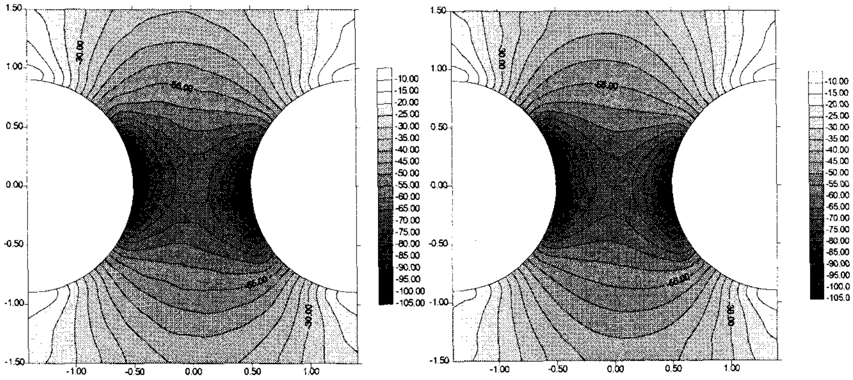
BEM model was calculated using the stress inversion technique, based on the initial stress fields produced by both a 2D FEM and a 3D BEM models at different excavation steps and heating time, with very good agreements (Fredriksson, 2003). The influence on redistributed stress fields caused by excavation of the tunnel and boreholes was modelled with a 3D BEM model (Andersson, 2003) without heating and fracturing effects. The induced stresses by heating were calculated with a 2D FE model (Fredriksson, 2003), also without fracturing simulation. The resultant stress fields by these models were used as input for the stress reconstruction analysis using the newly developed BEM code. The equivalent boundary tractions was calculated for steps from excavation to heating times at 30, 60, 90 and 120 days with the inverse BEM technique, and are used by FRACOD as pre-scribed boundary conditions for fracture analysis in an incremental form. The material properties of the rock and fractures are: 1) Intact rock: Young's modulus, 68 GPa; Poisson's ratio, 0.24; cohesion, 31 MPa; friction angle, 49°; and tensile strength, 14.8 MPa. 2) Rock fractures: fracture toughness, 2.54 MPa$m^{1/2}$ (Mode I) and 6.35 MPa$m^{1/2}$ (Mode II); normal stiffness, 4643 GPa/m; shear stiffness. 320 GPa/m. The friction angle and cohesion of the fractures are the same as that of the intact rock.

3. Results

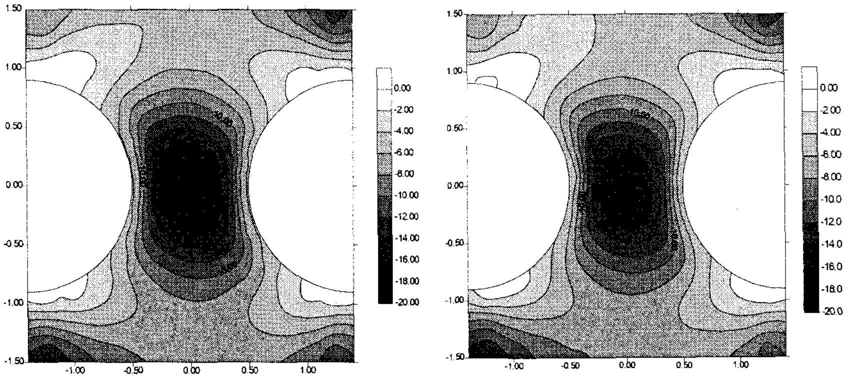
Reconstructed stresses by excavation and thermal loading

Two sections of stress distribution (1.5m, 0.5m) by excavation and four stages of stress distribution by heating (30, 60, 90 and 120 days) are reconstructed for the simulation of fracture process. Fig. 4 shows the comparison between original and the reconstructed stress field for excavation at 1.5 m below the tunnel floor.

The reconstructed stress distribution shows nearly same for both major and minor principal stresses, so it is difficult to figure it out from original distribution. Reconstructed stresses close to boundaries show less accuracy, but it comes from limitation of constant element. Stress distributions could be reproduced very well for all loading steps. In most cases, errors for the major principal stress show below 1% except in the case of 0.5 m below the tunnel floor. Stress distribution of thermal stresses can be reconstructed with better accuracy than that from that of excavation because original distribution is modeled with 2 dimensional. At 0.5 m section below the tunnel floor, worst accuracy was obtained due to artificial reconstruction of 3 dimensional stress distribution to 2 dimensional one. Though errors for minor principal stress seem to be big at near boundary, real differences are small since the values are close to zero.



(a) Major principal stress (σ_1).



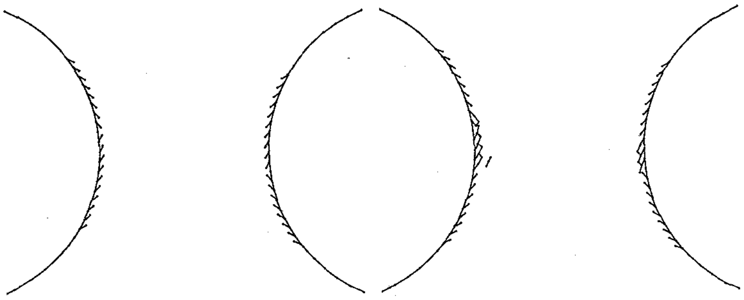
(b) Minor principal stress (σ_3).

Fig. 4. Comparison between the original and the reproduced stresses before heating at the horizontal level of 1.5 m below the tunnel floor (left: original stress, right: reconstructed stress).

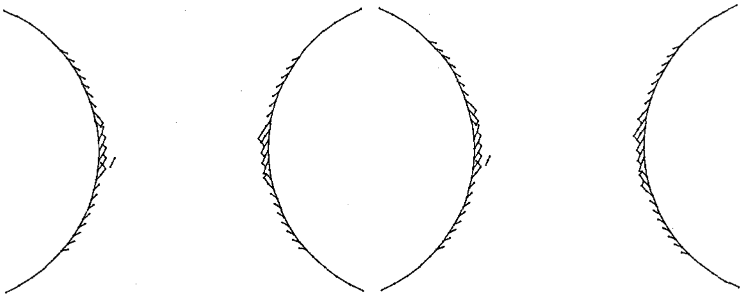
Fracture process in the pillar

Fracture processes at the borehole pillar are simulated using the reconstructed stress distribution for each stage. Fig. 5 shows the stepwise evolution of fracture initiation and propagation at 1.5 m below the tunnel floor.

After borehole excavation, fracture initiation along the borehole boundary is occurred, which represents slight damage of borehole wall. With increasing thermal loading, fracture propagation and coalescence are observed only

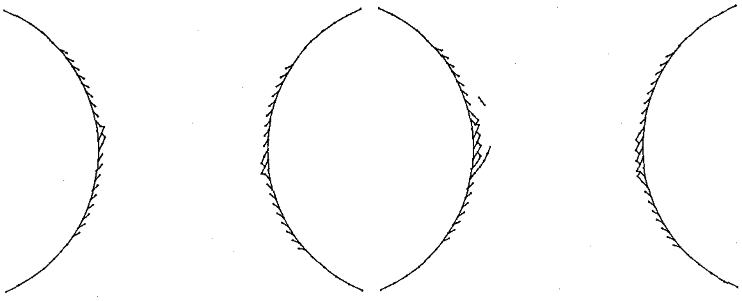


(a) After excavation (b) After 30 days of heating

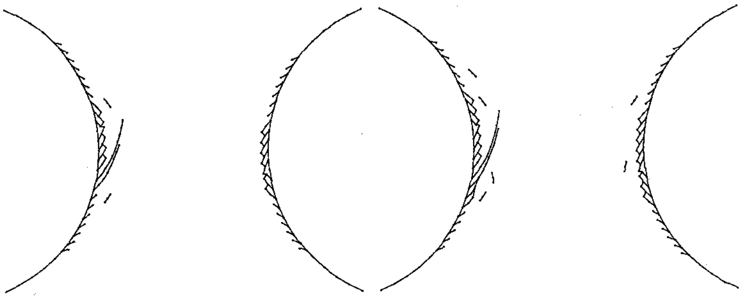


(c) After 60 days of heating (d) After 120 days of heating

Fig. 5. Fracture evolution at 1.5 m below the tunnel floor.



(a) After excavation (b) After 30 days of heating



(c) After 60 days of heating (d) After 120 days of heating

Fig. 6. Fracture evolution at 0.5 m below the tunnel floor.

near central pillar boundaries. Overall rock mass inside pillar region would be stable during experiment with planned loading stages. All fractures are created by shear mechanism, which is major process in deep rock mass (Guenot, 1989). Fracture evolution at 0.5 m below the tunnel floor is shown in Fig. 6

Higher stress concentration at this level can make more fracture propagation after excavation. Compared to the results at 1.5 m section, more pronounced fracture propagations are observed during the planned loading step. Major fractures are also generated with increasing thermal loading, and they can make possible wedge-shaped spalled area with further loading.

4. Conclusions

In this paper, we presented the hybrid approach for predicting fracturing processes in a rock pillar during a planned in situ heater test at Äapö URL of SKB, Southern Sweden. We presented both the hybrid modeling approach, the DDM methodology and the F-criterion for initiation and propagation of fractures in rock. The results of the prediction indicate that the fracturing may be limited mainly in small areas near the all of the pillar without forming significant fracture clusters, and spalling may only occur near the intersection of the deposition holes and the test tunnel floor, without endanger the overall stability of the pillar-hole system.

The FRACOD has been further developed to simulated AE effects associated with fracture initiation and growth. The future works will focus on validation of the prediction with measured AE signals that will be measured in situ during the heater test.

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