3D-DISKRET ELEMENTMODELLERING AV DYNAMISKA BROTT I SAMBAND MED FÖRKASTNINGSRÖRELSER: EN TILLÄMPNING VID SÄKERHETSBEDÖMNINGEN AV ETT SLUTFÖRVAR FÖR ANVÄNT KÄRNBRÄNSLE

3D-DISCRETE ELEMENT MODELLING OF FRACTURE SLIP INDUCED BY A FAULT DYNAMIC RUPTURE: APPLICATION TO SPENT FUEL REPOSITORY SAFETY ASSESSMENT

Jeoung Seok Yoon, DynaFrax UG, Germany

Arno Zang, Helmholtz Centre Potsdam, Germany

Ove Stephansson, Helmholtz Centre Potsdam, Germany

Carl-Henrik Pettersson, Swedish Radiation Safety Authority, Sweden

Flavio Lanaro, Berggeologiska Undersökningar AB, Sweden

Summary

When assessing the safety of a repository for spent fuel it is important to understand i) in what conditions fracture slip can occur in the repository rock volume, ii) the size of the resulting slip displacements and iii) their potential impact on the long-term safety. A 3D-thermo-mechanical coupled study conducted by the Authors (Yoon and Zang 2019, SSM Report 2019 in press) has investigated the induced fracture slip due to thermal and/or seismic loads. The investigation is conducted for SKB's proposed site for a geological repository for spent nuclear fuel in Forsmark, Sweden. This paper reports one of the examined cases in the performed study, the case with seismic loads.

The simulation code used is Particle Flow Code 3D (PFC3D), a commercial code by Itasca. Based on the site characterization work performed by SKB, a 3D geological model with the major faults and deformations zones was created. Furthermore, a discrete fracture network in the repository volume is generated based on DFN data from Forsmark. The deformation zones and repository fractures are implemented using the PFC3D's smooth joint model. In this case, we simulated an earthquake event occurring at a gently dipping fault, ZFMA3, above the repository rock volume for the present day reverse faulting stress condition. We investigated the temporal and spatial changes in the fault slip and the slip of the repository fractures in these conditions. The simulated magnitude associated with the fault dynamic rupture of zone ZFMA3 is M5.7 with slip displacement of 0.42 m, which reasonably fit into the scaling parameters of natural earthquake faults for a zone of this length. The fault slip concentrates at shallow depth and decreases along the dip of ZFMA3. The slip displacements of the repository fractures change with time, showing that some fractures record displacements increasing to a peak and then decreasing, and some show a gradual increase with time without recovery, resulting in a permanent slip displacement. This study demonstrates that the repository fractures can slip due to an earthquake event occurring at a nearby fault. Further studies are needed to fully understand the potential impact of fracture displacements on the engineered barrier system in the repository.

Sammanfattning

Vid utvärderingen av den långsiktiga säkerheten för att slutförvar för använt kärnbränsle är det viktigt att förstå under vilka förhållanden som sprickrörelser sker och hur mycket de rör sig och vilken betydelse det har för den långsiktiga säkerheten. En 3D kopplad termisk-mekanisk studie (Yoon and Zang 2019, SSM 2019 kommande publikation) har undersökt sprickrörelser orsakade av termiska och/eller seismiska laster. Studien utgår från SKBs ansökta plats för ett geologiskt slutförvar för använt kärnbränsle i Forsmark, Sverige. Denna artikel baseras på en av studiens modelleringsfall utan termiska laster.

Vid simuleringarna av jordskalv använde vi Particle Flow Code 3D (PFC3D v4) som är en 3-D diskret elementkod utvecklad av Itasca. För att simulera jordskalv av en magnitud större än M5, utgår studien från SKB:s regionala geologiska modell för Forsmark med fokus på zon ZFMA3. Resultaten visar att källparametrarna vid simuleringen av jordbävningen, t.ex. en skjuvrörelse i zon ZFMA3 på 0,42 m, är i god överensstämmelse med dokumenterade skalningsförhållanden från observationer av jordskalvsförkastningar. En av slutsatserna från denna studie är att simuleringarna av dynamiska brott i samband med förkastningsrörelser väl kan återge brottmekanismer vid naturliga jordskalvsförkastningar. Resultaten visar också att enskilda sprickor i slutförvaret förskjuts i samband med ett jordskalv vid någon av de närliggande större förkastningarna i Forsmark. Skjuvrörelserna i vissa sprickor går upp till ett värde men sen minskar igen, i andra sprickor permanenta förskjutningar uppstår. Ytterligare studier krävs dock för att fullt ut förstå sprickförskjutningarnas inverkan på det tekniska barriärsystemet i slutförvaret.

1. Introduction

To ensure a long term safety of a repository for spent nuclear fuel, it is necessary to consider all possible scenarios that could impair the physical integrity of geological and technical barriers of the disposal facility. One type of scenario is an earthquake event occurring at a fault nearby the repository. This primary event can induce secondary shearing along fractures intersecting the deposition holes that contain the canisters with spent nuclear fuel. It is therefore necessary to estimate what effects an earthquake event have on the repository, both on the nearby system of faults and on the repository fracture network. To do so, one should rely on a simulation tool that can capture the physics involved in a dynamic fault rupture. Moreover, to be applied to a safety analysis of an underground nuclear waste repository, the simulation tool should be able to model the complex geological system of the site, in particular, the heterogeneity of the rock mass and the geometrical complexity of the geological discontinuities at various scales (faults, joints and fractures).

Yoon et al. (2014, 2016, 2017) investigated the safety of the Forsmark repository against earthquake events occurring at nearby faults by conducting 2D discrete element-fracture dynamic modelling using Particle Flow Code 2D (PFC2D). In this paper, we present a development of these studies into a 3D numerical modelling of the proposed underground repository at Forsmark, Sweden. We simulate an earthquake event with magnitude M~6, we investigate the dynamic features of the fault rupture and analyze the impact of the earthquake to the repository fracture system.

2. Particle Flow Code and fracture modelling using the smooth joint model

The modelling code Particle Flow Code 3D (PFC3D) is a commercial software of Itasca. We used the combination of Bonded Particle Model approach (Potyondy and Cundall 2004) and Synthetic Rock Mass approach (SRM, Mas Ivars et al. 2011), where the discrete fracture network (like that shown in Fig.1a) and faults are imbedded in a bonded particle assembly to represent the *in-situ* jointed rock mass.

Each individual joint in the rock mass is represented explicitly by the use of the smooth joint contact model (Mas Ivars et al. 2011). When a fracture is embedded in a randomly distributed bonded particle assembly, the fracture is represented as a collection of many smooth joints that are oriented in the same direction but placed with an off-set from each other. Such feature of the SRM approach allows the irregularity of the geological discontinuities to be modelled. However, it also bears one disadvantage which is that the irregularity in the smooth joint alignment depends highly on the particle size distribution, i.e. the coarser particles, the more diffused pattern of the smooth joints is obtained, as demonstrated in Figure 1b and 1c.

3. The 3D geological model of Forsmark repository site

A 3D geological model of Forsmark repository site is generated using PFC3D. The model contains the geological discontinuities such as deformation zones and the repository fractures. The major deformation zones in the model are the steeply dipping zones, ZFMWNW0001 (Singö), ZFMNW0003 (Eckarfjärden), ZFMWNW0004 (Forsmark), and the gently dipping zones, ZFMA1 (beneath the repository rock volume), ZFMA2 and ZFMA3 (above the repository rock volume). These deformation zones are estimated to be large enough to host a magnitude M~6 earthquake event.

Figures 2 is the top view of the 3D geological model of Forsmark repository site generated by PFC3D using ACDC (Adaptive Continuum and Discontinuum Method, Dedecker et al. 2007). The two sets of arrows indicate the orientations of the present day *in-situ* maximum (SH,max) and minimum (Sh,min) horizontal stresses at the repository depth with magnitude of 40 MPa and 22 MPa, respectively (Martin 2007).

The traces of the deformation zones and the fractures systems are shown in blue and red, respectively.

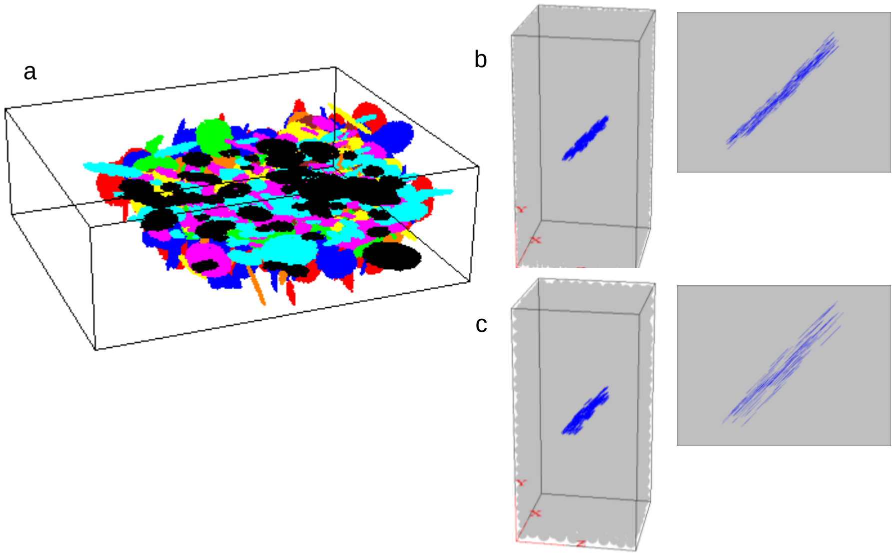

Figure 1. (a) Discrete Fracture Network used in this study, (b) a single fracture model embedded in a particle assembly with fine resolution and (c) in a particle assembly of coarse resolution. The figures on the right show the smooth joints placed in different particle models with high resolution.

4. The 3D geological model of Forsmark repository site

A 3D geological model of Forsmark repository site is generated using PFC3D. The model contains the geological discontinuities such as deformation zones and the repository fractures. The major deformation zones in the model are the steeply dipping zones, ZFMWNW0001 (Singö), ZFMNW0003 (Eckarfjärden), ZFMWNW0004 (Forsmark), and the gently dipping zones, ZFMA1 (beneath the repository rock volume), ZFMA2 and ZFMA3 (above the repository rock volume). These deformation zones are estimated to be large enough to host a magnitude M~6 earthquake event.

Figures 2 is the top view of the 3D geological model of Forsmark repository site generated by PFC3D using ACDC (Adaptive Continuum and Discontinuum Method, Dedecker et al. 2007). The two sets of arrows indicate the orientations of the present day *in-situ* maximum (SH,max) and minimum (Sh,min) horizontal stresses at the repository depth with magnitude of 40 MPa and 22 MPa, respectively (Martin 2007). The traces of the deformation zones and the fractures systems are shown in blue and red, respectively.

Natural pre-existing fractures in the repository rock mass are implemented as Discrete Fracture Network (DFN) and embedded in the models. The DFN is stochastically generated (Fig.1a) within the repository rock volume (grey shaded region in Fig.2a).

The fractures that are stochastically generated by the DFN generator are planar disks (Fig.1a). However, in PFC3D, when a planar fracture is embedded in a PFC discrete element model, the fracture is represented by a collection of smooth joints as shown in Figure 1b and 1c.

5. Simulation of fault dynamic rupture

To simulate an earthquake event by a dynamic fault rupture, we used the method developed in Yoon et al. (2014, 2016, 2017) where the deformation of the particle contacts (smooth joint contacts) along the earthquake hosting fault is locked during the initial *in-situ* stress loading of the model (Step 1 – Locking). In this way, the strain energy from the *in-situ* stress loading accumulates at the smooth joints of the locked deformation zone.

The strain energy is then released by instantaneously unlocking the particle contacts (smooth joint contact) of the deformation zone (Step 2 – Unlocking), which results in generation of a seismic wave. The unlocking is done by lowering the tensile strength and cohesion of the smooth joints to zero. In addition, the friction coefficient, friction angle and dilation angle of the smooth joints are lowered to 10% of their initial values. This is intended to mimic the dynamic rupturing process where the fault surface asperities are sheared by the rupturing.

After unlocking the fault, we confirmed that a seismic wave is generated from the ruptured fault trace. The seismic wave then travels through the model, and at the same time attenuates due to the damping in the model (Step 3 – Propagation & Attenuation). By monitoring stress evolution at certain locations in the model and distant from the seismic source, we confirmed the occurrence of a dynamic peak stress level followed by a static stress level, which are typically observed in tectonic earthquake faulting (Belardinelli et al. 1999, Kilb et al. 2000).

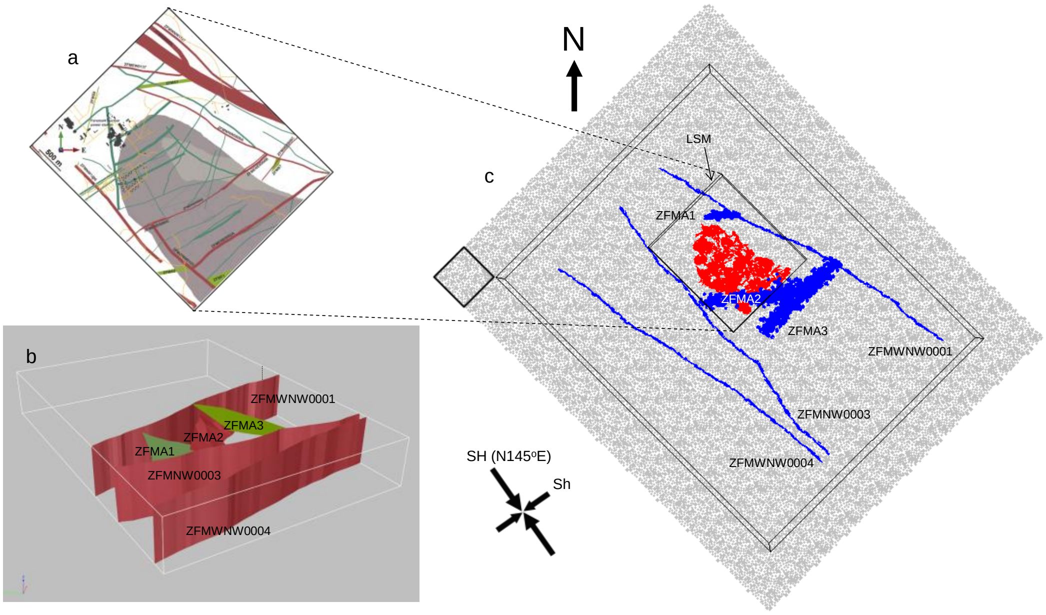

Figure 2. (a) Integrated geological model of Forsmark showing the deformation zones (Stephens et al. 2015). Gray region: repository rock volume, red: steeply dipping or vertical deformation zone with surface trance length > 3 km, dark green: steeply dipping or vertical deformation zone with surface trance length < 3 km, green: gently dipping deformation zones, (b) large major deformation zones embedded in the model, (c) the PFC3D geological model. The traces of the discontinuities at the repository depth are presented in different colors (red: repository fractures, blue: deformation zones). The arrows indicate the orientation of the maximum and the minimum horizontal stresses at the depth of the repository.

6. Results and discussion

6.1. Activation of deformation zone ZFMA3 under present day in-situ stress conditions

In this modelling case, we simulate an activation of ZFMA3 (gently dipping zone above the repository rock volume) occurring under present day reverse faulting *in-situ* stress conditions. Figure 3 shows the slip magnitudes of the smooth joints that compose the deformation zone. Large slip concentrates in a shallow region close to the surface, and the slip decreases with dipping towards the fault deep end. The average slip magnitude of the activated ZFMA3 is 0.42 m and the moment magnitude calculated using the equation by Hanks and Kanamori (1979) is Mw 5.71:

$$M_w = \frac{2}{3}\log(GAd) - 6$$

Where, G is the shear modulus (i.e. 30 GPa), A is the fault surface area, and d is fault slip displacement.

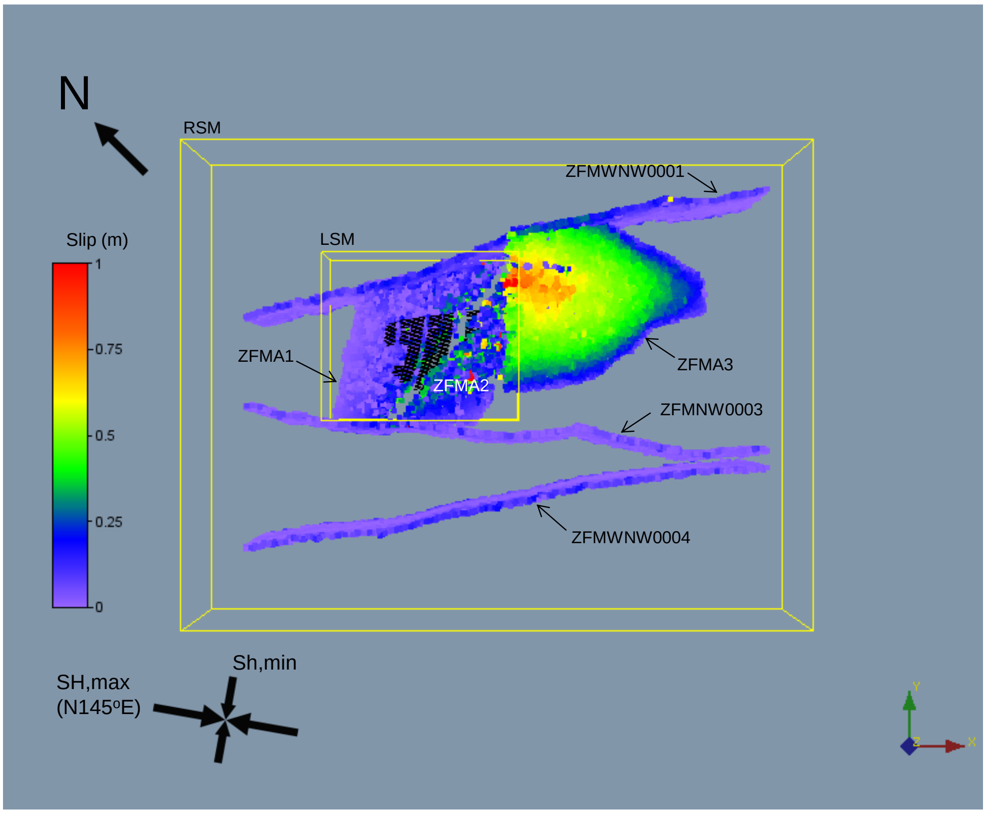

Figure 3. Distribution of co-seismic slip of the deformation zones in the Regional Size Model (RSM) induced by full plane activation of ZFMA3 under present day reverse faulting *in-situ* stress conditions.

Temporal and spatial evolution of slip on the primary fault ZFMA3 is shown in Figure 4. The displacements of the smooth joints of the primary fault are calculated at selected times. The slip is mostly concentrated in the upper center part of the fault, and diminishes with depth. The slip increases with time until ca. 1 second and then decreases slightly after reaching a peak and then falls to a permanent residual slip value. The failure mechanism results in a change in the local stress field in the repository rock volume (i.e. dynamic stress transfer) followed by a stress redistribution of stresses due to permanent slip of the fault (i.e. static stress transfer).

6.2. Analysis of fracture slip

Slip of the repository fractures induced by the activation of ZFMA3 is shown in Figure 5. The induced fracture slip, similar to the fault slip at ZFMA3, changes with time as shown in Fig. 5a. The fracture slip records a peak after ca. 1 second. After reaching the peak values, the slip on some of the fractures decreases and on some shows gradual increase. However, the fracture slip changes end after 3 seconds, which gives the permanent residual fracture slip displacements.

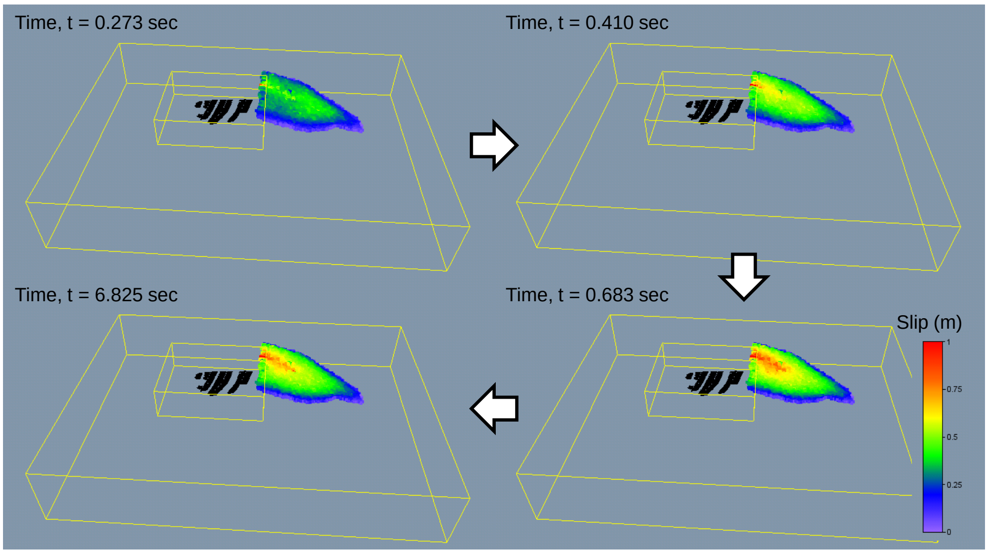

Figure 4. Temporal and spatial evolution of the primary slip on a gently dipping fault (ZFMA3) ruptured under present day reverse faulting stress condition.

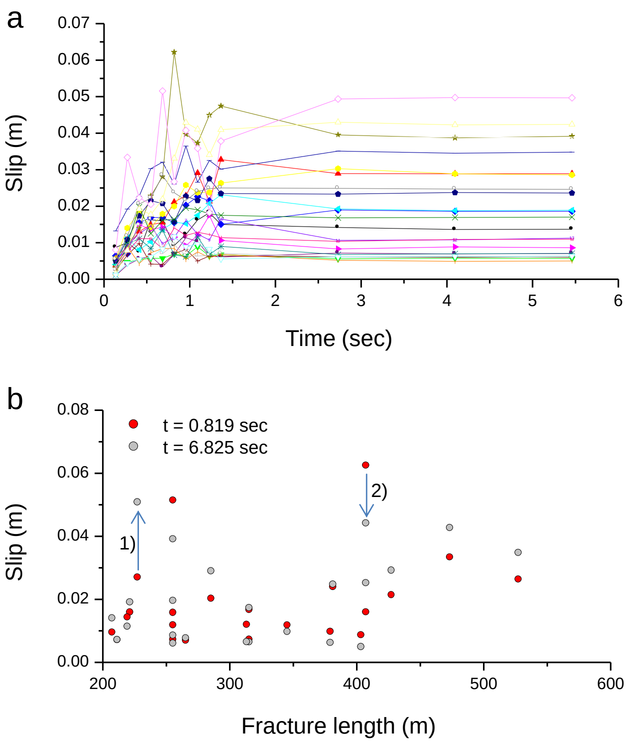

Figure 5. (a) Fracture slip as a function of time and (b) fracture slip as a function of fracture length at different selected times.

Figure 5b shows the slip displacement with respect to the fracture length (i.e. diameter). The data points in gray are the fracture slip displacements at 0.819 seconds after the fault activation. The data points in red are the results at 6.825 seconds after the fault activation. The results demonstrate that some fractures undergo a peak slip at 0.819 seconds and the slip decreases with time after that (Fig.5b, 2). However, for some of the fractures the slip continues to increase with time (Fig.5b, 1). It is considered that such different responses depend on how the fractures are oriented in the target area, on how close the fractures are located with respect to the seismic source and on how they are interconnected with neighboring fractures.

7. Conclusions

In this study we investigated the impact of an earthquake occurring at a gently dipping fault near to the proposed repository site at Forsmark, Sweden. A 3D geological model is generated using PFC3D, which contains the major deformation zones and the repository fractures. This study focus on rock fracture shear displacements induced by a dynamic rupture of a gently dipping fault, named ZFMA3, located above the repository rock volume.

From the simulation we found that under the present day reverse faulting *in-situ* stress conditions, an earthquake event occurring at fault ZFMA3 could have a magnitude of M5.7. The slip distribution along the fault surface shows that slip concentrates at the central and upper part of the fault, and decrease along the dip of the fault. This feature demonstrates that the PFC3D modelling reasonably captures the detail facets of the rupturing process of a natural fault during an earthquake.

Slip of the repository fractures is investigated and shows for studying the changes with time after the earthquake release. The results indicate that fracture slip may record a peak at the same time as for the peak slip of the activated fault and then decreases. Slip may also gradually increase until the seismic disturbance by the fault ceases. This study demonstrates that the repository fractures can increasingly slip during the whole seismic event of an earthquake occurring at a nearby fault, but further studies are needed to fully understand the potential impact of this on the integrity of the engineered barrier system in a spent fuel repository in crystalline rocks.

8. Acknowledgement

The authors would like to thank Prof. Dr. Hilmar Bungum (NORSAR), Prof. Dr. Fabrice Cotton (GFZ) for their discussion on the results and feedbacks in a seismological perspective. We also thank Dr. Joel Geier (Clearwater Hardrock Consulting) for providing the DFN data sets.

9. References

Belardinelli ME, Cocco M, Coutant O, Cotton F. 1999. Redistribution of dynamic stress during coseismic ruptures: Evidence for fault interaction and earthquake triggering. *J Geophys Res* **104**, 14925-14945.

Dedecker F, Cundall P, Billaux D, Groeger T. 2007. Evaluation of damage-induced permeability using a three-dimensional Adaptive Continuum/Discontinuum Code (AC/DC). *Physics and Chemistry of the Earth* **32**, 681-690.

Hanks TC, Kanamori H. 1979. A moment magnitude scale. *J Geophys Res* **84**, 2348-2350.

Kilb D, Gomberg J, Bodin P. 2000. Triggering of earthquake aftershocks by dynamic stresses. *Nature* **408**, 570-574.

Martin CD. 2007. Quantifying in situ stress magnitudes and orientations for Forsmark. Forsmark state 2.2., SKB R-07-26, Swedish Nuclear Fuel and Waste Management Co.

Mas Ivars D, Pierce ME, Darcel C, Reyes-Montes J, Potyondy DO, Young RP, Cundall A. 2011. The synthetic rock mass approach for jointed rock mass modelling. *Int J Rock Mech & Min Sci* **48**, 219-244.

Potyondy DO, Cundall PA. 2004. A bonded-particle model for rock. *Int J Rock Mech & Min Sci* **41**, 1329-1364.

Stephens MB, Follin S, Petersson J, Isaksson H, Juhlin C, Simeonov A. 2015. Review of the deterministic modelling of deformation zones and fracture domains at the site proposed for a spent nuclear fuel repository, Sweden, and consequences of structural anisotropy. *Tectonophysics* **653**, 68-94.

Yoon JS, Stephansson O, Min KB. 2014. Relation between earthquake magnitude, fracture length and fracture shear displacement in the KBS-3 repository at Forsmark Main Review Phase. SSM Technical Note 2014:59, Swedish Radiation Safety Authority.

Yoon JS, Stephansson O, Zang A, Min KB, Lanaro F. 2016. Numerical modelling of earthquake and induced seismicity under various in situ stress conditions at Forsmark, Sweden, the site for a final repository of spent nuclear fuel. In: Proc of the 7th Int Symp on In-Situ Rock Stress – RS2016 Symposium, May 2016, Tampere, Finland.

Yoon JS, Stephansson O, Zang A, Min KB, Lanaro F. 2017. Discrete bonded particle modelling of fault activation near a nuclear waste repository site and comparison to static rupture earthquake scaling laws. *Int J Rock Mech & Min Sci* **98**, 1-9.

Yoon JS, Zang A. 2019. 3D Thermo-Mechanical Modelling of Induced Seismicity related to the Final Disposal of Spent Nuclear Fuel and Nuclear Waste in Hard Rock. SSM Report in press.