

# Application of *PFC3D* in earthquake modelling and seismic hazard assessment of an underground nuclear waste repository

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## 1 INTRODUCTION

To ensure the long-term safety of an underground repository for nuclear waste disposal, it is necessary to consider all possible scenarios that could impair the physical integrity of geological and technical barriers of the disposal facility. In this study, we considered, as one type of scenario, an earthquake event occurring at a fault nearby the repository. The impact of an earthquake to the repository can be that a slip of a fracture intersecting a deposition hole induced by the static and dynamic effect of an earthquake event can be larger than a slip threshold of a canister containing the nuclear waste and results in a release of radioactive material. 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 dynamic fault rupture phenomena. Moreover, to be applied to a safety analysis of an underground nuclear waste repository, the simulation tool should be able to mimic the complex nature of the Earth crust, 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 an underground repository for final disposal of spent nuclear fuel in Forsmark, Sweden. In this paper, using *PFC3D*, we present a numerical modelling technique to mimic a fault dynamic rupture (an earthquake event) and investigate the impact of the earthquake to the repository fracture system.

## 2 FRACTURE MODELLING USING SMOOTH JOINT MODEL IN *PFC*

The modelling code Particle Flow Code 3D (*PFC3D*) is a commercial software of Itasca (Itasca 2018). We used the combination of Bonded Particle Model approach (BPM, Potyondy & Cundall 2004) and Synthetic Rock Mass approach (SRM, Mas Ivars et al. 2011), where the discrete fracture network (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 & 1c.

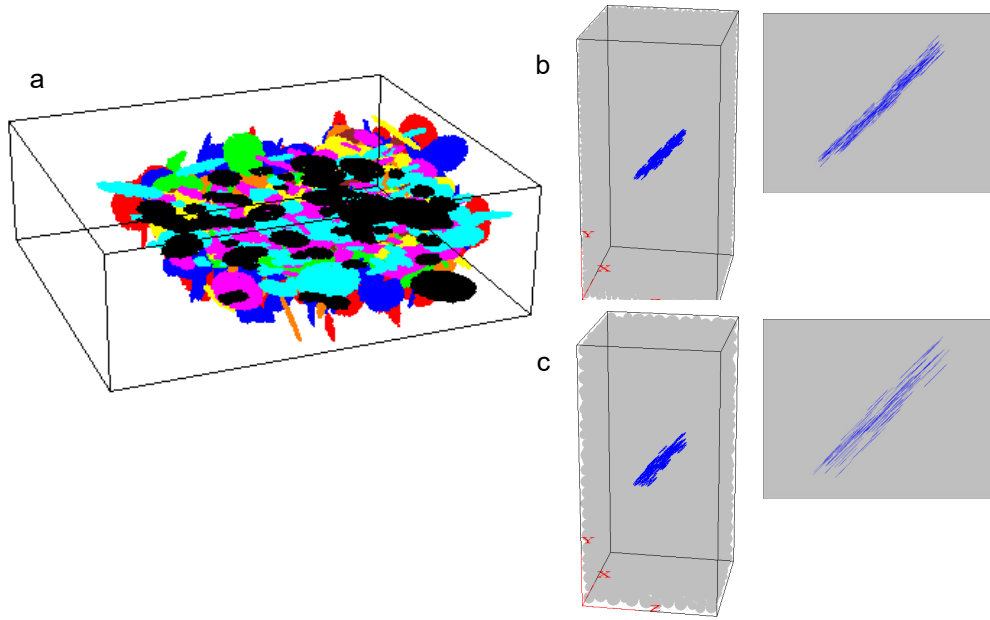


Figure 1. (a) Discrete Fracture Network used in this study, (b) a single fracture model embedded in a particle assembly with fine resolution and (c) in a particle assembly of coarse resolution.

### 3 GENERATION OF GEOLOGICAL MODEL USING *PFC3D*

A 3D geological model of the 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 large enough to host a magnitude M~6 earthquake event. Figure 2 is the top view of the 3D geological model of Forsmark repository site generated by *PFC3D* using Adaptive Continuum and Discontinuum Method (ACDC, De-decker et al. 2007). The two sets of arrows indicate the orientations of the present day *in-situ* maximum ( $S_H, \max$ ) and minimum ( $S_h, \min$ ) 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 model (Fig.1a). The DFN is stochastically generated within the repository rock volume (grey shaded region in Fig.2a).

### 4 SIMULATION OF FAULT DYNAMIC SLIP USING *PFC*

To simulate a dynamic fault slip by brittle rupture, we used the ‘lock-stress & unlock-release’ method (Yoon et al. 2014, 2016, 2017). In this method the deformation of the particle contacts (smooth joint contacts) along the earthquake hosting fault is locked during the *in-situ* stress loading on the model. In this way, the strain energy from the *in-situ* stress loading accumulates at the smooth joints of the locked fault plane. The strain energy is then released by instantaneously unlocking the particle contacts (smooth joint contact) of the faults, 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 activated fault trace. The seismic wave then travels through the model, and at the same time attenuates due to the damping in the model. 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).

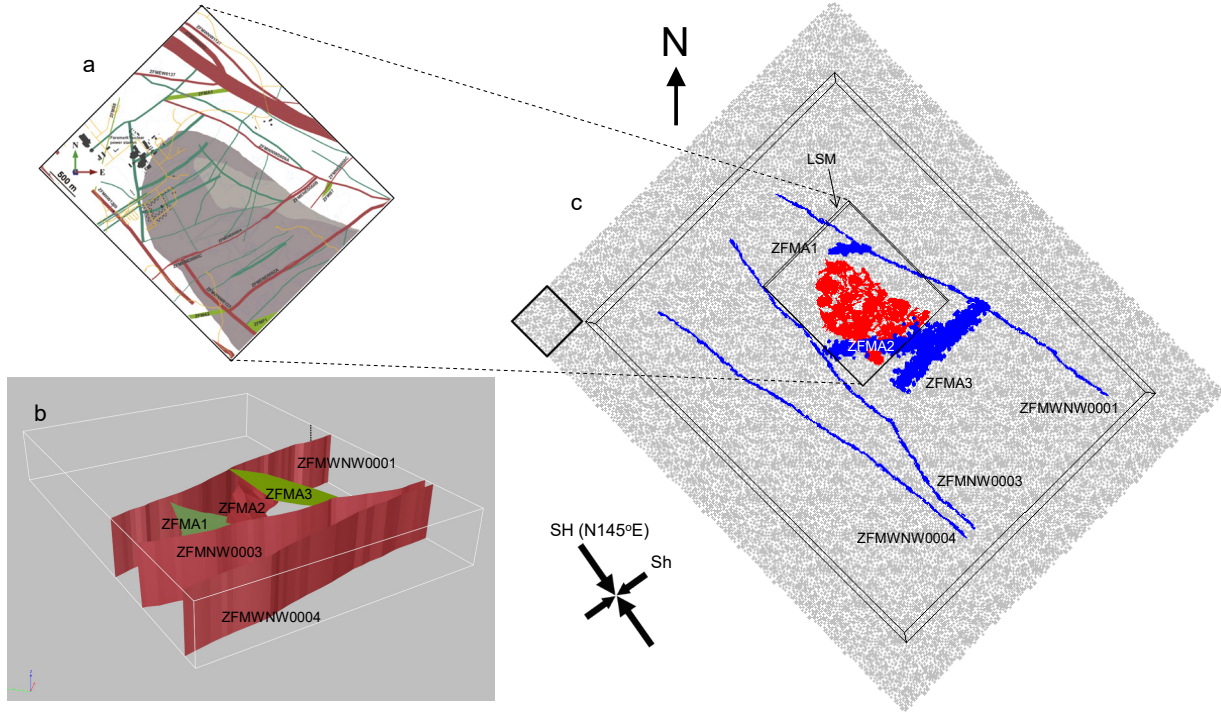


Figure 2. (a) Integrated geological model of Forsmark showing the deformation zones (Stephens et al. 2015). Gray region: repository rock volume, red: steeply dipping or vertical faults with surface trace length > 3 km, dark green: steeply dipping or vertical faults with surface trace length < 3 km, green: gently dipping faults, (b) large major faults 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: faults). The arrows indicate the orientation of the maximum and the minimum horizontal stresses at the depth of the repository.

In this paper, we present one simulation case where a gently dipping fault is activated under present day *in-situ* stress condition. Figure 3 shows the slip magnitudes of the smooth joints that compose the faults when a gently dipping fault is activated. 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,  $d$ , of the activated fault is 0.42 m and the moment magnitude,  $M_w$ , calculated using the equation by Hanks & Kanamori (1979) is 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.

Temporal and spatial evolution of slip on the gently dipping fault is shown in Figure 4. The displacements of the smooth joints of the activating 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.

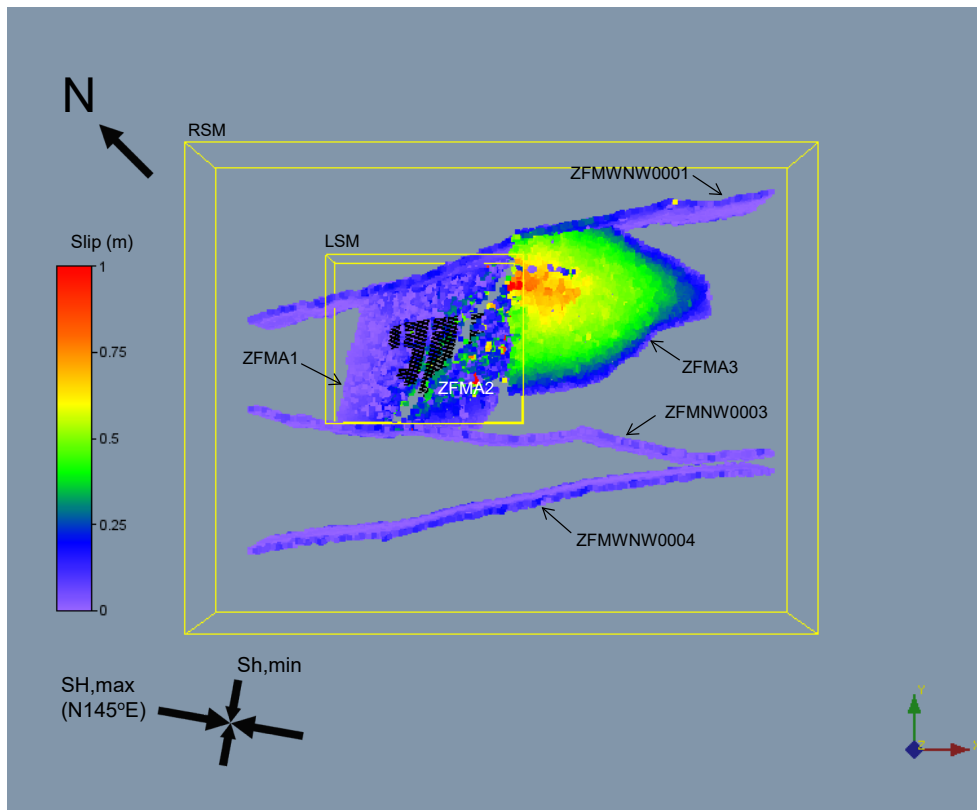


Figure 3. Distribution of co-seismic slip of the faults induced by full plane activation of a gently dipping fault ZFMA3 activated under the present day reverse faulting *in-situ* stress condition.

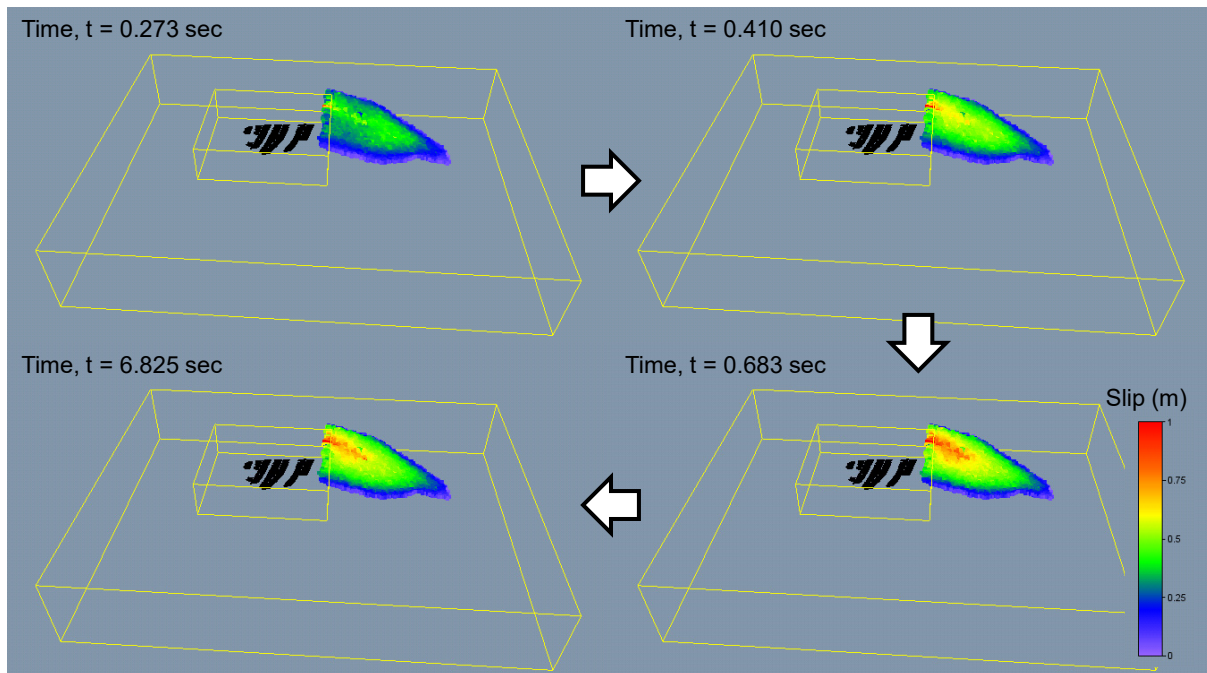


Figure 4. Dynamic slip of a gently dipping fault activated under the present day reverse faulting *in-situ* stress condition.

## REFERENCES

- Belardinelli, M.E., 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). *Phys Chem Earth* 32, 681-690.
- Hanks, T.C. & Kanamori, H. 1979. A moment magnitude scale. *J Geophys Res* 84, 2348-2350.
- Itasca Consulting Group, Inc. 2018. *PFC3D – Particle Flow Code in 3-Dimensions, Ver. 6.0*. Minneapolis: Itasca.
- Kilb, D., Gombert, J. & Bodin, P. 2000. Triggering of earthquake aftershocks by dynamic stresses. *Nature* 408, 570-574.
- Martin, C.D. 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, M.E., Darcel, C., Reyes-Montes, J., Potyondy, D.O., Young, R.P. & Cundall, P.A. 2011. The synthetic rock mass approach for jointed rock mass modelling. *Int J Rock Mech & Min Sci* 48, 219-244.
- Potyondy, D.O. & Cundall, P.A. 2004. A bonded-particle model for rock. *Int J Rock Mech & Min Sci* 41, 1329-1364.
- Stephens, M.B., 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, J.S., Stephansson, O. & Min, K.B. 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, J.S., Stephansson, O., Zang, A., Min, K.B. & 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, J.S., Stephansson, O., Zang, A., Min, K.B. & 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, J.S. & 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.