International Journal of Rock Mechanics & Mining Sciences 98 (2017) 1–9

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Discrete bonded particle modelling of fault activation near a nuclear waste repository site and comparison to static rupture earthquake scaling laws

Jeoung Seok Yoon[a,*], Ove Stephansson[a], Arno Zang[a], Ki-Bok Min[b], Flavio Lanaro[c]

[a] GFZ German Research Center for Geosciences, Potsdam, Germany
[b] Seoul National University, Seoul, South Korea
[c] Swedish Radiation Safety Authority, Stockholm, Sweden

ARTICLE INFO

Keywords:
Discrete element model
Fault activation
Nuclear waste repository
Earthquake scaling laws

1. Introduction

To be able to assess the safety of a repository for radioactive waste and spent nuclear fuel, and to make proper adjustment in its engineering design if necessary, it is required to consider all possible threats that could impair the physical integrity of the barriers. One of the environmental threats to an underground nuclear waste repository is an earthquake occurring at nearby faults. The effect of an earthquake relevant to the repository safety is the shear displacement of rock fractures induced by the seismic loading coming from a nearby activated fault hosting an earthquake event.

It is therefore necessary to reliably estimate the seismic magnitudes of the fault activation. To be able to do so, it is necessary to use a simulation tool that can capture the underlying physics involved in an earthquake faulting process. Moreover, to be able to apply the earthquake simulation tool to safety analysis of a specific repository site, the simulation tool should be able to model complex geological system of the site.

Lately in Sweden in 2011, the Swedish Nuclear Fuel and Waste Management Company (SKB) has submitted an application to the Swedish Government to obtain a construction license for a final repository for spent nuclear fuels at Forsmark. The license application is currently under regulatory review by the Swedish Radiation Safety Authority (SSM) and by the Land and Environmental Court.[1]

This study introduces a workflow that we have developed for simulation of fault activation and its application to a nuclear waste repository site. For the modelling, we used Particle Flow Code 2D version 4 (PFC2D v4), a distinct element based numerical code.[2] We chose PFC2D v4 as the code is well able to simulate rock heterogeneity ,[3–8] complex brittle rock fracturing processes[7] under different source of loading, e.g. blasting,[9,10] hydraulic,[11–17] thermal[18–21] and the associated seismicity.[11–14,17,20–23] Moreover, the code has a significant advantage, in particular in our application, that complex geometries of discontinuities in various scales (m-scale repository fractures to km-scale faults) can be embedded into a discrete element rock model.[20,21,24] Also, as the code runs in dynamic mode, it enables simulation of dynamic wave propagation and attenuation.[25–28]

In this study, as a continuation of our preliminary study,[29] we simulated activation of one specific fault near the repository site under various stress conditions including future glacial cycle reaching up to 70k years from present. The modelling results, which include activation magnitude, slip displacement, and stress drop, are compared with earthquake fault scaling relations.

2. Modelling method and its application

2.1. Bonded particle method

The numerical code we used in this study is PFC2D v4[2] that is based on the ‘Bonded Particle Method’ (BPM).[3,4] In BPM a simulation model which is repository rock mass in this study is represented by an assembly of circular rigid particles in disks bonded at their contacts. The bonds have stiffness and strength, therefore can deform and may break. In BPM, unlike in Finite Element Method (FEM), rock damage is represented directly by the bond breakages. The rigid particles interact only at deformable contacts, which possess finite normal and

---

[*] Correspondence to: Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg 14473, Potsdam, Germany.
E-mail address: jsyoon@gfz-potsdam.de (J.S. Yoon).

http://dx.doi.org/10.1016/j.ijrmms.2017.07.008
Received 22 December 2016; Received in revised form 25 June 2017; Accepted 7 July 2017

shear stiffness. The mechanical behavior of the model is described by the movement of each particle with respect to all the other particles and the force and moment acting at each contact. Newton's law of motion provides the basic relation between particle motion and the resultant forces and moments causing that motion.

BPM has been previously applied in many of rock mechanics and rock engineering problems. Among others, Yoon et al.[7] have investigated fracture and friction behavior of brittle granite deformed under confined asymmetric loading. The results were in good agreement with laboratory observations in terms of initiation and propagation of the fractures and related acoustic emissions. Recently, BPM was applied to modelling of hydro-mechanically (HM) coupled dynamic fracturing process in geothermal reservoirs and in particular fluid injection induced seismicity in naturally fractured rocks[11–16] and fault reactivation.[14,17] Another application of BPM is modelling of thermo-mechanically (TM) coupled fracturing processes in rock[18,19] and lately in fractured rock mass for repository of spent nuclear fuel.[20,21] All these applications demonstrate that the BPM is capable of handling complex HM and THM and dynamic coupled processes in rock mechanics and rock engineering problems.

2.2. *Representation of rock discontinuities*

Discontinuities in rock mass, e.g. joints, fractures and faults, can be modelled by a randomly distributed bonded particle assembly where the contacts along a line or a plane are assigned lower strength and stiffness properties.[30,31] However, this can be problematic because of the inherent roughness of the surfaces of modelled interface. Assigning low friction to the contacts does not produce realistic sliding behavior because of the waviness induced by the particles especially in a randomly distributed bonded particle assembly (Fig. 1a). To solve this problem, small particles might be used to represent the interface and create a softer and weaker layer of particles to minimize the effect of roughness. However, this may not be feasible in this study as large number of smaller sized particle should be placed along each of the fault traces in the very complex geological model which already contains a large particle. Instead, we used the smooth joint model in PFC2D v4.[24] The smooth joint model simulates the behavior of a smooth interface, regardless of the local particle contact orientations along the interface (Fig. 1b). Smooth joints have been previously used for representing pre-existing joints and the method is called Synthetic Rock Mass (SRM) approach.[24] This study uses the smooth joint model for representing the faults and the repository fractures.

3. Forsmark repository model

3.1. *Deformation zones and repository fractures*

The numerical model of the repository is generated based on the Forsmark integrated geological model shown in Fig. 2a.[32] The repository rock mass is represented by a particle assembly where the particle contacts are bonded by parallel bond model of PFC2D v4. The geological model contains mostly two sets of deformation zones: Zones with surface trace length greater than 3 km (in blue) and those with surface trace length smaller than 3 km (in green). The traces of the deformation zones are mapped and simplified by a single or by multiple segments as shown in Fig. 2b. The segments forming a deformation zone ZFMWNW0809A (red trace in Fig. 2b) are used here for modelling activation. The segments are replaced by collections of smooth joints to construct the fault geometry as in Fig. 2c. The traces of the repository fractures at the depth of the repository are denoted in red in Fig. 2c. The repository fracture traces are taken from a stochastically generated discrete fracture network (DFN) in 3D as disks with diameters ranging from 125 m to 600 m, according to the site DFN model.[20]

The deformation zones are modelled explicitly with their full trace length. However, ZFMWNW0001 (named Singö Deformation Zone in Fig. 2a) is 30 km long and was truncated in the model. In the model, vertical and steeply dipping deformation zones are modelled using the smooth joint model. When modelled with smooth joints, a deformation zone is represented as a combination of segments aligned in en echelon structure (Fig. 1b). This is considered reasonable as a way of representing structural heterogeneity of the deformation zones as they do not usually show planar structures but rather undulated or stepped shapes on the large scale. Due to 2D nature of the model, those gently dipping deformation zones (indicated in Fig. 2a) are not incorporated in the model.

Table 1 lists the mechanical properties of the repository rock mass and the pre-existing discrete fracture network. Table 2 is the list of parameters of the parallel bond model and the smooth joint model that are used to generate the repository model. One thing should be noted is that the normal stiffness of the smooth joint for the repository fractures is calibrated from normal stiffness obtained in the laboratory test (656 GPa/m). We used the following scaling relation of the fracture normal stiffness to the length[33]:

$$K_n = 7420\,L^{-0.631} \tag{1}$$

where L is fracture length in cm. As the smooth joint maximum length is 20 m, the calibrated normal stiffness is ca. 60 GPa/m.

3.2. *In situ stresses*

In order to simulate an earthquake event, i.e. a fault activation, occurring at present day and during future glacial period, five in situ stress conditions are considered (Table 3). The first represents the most likely condition at present day at Forsmark where the maximum horizontal stress (SH) and the minimum horizontal stress (S_h) at the depth of the repository are 40 MPa and 22 MPa, respectively.[34] The orientation of SH is N145°E and is shown in Fig. 2c.

The other four correspond to the stress conditions that can evolve during next glacial period (time up to 70k years from present) based on a reconstruction of the Weichselian glaciations.[35] For the purpose of the modelling, only the stresses at two major advance and retreat of the ice cover are considered as shown in Fig. 3. Glacially induced stress

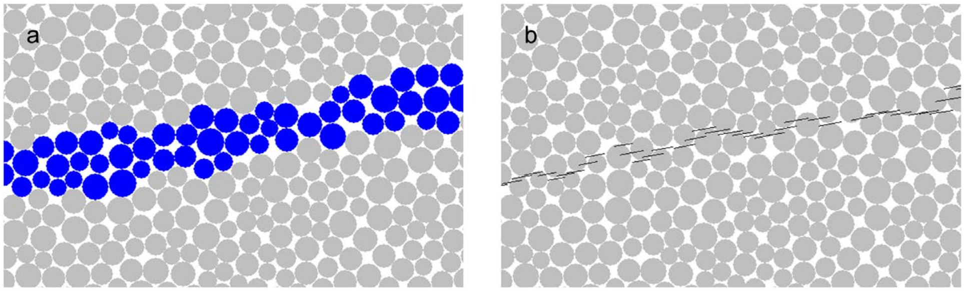

Fig. 1. Representation of a discontinuity in a randomly packed bonded particle assembly by (a) assigning low strength and stiffness to the particles (blue) and the contacts and by using (b) smooth joint model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)