Hydraulic-mechanical modeling research on coseismic fracture behavior

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Abstract. We establish hydraulic-mechanical modeling technique combined with simulation of fracture coseismic behavior based on discrete element method and well accepted equations to investigate the influence of earthquake on pore pressure and transmissivity of fractures. This study concludes 2 models with different hydraulic boundary condition, one designed for stable region with low hydraulic gradient (Mode I) while the other designed for regions with high hydraulic gradient (Model II). Model I shows that pore pressure of fractures interact with aperture and can be summarized into two possible patterns. Besides, the post-seismic transmissivity is 29~138 % of pre-seismic transmissivity depending on location of fractures. Results of Model II indicate that pore pressure is controlled by the inflow of groundwater at the beginning of earthquake and later becomes dominated by opening and closure of aperture. Because of high hydraulic gradient and pore pressure boundary conditions set into Model II, post-seismic transmissivity is 102~1989 % of pre-seismic transmissivity. With this technique, well-established source parameter and site-specific hydraulic conditions, we are able to evaluate the possible post-seismic pore pressure and transmissivity of fractures which can be applied to underground facilities designing and evaluation of pollution transportation.

1. Introduction
Earthquake can affect facilities in several ways, including shaking, rock failure and pre-existing fracture. Earthquake can also cause the change of hydraulic conditions, such as discharge, stream flow and water head [1-2]. One of the hypotheses used to explain this phenomenon is the changes in hydro-mechanical properties of fractured rock masses [3-4].

Since the coseismic behavior of rocks and fractures is an important issue for engineering and scientific research, simulation becomes a possible way for us to evaluate the hydraulic and mechanical properties of fractures, especially for fractures underground that is difficult to observe directly. Swedish Nuclear Fuel and Waste Management Company (SKB) and Posiva Oy have published reports about earthquake induced shear displacement of pre-existing fractures based on simulation techniques that include seismic waves and host rock deformation [5-9]. They used 3DEC to construct their model and performed in various source parameters and stress conditions, which allowed them to evaluate the possible impact of seismic activities on fractures. In their studies, normal displacement and hydro-mechanical coupling were not considered, leading to the lack of evaluation of hydraulic properties change. Unlike SKB and Posiva Oy, Lak et al. (2017) [4] used UDEC to investigate the effect of seismic waves on the hydraulic properties of rock masses. Results showed that seismic waves could affect deep earth and increase the permeability and change the flow rate patterns in a fractured rock mass. However, the impact of host rock deformation was not considered in the study.
In this study, we try to improve the simulation technique, combining the hydro-mechanical coupling technique and earthquake simulation that conclude seismic waves and host rock deformation to research the influence of an earthquake on pre-existing fractures. This will help us to calculate the aperture change and the transmissivity change of fractures.

2. Model description

We constructed a 191 km × 120 km × 60 km rectangular hexahedron model with a fault in the middle. Earthquake simulation related parameters required fault geometry parameters, macro-parameters, micro-parameters and crustal structure parameters. The planar fault we created in the model dips 54 degree toward east and was 71 km long, 34 km wide. The seimogenic depth was set to be 25 km with a hypocenter in the center of fault at 12.5 km depth. In this study, we used time-weakening law [10] and generated stress drop by weakening the strength of fault. The magnitude we set was 8.0, which represented an extreme situation that stress accumulated in the fault was released in one earthquake.

In order to make our simulation more reliable and comparable to nature environments, stress regime was input as the equations:

\[
\sigma_{xx} = 1.55 - 0.0251z \\
\sigma_{yy} = 0.87 - 0.0240z \\
\sigma_{xy} = 1.45 - 0.0024z \\
\sigma_{zz} = -0.0265z
\]

This stress setting could lead to a strike-slip fault and create compression zones and dilation zones.

In our research, the rocks were homogeneous and isotropic to make seismic wave attenuate linearly. Since the continental crust was mainly composed of granitic rocks, the density and poisson’s ratio of host rock was set to be 2700 km/m³ and 0.25 accordingly. Besides, we are not targeting any specific site, using general parameters will be more appropriate for technique development. The geometry of our model is shown in Figure 1.
Figure 2. Layout of fractures. Z1 to Z6 are names of the fracture zone. Faults and all fractures locate in the center of the model and meshed with same grid size.

As for the strength of faults, we set 0˚ to friction angle and dilation angle, 0 MPa to tensile strength. Since that data of normal and shear stiffness was rare, we used 10 GPa/m referenced to SKB and Posiva company [5-9]. The cohesion of fault was set high before seismic to prevent slip and to simulate the lock behavior in inter-seismic period. After the rupture of fault, the cohesion of fault would decrease with time so the rupture could propagate along the fault plane. Based on the depth, we divided our model into three segment 0~20 km, 20~40 km and 40~60km to set up corresponding shear wave velocities, which was 3300, 3980 and 4350 m/s. On the other side, our simulation used a nonspontaneous rupture model and the rupture velocity was 2400 m/s. The setting coincided with the range of rupture velocities of crustal earthquakes collected by Somerville et al. (1999) [11]. The rock mechanic parameters of fractures were also set in the model, including normal stiffness, shear stiffness, friction angle, cohesion, residual friction angle, residual cohesion and dilation angle (Table 1). Besides, strike and dip of fractures were set to be 0˚ and 54˚.

In order to study the importance of the distance from the source earthquake and of the fracture location, we have set 54 target fractures at different area including the central axis (Z1, Z2), dilation zone (Z3, Z6) and compression zone (Z4, Z5) in both hanging wall and footwall (Figure 2). The mechanical properties are listed in Table 1.

| Fracture Parameters       | Value       |
|---------------------------|-------------|
| Normal Stiffness          | 10 GPa/m    |
| Shear Stiffness           | 10 GPa/m    |
| Friction Angle            | 34˚         |
| Cohesion                  | 0 MPa       |
| Residual Friction Angle   | 34˚         |
| Residual Cohesion         | 0 MPa       |
| Dilation angle            | 0           |
For the purpose of doing hydro-mechanical modeling to study how water pressure and aperture can change due to earthquake, we designed two models with different boundary conditions of water pressure and fracture flow. Both models share the same geometry and mechanical properties. The differences only occur in the setting of water pressure gradient. In model 1, the water pressure in fractures and adjacent area was all 5 MPa but only the water pressure in fractures can change during earthquake. This model was used to simulate stable areas with low or no hydraulic gradients. We want to know the instant response of fractures during seismic event. In model 2, the water pressure was set to be 50 MPa in south side of fractures, while the north side only had 5 MPa of water pressure. Besides, the water could only flow into the fractures after they failure. This model was designed to simulate areas with high hydraulic gradients and we want to know whether the water pressure will significantly affect the behavior of fractures.

3. Results and discussion

Results showed that the location of fractures was one of the factors that could affect the fracture coseismic behavior, including post-seismic water pressure and aperture. Due to the fluctuation, in this paper we focused on the trend and average aperture.

In model 1, the post-seismic fracture transmissivity was calculated from the average aperture of 60-70s after the onset of earthquake. Results are listed in Table 2. In general, water pressure of fractures and aperture influenced each other and can be summarized into two patterns. (1) When the change of aperture was smaller and shear displacement has not occurred, which means that the fracture was not reactivated, water pressure inside the fractures tended to increase due to the closure of aperture. (2) After the reactivation of fractures, both aperture and water pressure changed significantly. In this case, the pattern of water pressure was related to pre-reactivation water pressure gradient and aperture size. If aperture decreased rapidly followed by slow opening, the post-seismic water pressure would be less than 5 MPa. In contrast, if aperture increased rapidly followed by slow closure, the post-seismic water pressure would be higher than 5 MPa. On the other side, fracture transmissivity was controlled by aperture size thus they shared the same pattern and were both location-dependent. Comparing the variation of fracture transmissivity between Z1 to Z6, there were several phenomenon could be observed. Z1 and Z2 located at the central axis of fault trace. The coseismic behavior of fractures was consistently showing a decreasing aperture and transmissivity. Also, the decreasing amount of aperture and transmissivity reduced when fracture – fault distance became larger. The data implied that when considering Mw 8.0 strike-slip earthquake, fractures in Z1 area with fracture – fault distance larger than 16 km might not show significant aperture and transmissivity change. Besides, fracture transmissivity changes were less than 1 % in Z2 area, which meant footwall were less likely to be affected by earthquake events. Z4 and Z5 area were located in the compressional zone. Though the behaviors of proximal and distal fractures were different, most of the transmissivity of the fractures decreased due to the closure of aperture in the compressional zone. Z3 and Z6 area were located at the dilation zone. The behaviors of proximal and distal fractures were different and the change of fracture transmissivity was more obvious in Z3 area. Overall, changes of aperture and fracture transmissivity were more significant in hanging wall of the fault.

| Fracture area | Fracture ID | Initial aperture | Initial fracture transmissivity | Post-seismic aperture | Post-seismic fracture transmissivity | Post/Initial fracture transmissivity |
|---------------|-------------|------------------|-------------------------------|----------------------|-------------------------------------|-------------------------------------|
| Z1            | 101         | 0.00146          | 0.00252                       | 0.00103              | 0.00089                             | 35.51%                              |
|               | 102         | 0.00145          | 0.00249                       | 0.00101              | 0.00083                             | 33.43%                              |
|               | 103         | 0.00145          | 0.00247                       | 0.00105              | 0.00093                             | 37.84%                              |
|               | 104         | 0.00146          | 0.00252                       | 0.00109              | 0.00107                             | 42.48%                              |
|               | 105         | 0.00148          | 0.00266                       | 0.00122              | 0.00148                             | 55.46%                              |
|   |     |     |     |     |     |
|---|-----|-----|-----|-----|-----|
| 106 | 0.00146 | 0.00254 | 0.00129 | 0.00175 | 68.93% |
| 107 | 0.00146 | 0.00255 | 0.00136 | 0.00207 | 81.08% |
| 108 | 0.00146 | 0.00254 | 0.00145 | 0.00248 | 97.68% |
| 109 | 0.00146 | 0.00256 | 0.00147 | 0.00262 | 102.25% |
| 110 | 0.00146 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 111 | 0.00145 | 0.00255 | 0.00145 | 0.00250 | 99.68% |
| 112 | 0.00145 | 0.00256 | 0.00147 | 0.00262 | 99.64% |
| 113 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 114 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 115 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 116 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 117 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 118 | 0.00145 | 0.00256 | 0.00146 | 0.00256 | 99.77% |
| 119 | 0.00146 | 0.00258 | 0.001126 | 0.001166 | 45.17% |
| 120 | 0.00146 | 0.00254 | 0.001022 | 0.000872 | 34.33% |
| 121 | 0.00146 | 0.00258 | 0.000974 | 0.000755 | 29.22% |
| 122 | 0.00145 | 0.00253 | 0.000921 | 0.000823 | 24.24% |
| 123 | 0.00145 | 0.00253 | 0.000974 | 0.000755 | 29.22% |
| 124 | 0.00146 | 0.00256 | 0.001198 | 0.001405 | 54.73% |
| 125 | 0.00146 | 0.00254 | 0.001337 | 0.001005 | 42.29% |
| 126 | 0.00147 | 0.00259 | 0.001472 | 0.002606 | 100.26% |
| 127 | 0.00147 | 0.00259 | 0.001623 | 0.00349 | 134.40% |
| 128 | 0.001465 | 0.00257 | 0.00163 | 0.00255 | 138.43% |
| 129 | 0.001449 | 0.002485 | 0.001184 | 0.001354 | 54.50% |
| 130 | 0.00147 | 0.002593 | 0.001103 | 0.001096 | 42.29% |
| 131 | 0.001463 | 0.002556 | 0.000983 | 0.000775 | 30.32% |
| 132 | 0.001454 | 0.002511 | 0.000979 | 0.000766 | 30.50% |
| 133 | 0.001467 | 0.00252 | 0.000987 | 0.000785 | 30.42% |
| 134 | 0.001472 | 0.0026 | 0.001469 | 0.002587 | 99.37% |
| 135 | 0.001455 | 0.002516 | 0.001452 | 0.002501 | 99.42% |
| 136 | 0.001476 | 0.002628 | 0.001033 | 0.000901 | 34.29% |
| 137 | 0.001432 | 0.002397 | 0.001243 | 0.00157 | 65.52% |
| 138 | 0.001446 | 0.002467 | 0.001273 | 0.001685 | 68.32% |
| 139 | 0.001448 | 0.00249 | 0.001305 | 0.001813 | 73.08% |
| 140 | 0.001437 | 0.002422 | 0.001437 | 0.002422 | 99.97% |
| 141 | 0.00146 | 0.002542 | 0.001485 | 0.002673 | 105.16% |
| 142 | 0.001436 | 0.002419 | 0.001548 | 0.00303 | 125.26% |
| 143 | 0.001456 | 0.00252 | 0.001457 | 0.002524 | 100.15% |
| 144 | 0.001459 | 0.002537 | 0.00146 | 0.00254 | 100.14% |
| 145 | 0.001473 | 0.00261 | 0.001474 | 0.002613 | 100.12% |
In model II, results (Table. 3) indicated that the water pressure in fractures was first controlled by the inflow along the reactivated fractures and then affected by the behavior of aperture. Besides, both fracture transmissivity and aperture became larger after the onset of earthquake. The post-seismic fracture transmissivity is 1.02 to almost 20 times compare to pre-seismic fracture transmissivity. We believed that the high water pressure and pressure gradient was the main responsible for increase of fracture transmissivity. In this model, water was designed to flow into the fractures only when the fractures were reactivated. When cracks occurred along the fractures, high pressure water flow through and applied pressure on the walls of fractures, which enlarged the size of aperture and fracture transmissivity. Based on our simulations, we inferred that earthquakes would increase fracture transmissivity under high water pressure and high pressure gradient environments. The amount of increase would be obvious when close to the faults.

Table 3. Aperture and fracture transmissivity of model II

| Fracture area | Fracture ID | Initial aperture | Initial fracture transmissivity | Post-seismic aperture | Post-seismic fracture transmissivity | Post/Initial fracture transmissivity |
|---------------|-------------|------------------|---------------------------------|-----------------------|--------------------------------------|-------------------------------------|
| Z1            | 101         | 0.000962         | 0.000728                        | 0.001853              | 0.005197                             | 714.04%                            |
|               | 102         | 0.000956         | 0.000714                        | 0.001018              | 0.00086                              | 120.42%                            |
|               | 103         | 0.000951         | 0.000703                        | 0.000959              | 0.000721                             | 102.44%                            |
|               | 104         | 0.000963         | 0.00073                         | 0.00097               | 0.000746                             | 102.32%                            |
|               | 105         | 0.000989         | 0.000791                        | 0.001002              | 0.000822                             | 103.89%                            |
|               | 106         | 0.000966         | 0.000736                        | 0.001015              | 0.000854                             | 115.99%                            |
|               | 107         | 0.000969         | 0.000742                        | 0.001028              | 0.000888                             | 119.73%                            |
|               | 108         | 0.000965         | 0.000734                        | 0.001073              | 0.001008                             | 137.42%                            |
|               | 109         | 0.000969         | 0.000744                        | 0.001097              | 0.001077                             | 144.81%                            |
| Z2            | 110         | 0.000997         | 0.000745                        | 0.001204              | 0.001427                             | 191.44%                            |
|               | 111         | 0.000996         | 0.000722                        | 0.001095              | 0.001071                             | 148.40%                            |
|               | 112         | 0.000967         | 0.000739                        | 0.001003              | 0.000825                             | 111.60%                            |
|               | 113         | 0.000959         | 0.000719                        | 0.000967              | 0.000739                             | 102.79%                            |
|               | 114         | 0.000919         | 0.000635                        | 0.000936              | 0.000669                             | 105.48%                            |
|               | 115         | 0.000961         | 0.000725                        | 0.000979              | 0.000767                             | 105.78%                            |
|               | 116         | 0.000962         | 0.000727                        | 0.000981              | 0.00077                              | 105.90%                            |
|               | 117         | 0.000956         | 0.000715                        | 0.000975              | 0.000757                             | 105.90%                            |
|               | 118         | 0.000981         | 0.00077                         | 0.001001              | 0.000818                             | 106.18%                            |
Z3

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 119 | 0.000974 | 0.000754 | 0.001623 | 0.003489 | 462.56% |
| 120 | 0.000966 | 0.000737 | 0.001076 | 0.001017 | 138.01% |
| 121 | 0.000974 | 0.000755 | 0.001004 | 0.000826 | 109.32% |
| 122 | 0.000966 | 0.000735 | 0.000986 | 0.000782 | 106.39% |
| 123 | 0.000974 | 0.000755 | 0.001004 | 0.000826 | 109.32% |
| 124 | 0.000971 | 0.000775 | 0.001076 | 0.001017 | 138.01% |
| 125 | 0.000966 | 0.000737 | 0.001076 | 0.001017 | 138.01% |
| 126 | 0.000974 | 0.000755 | 0.001004 | 0.000826 | 109.32% |
| 127 | 0.000966 | 0.000737 | 0.001076 | 0.001017 | 138.01% |

This hydraulic-mechanical modelling can be applied to the fields of engineering design, hydrogeological characteristics evaluation and pollution transportation. For engineering design, we can use this technique to simulate how this site responds to seismic events. Thus we can adjust our design to accommodate the influence of earthquakes. For evaluation of hydrogeological characteristics,
our results showed that different hydraulic gradient and water pressure could lead to various respond. With our model, we can assess the hydrogeological characteristics and investigate why water head changes after earthquake. Also, the assessment of post-seismic fracture transmissivity can be helpful for judging the possibility or rate of pollution transportation, which can provide important information for us to decide a reasonable pollutant treatment plan.

4. Conclusions
Our models suggest that different hydraulic conditions can lead to various results of post-seismic fracture behavior. In general, pore pressure can change in two kinds of pattern under stable and low hydraulic gradient conditions. On the other side, aperture and pore pressure generally increase after seismic events under high hydraulic gradient environments. This hydraulic-mechanical modelling technique can help us to evaluate the possible shear displacement, normal displacement, aperture change, fracture transmissivity and water pressure. And this can be applied to engineering design, evaluation of hydrogeological characteristics and transportation of pollutants.

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