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Breakout Orientation Perturbation Modeling in Fractured Crystalline Rock

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ABSTRACT

The key component of a comprehensive geomechanical model is knowledge of the current state of stress. Breakouts are commonly used as principal indicator of stress direction. However, variation of breakout orientation with depth, especially in the vicinity of fracture zones, is frequently observed. Numerical modeling which taking into account the elastic property changes as a result of fracturing and fracture filling is developed to better quantify the breakout orientation heterogeneity observed in this study. Two different mechanisms for the breakout rotation are proposed. Anomalies of breakout orientation in the vicinity of fracture zones reflect the large-scale stress heterogeneity which might be caused by the previous slip acting on the fault plane. While the local breakout orientation anomalies around minor fractures might be the effect of the material heterogeneities around borehole due the intersection between the borehole with the fracture. The results of this study provide a better understanding of stress-induced borehole elongations in fractured rocks. Borehole breakout heterogeneities do not seem to be related merely to the principal stress heterogeneity, but also to the effect of mechanical properties heterogeneities, i.e. weak zones with different elastic moduli, rock strength and fracture patterns. Consequently, care has to be taken when inferring the principal stress orientation from borehole breakout data observed in fractured rock.

1. INTRODUCTION

Borehole breakouts are cross-sectional elongations in the minimum horizontal stress direction, which are caused by localized failure around a borehole due to stress concentrations (Bell and Gough, 1979; Zoback et al., 1985). Breakouts are one of the direct indicators of the contemporary tectonic stress field. However, breakout orientations are frequently observed differ from the mean minimum horizontal stress orientation, especially in a fractured rock.

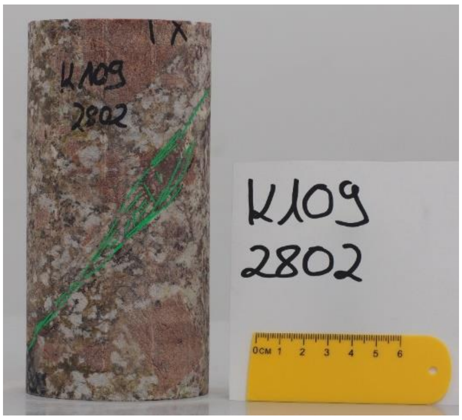

Figure 1: One example of fracture observed in drill-core from Soultz-sous-Forêts. Interpreted microcracks are drawn in green lines.

Some previous studies showed that the changes in mechanical properties, in particular in the Young's modulus and the Poisson's ratio, induced by the high microcrack density of the fault zone affect the breakout orientation. Fault zones have a high microcrack density near the fault core. This microcrack density decreases exponentially with distance from the fault core (Vermilye and Scholz, 1998). One example of increasing microcrack in the fracture core observed in a drill core in Soultz-sous-Forêts is shown in Figure 1. Changes of rock mechanical parameters due to changing crack density could lead to local heterogeneous zones around the fault core (Heap and Faulkner, 2008). Faulkner et al. (2006) showed that crack density influences the elastic properties of rock and, hence, the stress state of surrounding faults. Furthermore, they found that the mean stress as well as the magnitude of the highest principal stress decrease and the least principal stress increase as the fault core is approached, resulting in overall decrease in the differential stress. Thus, the breakout orientation anomalies might also be attributed to varying crack density.

Sahara et al. (2014) analyzed breakouts patterns in a 5 km deep wells of the enhanced geothermal system in Soultz-sous-Forêts (France). Breakout orientation rotations are clearly identified in the vicinity of both major fracture zone and minor fracture. He suggests the breakout anomalies around minor fractures might be the effect of the material heterogeneities around borehole due the intersection between the borehole with the fracture. Following the work from Sahara et al. (2014), numerical modeling of the stress field distribution around a borehole in a heterogeneous model is developed. The results of this modeling is expected to better characterize the impact of the natural fracture network in affecting the stresses distribution around borehole and eventually alter the breakout shape and orientation.

2. MODELING OF BREAKOUT ORIENTATION PERTURBATION

A model that take into account the effect of the material heterogeneities to the stress distribution around borehole is developed. The effect of fracturing on the mechanical properties of rock was analyzed in many studies. In-situ laboratory measurements on Soultz-sous-Forêts granite (Valley, 2007) revealed the effect of fractures on rock mechanical parameters. Young's modulus of intact Soultz-sous-Forêts granite was determined to be around 54 GPa, but significantly decreased to 39 GPa for fractured granite. Furthermore, the uniaxial compressive strength is also found to decrease with increasing fracture density (Alm et al. 1985).

Table 1: List of elastic properties used in this modeling

Parameter	Intact rock	Weak zone
Young's modulus	40 GPa	24 GPa
Poisson's ratio	0.36	0.42
Applied far field stress		
SHmax	55 MPa	
Shmin	110 MPa	
Friction Coefficient	0.9	0.8

Numerical modeling is used to compute the stresses distribution around wellbore in the heterogeneous material. We use the commercial finite element software Abaqus (Simulia). Boundary conditions are chosen after Ewy (1993), i.e. the outer nodes are fixed, inner nodes of the wellbore wall are free. At the beginning of the simulation the nodes at the wellbore wall are fixed to simulate the undisturbed rock. Drilling of the well is simulated by instantaneous release of this boundary condition. The effect of the weight of the drilling mud, which is used to stabilize the wellbore wall, could also be simulated by additionally apply a radial pressure to the wellbore wall. The parameters used in this simulation are listed in the table 1.

Figure 2 left shows the mesh used in this simulation. Weak zone is modeled by a narrow zone which has lower elastic properties. Elastic properties reduction of 40% from the intact rock is applied in the center of the weak zone. Gradual elastic properties changes is applied to make the numerical calculation stable. In this model, weak zone is set close to the Shmin direction to highlight the stress perturbation due to the weak zone. Stresses distribution around borehole is concentrated in the Shmin direction hence the highest stresses perturbation due to weak zone is expected to occur in this direction.

We can see in the Figure 3 right, a small weak zone, comparable to the size of the damage zone due to fractures, alters the stress distribution around boreholes. The stress magnitude at the weak zone is lower than it should be observed in the homogeneous material. The stress perturbation is concentrated in the weak zone. Several models with different elastic properties at the weak zone but with the same percentage of the material reduction relative to the intact rock have been tried. Model which has higher elastic properties at the weak zone also has higher intact rock properties. Interestingly, the stresses distribution at the borehole wall are the same. It seems that the stress distribution outside a hollow inclusion depends mainly on the elastic properties difference between intact rock and weak zone, rather than its absolute value.

Yield criterion is then applied to model the damage zone. The damage zone is defined as the zone in which the stresses acting in that zone have reached the yield surface. The step failure model is incorporated in Abaqus using a self-developed subroutine. Here the damage state of the model is read and updated according to the current stress state at each time step. The weak zone is only modeled in one side of the borehole as a single fracture are typically only created a single weak zone. The simulation is run in two cases. First the weak zone is set in the vicinity of the Shmin direction, while in the second run it was moved close to the SHmax direction. The purpose is to model how the stress perturbation around those weak zones alter the damage zone.

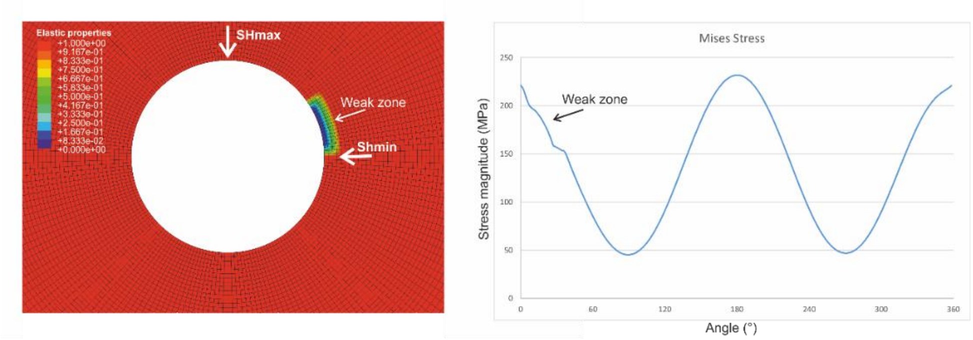

Figure 2: The mesh used in the numerical modeling. Narrow weak zone was used to model the borehole intersection with the fracture. Weak zones has lower elastic properties compare to the surrounding material (left). Stress distribution at the borehole wall. The occurrence of the weak zone promote a lower stress region (right).

Increased crack density leads to degradation of the elastic moduli, thus reducing the capability of rock to support stress (Heap et al., 2010; Kemeny and Cook, 1986). Hence we also lowering the friction coefficient value at the weak zone (table 1). In the first model, the failure was initiated in the weak zone and then followed by the failure in the Shmin direction. The damage zones are then develop according to this initial failure. As a result an asymmetric damage zone pair is formed. The orientation of the modeled breakout is perturbed by the occurrence of the weak zone, rotated from the Shmin direction. In this case care has to be taken since the breakout orientation do not show the true direction of the Shmin, instead it was affected by the weak zone.

It is not the case for the second model. Here a symmetric breakout shape parallel to the direction of the Shmin is observed. In this model, the stress perturbation due to the weak zone is not enough to facilitate the breakout to be developed in the weak zone direction. It is because in the direction of the SHmax stress the stresses are less concentrated. A huge reduction of material strength is required to facilitate the damage to be developed in the SHmax direction.

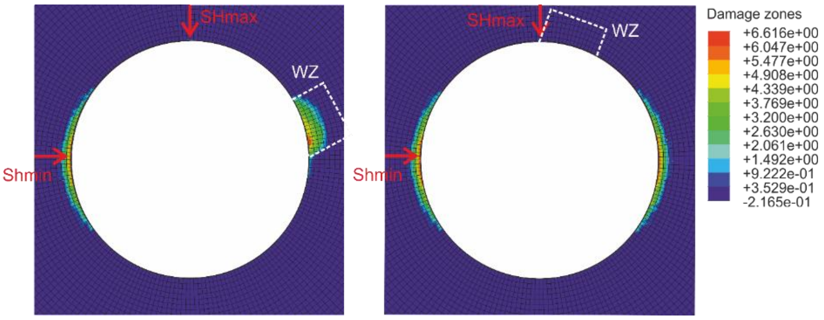

Figure 3: The final damage zone modeled in the heterogeneous material with the weak zone is located in the vicinity of Shmin direction (left) and SHmax direction (right).

3. DISCUSSIONS

Breakout orientation heterogeneities are well observed in the vicinity of both major and minor fractures. The dimensions of natural fractures are, however, too small to induce local stress perturbations required to alter the breakouts orientation (Barton and Zoback, 1994). Hence, we attribute the observed small wavelength breakout rotation in the vicinity of a natural fracture to the material heterogeneity due to the occurrence of weak zones in the vicinity of fractures.

Based on the results of the stresses perturbation around borehole on a simple heterogeneous model, a hypothesis of the breakout orientation rotation in the vicinity of a fracture could be developed as follow. If a fracture has an associated fractures damaged zone, the stresses are expected to be perturbed and rotated depending on the change in elastic properties of the damaged material. As the fracture core bears the most damage, the stress perturbation is assumed to be concentrated in that zone and to decrease with distance to the core. Breakouts will then develop according to this local stress perturbation. In such a case, a breakout orientation rotation centered at the fault core is expected to result. This rotation trend starting from the fault core is observed well in the vicinity of major faults in Soultz-sous-Forêts (Sahara et al. 2014)

It is shown that the breakout shape depend on the initial failure. It is because after the yield strength of the material has been reached, stress will concentrate in this damage zone hence the damage zone will grow in this zone. Hence emphasize the importance of the weak zone in affecting the breakout orientation. The results of this simulation show that the breakout perturbation depend on the weak zone elastic properties contrast, relative to the intact rock, and its position relative to the minimum horizontal stress.

5. CONCLUSIONS

Analyzing breakout heterogeneities and their correlation with fracture occurrence at great depth is a challenging task, in particular because of lacking information on in-situ material properties of fractured rock. We propose two different mechanisms for the breakout rotation in the vicinity of fracture zones and natural fractures. For breakouts around fracture zones, Sahara et al. (2014) showed systematic sinusoidal perturbations to breakout orientation, initiation and inhibition of breakout formation. Therefore we conclude, that anomalies of breakout orientation in the vicinity of fracture zones reflect the large-scale stress heterogeneity caused by the fracture zones.

Since it was found that natural fractures are too small to perturb the stress field even locally, the observed perturbations of breakout orientation cannot be explained by a perturbation of the stress field. A numerical model of stress distribution around borehole that incorporate the material heterogeneities could explain the observed breakout heterogeneities in this field. It was shown that for, heterogeneous isotropic elastic material, the stresses distribution around borehole is dependent of the elastic properties of the material. It improves the analytical formulation of the stress distributions which developed under homogeneous material assumption, i.e. Kirsch solution. Furthermore, the results presented in this study might help us to infer the mechanical properties of fractures and their immediate surroundings from the breakout observation.

The results of this study provide a better understanding of stress-induced borehole elongations in fractured rocks. The impact of the fracture network on breakout heterogeneities is very pronounced in crystalline rock, which is mechanically isotropic. This is why we could attribute the perturbation of breakouts to the occurrence of fractures and accompanying alteration of mechanical properties only. Numerical modeling taking into account the elastic property changes as a result of fracturing and fracture filling is required to better quantify the breakout orientation heterogeneity that typically observed in many wells.

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