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III - A 346 Constitutive modelling of hydraulic fracturing of HDR reservoirs

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1. Introduction

The feasibility of the Hot Dry Rock (HDR) geothermal energy extraction projects requires a significant permeability enhancement of the rock between the injection and recovery boreholes. This is usually achieved by a high-pressure water injection, often called stimulation. Although many stimulation models have been proposed to date [1.], the governing mechanisms of the mechanical response of fractured rock mass have not been sufficiently clarified yet.

During the stimulation, a massive volume of injected water causes large joint openings. Therefore the post-peak type behaviour of discontinuous rock mass should be considered. Moreover, the number of joints embedded in the rock mass is usually very large and it is impossible to treat each discontinuity individually. Thus, it is necessary to replace the discontinuous rock mass with an equivalent continuum for analysis.

Horii and Yoshida (1994) proposed a micromechanics-based constitutive model of the rock masses with fracturing joints that reflects the effects of joint properties, spacing and orientation. Their model is extended here to grasp the effects of water that penetrates into joints and acts on their surfaces. It is expected that before the water pressure can cause failure of the joint in the direction normal to its plane ('opening mode'), sliding condition is satisfied on either part of undulated joint ('sliding mode').

2. Modelling approach

Modelling is based on the average stress - average strain relationship over a body containing discontinuities [3]. For the non-linear problems the expression takes form

$$\Delta\bar{\varepsilon}_{ij} = D^{R}_{ijkl}\,\Delta\bar{\sigma}_{kl} + \frac{1}{2V}\sum_{\alpha}\int_{\Omega^\alpha}\left(\Delta[u_i]\,n_j + \Delta[u_j]\,n_i\right)dS\,, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $\Delta[u_i] = u_i^+ - u_i^-$ is the incremental displacement jump across the joint. In order to express $\Delta[u_i]$ as a function of acting stresses and the water pressure increments, the original problem is decomposed to 1) elastic problem, 2) open slit problem and 3) cut-out joint problem. Although joints are considered to be flat locally, due to undulations in a large scale, they are envisaged to have a saw-tooth shape in the analysis. Coulomb frictional law is used to evaluate the sliding condition on the local joint surfaces. After the condition is satisfied, tractions on the cut-out joint are arranged as shown in Fig. 1. The restriction of joint deformation by the surrounding rock mass is expressed in terms of the system stiffness. Effective moduli are introduced to describe the reduction of the overall stiffness due to presence of embedded joints. Finally, the overall constitutive equation can be obtained in the form

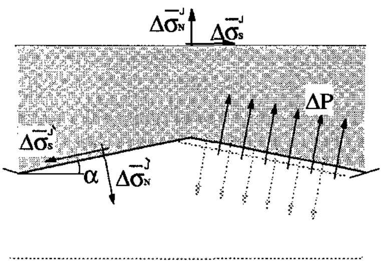


Fig. 1. Tractions acting on the undulated joint

$$\Delta\bar{\varepsilon}_{ij} = \bar{D}_{ijkl}\,\Delta\bar{\sigma}_{kl} + \Delta\bar{\varepsilon}^{P}_{rs}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $\bar{D}_{ijkl}$ is the tangential compliance tensor of the equivalent continuum and $\Delta\bar{\varepsilon}^{P}_{rs}$ is a strain tensor induced by the water pressure increment.

3. Results of the present model

Let us consider a two-dimensional problem of the rock mass with one set of regularly spaced joints. When the water pressure in joints reaches certain critical value, the sliding is initiated. Then, the amount of the displacement jump across the joint induced by the water pressure increment can be calculated.

Fig. 2 shows the critical water pressures normalized by the mean stress $\bar{\sigma}_{\text{mean}}$ for different stress conditions. In this illustration, compression is considered with a positive sign. Sliding condition on the joint surface specifies the effects of joint orientation (angle is measured from the direction of $\bar{\sigma}_2$) and joint undulation on critical water pressure levels. Fig. 3 presents the amount of the displacements jump across the joint calculated for the hydrostatic stress conditions as the water pressure in joints increases from 0 to $\bar{\sigma}_{\text{mean}}$. It is seen that, due to large scale undulations, sliding can occur even before the water pressure reaches the mean stress level.

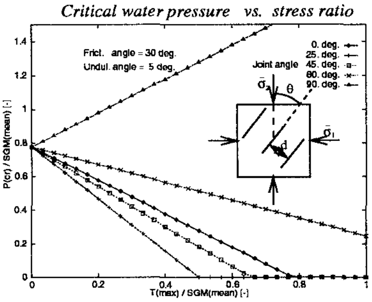


Fig. 2. Normalized critical water pressures for various joint angles and stress conditions.

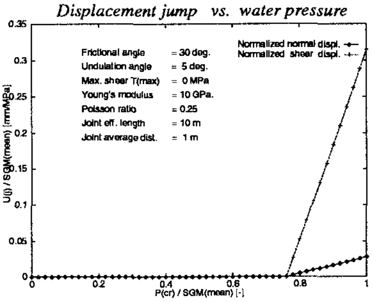
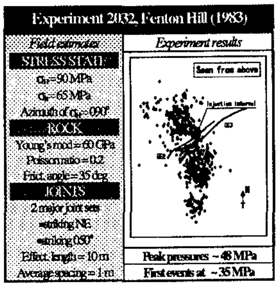


Fig. 3. Amount of displacement jump accross the joint for a hydrostatic stress state.



Experiment 2032, Fenton Hill (1983)	
Field estimates	*Experiment results*
STRESS STATE	
σ_H = 90 MPa	
σ_h = 65 MPa	
Azimuth of σ_H = 090°	
ROCK	
Young's mod = 60 GPa	
Poisson ratio = 0.2	
Frict. angle = 35 deg	
JOINTS	
2 major joint sets	
•striking NE	
•striking 050°	
Effect. length = 10 m	Peak presures ~ 48 MPa
Average spacing = 1 m	First events at ~35 MPa

Table 1. Experiment observations and input parameters for analysis (after [4.])

4. Finite element analysis

Although the formulated relationship is generally three-dimensional, a two-dimensional FEM analysis is presented here. The effects of high temperatures and chemical processes involved in stimulation are ignored. The surrounding undisturbed rock mass is treated as a linear elastic material. Shape of the reservoir is formed after a critical element on the boundary of stimulated region and corresponding critical water pressure are progressively determined. It is assumed here that the water pressure inside the stimulated region is constant.

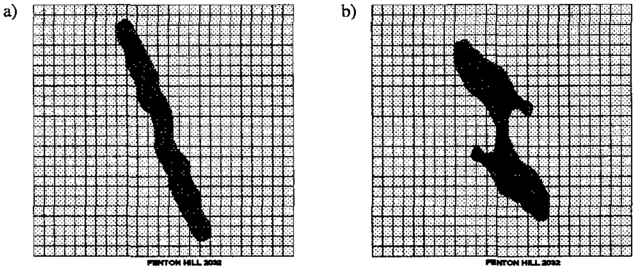


Fig. 4. Simulated fractured regions for joint undulation a) 5 deg. b) 15 deg.

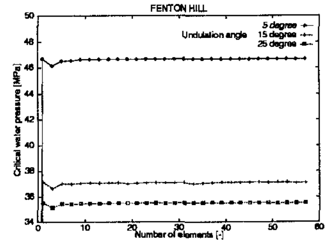


Fig. 5. Critical water pressures obtained for undulation angles 5, 15, and 25 deg.

To obtain a rough comparison of the proposed approach with the real performance of HDR experimental sites, the input parameters from one HDR project are analyzed. Table 1 presents the available data from the stimulation experiment carried out in Fenton Hill, USA. Two major joint sets are included in the analysis regardless of their dip angle. Since the estimations of the joint undulation angle are not known, two values are considered in the analysis.

Oblong simulated regions consisting of 60 elements (Fig. 4) disclose one preferred orientation for both joint undulations. The orientation is different from the direction of the maximum principal horizontal stress and roughly corresponds with the formation of acoustic emission source locations estimated during stimulation (Table 1). During this stimulation experiment, the first microseismic events were recorded at pressures around 35 MPa. This can be compared with the critical water pressures found for undulation angle 5, 15 and 25 degree (Fig. 5).

5. Concluding remarks

Fair agreement of the computed and observed critical water pressures can bee seen. It supports the premise that the shear failure of existing joints represents the governing mechanism of HDR stimulations. Simulated fractured regions match the tendency deduced from the acoustic emission source locations. In this case, the dip angle of the critical joint set is 90 degree and therefore the 2D simplification should give a good estimate. Both the analysis and the experiment observations demonstrate that the stimulated reservoir does not invariably develop in direction of principal stresses. Although presented analysis alone is not able to capture the whole complexity of HDR stimulation processes, it offers a simple basis for a more advanced and compound modelling.

References

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