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Integrated 3-D stress determination by hydraulic fracturing in multiple inclined boreholes beneath an underground cavern

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ABSTRACT

This paper presents a complete three-dimensional stress determination using hydraulic fracturing data from three inclined boreholes, drilled from the floor of an underground cavern at a depth of about 100 m. Both conventional hydraulic fracturing (HF) and hydraulic testing of pre-existing fractures (HTPF) were carried out at all test points to acquire reliable data and conduct the integrated stress analysis. We determined 3-D stress states using a numerical inversion code that integrates the entire data set from HF and HTPF methods, and employs a nonlinear least-squares optimization routine based on a modified Levenberg–Marquardt method and a finite-difference Jacobian algorithm. We present the trend of complete three-dimensional stress states, with depth expressed by correlation equations. We compare the 3-D stress inversion result for the integration of all data from the three boreholes with the results determined independently for each individual borehole. The results showed that the maximum principal stress was subhorizontal and oriented approximately NNE–SSW, and the ratio of maximum to minimum principal stress was 2.0 on average. The inverted scatter of misfit remained within 10% for both the integrated analysis of the entire data set and the measurement data for each individual borehole. From these findings, we conclude that the 3-D stress determination made by integration of HF and HTPF data from multiple inclined boreholes resulted in a reliable inversion of the 3-D stress field.

1. Introduction

With underground space utilization, such as for underground energy storage and nuclear waste disposal), calling for larger rock caverns at increasing depth, a thorough understanding of a rock formation's in situ stress state is critical for optimum design and safe maintenance of underground facilities. Hydraulic fracturing is known as a powerful technique for in situ stress measurement. It has the advantage of not requiring knowledge of the elastic properties of a given rock mass, because the stresses are directly measured at the test location [1,2]. Stephansson and Zang reported an overall review of rock stress models and rock stress estimation methods [3], which explains the historical advance of hydraulic fracturing technique (HF and HTPF) and integrated stress determination method. Hydraulic testing of pre-existing fractures (HTPF) as an alternative to the conventional HF has developed in the early 1980s [4,5]. Cornet presented the HTPF stress determination method together with the integrated stress determination method [6].

Since the theory of hydraulic fracturing for stress measurement was first suggested by Hubbert and Willis [7], significant research has been conducted on the subject, including analyses of factors such as rock permeability [8–10] and pre-existing fractures [11–15], the methodologies of stress analysis such as the fracture-mechanics approach [16], and numerical simulation of fracture behavior. However, most research related to hydraulic fracturing stress measurements has been limited to two-dimensional approaches, using vertical boreholes.

Three-dimensional stress measurement using hydraulic fracturing (HF) was suggested in the late 1980s [17,18] and has advanced with the integration of HF and HTPF, though mostly in vertical boreholes [19–22]. Three-dimensional stress measurement using arbitrary inclined boreholes has also been studied, in theory and in laboratory scale tests [17,23], as well as in the field

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[18,24]. However, these field applications [18,24] were based on conventional HF only and had restriction in fully 3-D stress determination. Stress measurements using inclined boreholes are still not common, and to the authors' knowledge, studies of 3-D stress determination by integrating HF and HTPF in multiple inclined boreholes have not been reported.

In conventional HF stress measurement, the main parameters evaluated in field testing are the fracture reopening pressure and fracture shut-in pressure [2,25]. These pressure parameters are related to coupled fluid pressure and fracture mechanical behavior in opening and closing stages. The values for these parameters are commonly determined from pressure versus time records obtained by conventional HF, or sometimes from pressure and flow rate versus time records obtained by HTPF, using statistical or graphical techniques [26–28]. There have been many studies on the uncertainties in interpreting pressure records and fracture patterns [13,29–31]. These pressure parameters should be carefully determined and applied to the proper governing equation of the stress analysis, depending on the fracture trace pattern at the test point [13,32].

In this study, we carried out a three-dimensional stress measurements, using hydraulic fracturing data from three inclined boreholes drilled from the floor of an underground cavern at a depth of ~100 m. At the site, both conventional HF and HTPF were carried out for all test points to acquire reliable data and to carry out the integrated stress analysis. Fracture traces on the borehole wall of test points were investigated before and after the test, using an acoustic borehole televiewer. We then determined the 3-D stress field using a numerical inversion code that integrates the entire data set from HF and HTPF, and employs a nonlinear least-squares optimization routine based on a modified Levenberg–Marquardt method and a finite-difference Jacobian algorithm for solving multivariable nonlinear equations [33]. We present depth trends for the complete three-dimensional stress field expressed by correlation equations, noting the scatter and reliability of the stress determination through misfit analysis. Finally, we compare the stress state determined by the integration of all data from three boreholes with the stress states determined independently for each individual borehole.

2. Principle of integrated 3-D stress determination by hydraulic fracturing and hydraulic testing of pre-existing fractures

2.1. Governing equations in 3-D stress analysis

In conventional HF or HTPF using arbitrary inclined boreholes, two types of fractures can be expected, depending on the initial stress state and the borehole orientation: (a) A longitudinal fracture, with its plane parallel to the borehole axis. (b) A transverse fracture, with its plane inclined to the borehole axis.

The state of stress at the borehole wall and the fracture plane is redistributed differently, depending on the fracture type. Therefore, the governing equations for 3-D stress determination also differ, depending on the fracture type.

The governing equations for 3-D stress analysis can be derived from elasticity theory, using a geometric system of interrelationship among coordinates, boreholes, and fractures [17,23,34]. Fig. 1 shows the configuration of coordinate systems that we adopt in this study to express the geometric relationship between boreholes and fractures. The N–E–V coordinate represents the azimuth of north, east, and vertical direction; the X–Y–Z coordinate is related to borehole geometry; and the x–y–z coordinate is related to fracture geometry. The stress components (S_X, S_Y, S_{XY}) in the X–Y–Z coordinate are expressed with the stress components (S_N, S_E, S_V, S_{NE}, S_{EV}, S_{VN}) in the azimuth coordinate as

$$S_X = S_N \cos^2\alpha \cos^2\beta + S_E \sin^2\alpha \cos^2\beta + S_V \sin^2\beta + S_{NE} \sin 2\alpha \cos^2\beta + S_{EV} \sin\alpha \sin 2\beta + S_{VN} \cos\alpha \sin 2\beta \quad (1)$$

$$S_Y = S_N \sin^2\alpha + S_E \cos^2\alpha - S_{NE} \sin 2\alpha \quad (2)$$

$$S_{XY} = -0.5(S_N - S_E)\sin 2\alpha \cos\beta + S_{NE} \cos 2\alpha \cos\beta - S_{EV} \cos\alpha \sin\beta + S_{VN} \sin\alpha \sin\beta \quad (3)$$

where α is the inclination of the borehole from the N-axis, β is the inclination of the borehole from the V-axis, and θ is the direction of the fracture from the X-axis.

In the case of a longitudinal fracture (Fig. 1a), two governing equations can be derived considering the relationship between the in situ stress field and the fluid pressures within the borehole or inside the fracture [17,23,34]. The two governing equations, expressed as

$$P_r = S_X\left(3\sin^2\theta - \cos^2\theta\right) - S_Y\left(3\cos^2\theta - \sin^2\theta\right) - 4S_{XY}\sin 2\theta \quad (4)$$

$$P_s = S_X \sin^2\theta + S_Y \cos^2\theta - S_{XY} \sin 2\theta \quad (5)$$

relate the fracture reopening pressure P_r and shut-in pressure P_s to six components of the in situ stress field, which through Eqs. (1)–(3) may also be expressed in azimuth coordinates. In Eq. (4), relating P_r to the in-situ stress components, the elastic theory accounts for stress concentrations at the borehole wall. In Eq. (5), P_s is assumed to be equal to the stress normal across the fracture, which in turn can be related to the in situ stress components through simple stress projection on the fracture plane.

When the hydraulic fracture is inclined to the borehole axis (Fig. 1b), the P_s relation to stress components can be defined by one governing equation, according to

$$P_s = S_N \cos^2\psi \cos^2\varphi + S_E \sin^2\psi \cos^2\varphi + S_V \sin^2\varphi + S_{NE} \sin 2\psi \cos^2\varphi + S_{EV} \sin\psi \sin 2\varphi + S_{VN} \cos\psi \sin 2\varphi \quad (6)$$

again considering stress projection onto the fracture plane [17,23]. In Eq. (6), P is the inclination of the normal to the fracture plane from the horizontal, and ψ is the bearing of the normal to the fracture plane from the N-axis. The derivation of governing equations above is described in detail as the matrix form of stress tensor in Appendix A.

In the HTPF, the orientation of the pressurized pre-existing fracture may not be directly related to the current stress field, because the fracture might have been created during past tectonic stressing. The stress acting normal across the fracture plane is commonly denoted P_n, the normal pressure acting on the fracture plane. P_n may be determined by analyzing the pressure-flow rate record from a stepwise flow rate test. P_n is related to the field stress state $S(X)$ at any point X as

$$P_n = S(X)(n \times n) \quad (7)$$

where n is the normal to the fracture plane [2,6,19,20]. In general, P_n is interpreted to be equivalent to the shut-in pressure P_s, in that both are assumed to be equal to the normal pressure acting on the fracture plane. Eq. (7) can also be expressed explicitly with stress components in azimuth coordinates according to Eq. (5) or Eq. (6), showing that P_n corresponds to P_s.