Numerical Simulation of Performance Tests on a New System for Stress Measurement by Jack Fracturing*

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A prototype probe for in-situ stress determination by borehole jack fracturing has been newly developed. The authors carried out a loading test in a steel pipe to study stress distribution on borehole surface induced by loading with the probe. Strain gages were glued on the external cylindrical surface of the steel pipe to know the actual stress distribution induced by probe loading. In order to obtain the stress distribution along the internal surface, a numerical simulation of the loading test was also carried out. Since the numerical simulation results agreed with the results measured with the strain gauges, reliability of the simulation was elucidated. Thus the stress distribution on borehole surface and a stress concentration factor at a point of fracture formation were obtained by this research. Through laboratory and field tests from now on, reliability and performance of the stress measurement using this probe will be checked.

KEY WORDS : Stress Measurement, Borehole Jack, Single-fracture, Numerical Simulation, FLAC^{3D}

1. Introduction

Rock masses are initially stressed in their natural state and understanding of this state of stress is essential for design calculations and prediction of rock mass behavior with excavations¹⁾. Over the past 30 years, many endeavors have been made to find a reliable technique for measuring in situ stresses²⁾. Although there are many kinds of in-situ stress measuring methods which can be carried out routinely, only hydraulic fracturing and sleeve fracturing appear most suitable for deep stress measurements because of their simple maneuverability³⁾. These two techniques, however, have some serious difficulties in finding real re-opening pressure. The followings are the reasons for that in hydraulic fracturing:

- We do not know actual fluid pressure distribution in the fracture
- Apparent re-opening pressure is affected by the stiffness of the hydraulic system and fluid injection rate.
- The fracture is already opened before pressurization in case that the ratio of the maximum principal stress and the minimum principal stress is greater than 3, because the direction of the fracture produced is always perpendicular to the direction of the minimum principal stress direction.

On the other hand, the reason for that in sleeve fracturing is that fracture re-opening pressure is to be found from pressure-diametral deformation curve, and diametral deformation is insensitive to detect the moment of fracture re-opening^{4, 5)}.

In this paper, a newly developed prototype probe for stress determination by borehole jack fracturing is introduced to solve

the above problems⁶⁾. The new borehole jack single-fracture probe consists of eight borehole jacks for loading instead of fluid pressure in hydraulic fracturing or sleeve fracturing techniques. Borehole jacks are adopted here considering their efficiency, sturdiness, and compactness⁷⁾. Two new specific tangential strain sensors (TSS) are installed in the middle of the probe to detect the opening displacement of the fracture on the borehole surface directly.

The final aim of this research is to demonstrate potentiality of the borehole jack single-fracture probe newly developed for precise stress determination. Although the stress distribution and a stress concentration factor at a point of fracture formation on the borehole wall surface are essential, it is difficult to find them theoretically due to complexity of the loading mechanism. Thus numerical and experimental tests of the probe by loading a steel pipe are carried out. In this paper, by comparing the numerical results with the experimental ones, the stress distribution and the stress concentration factor are clarified. Compressive stresses are expressed negative in this paper.

2. Borehole jack single-fracture method

2-1 Probe for the borehole jack single-fracture method

The borehole jack single-fracture probe mainly consists of eight loading jacks, upper and lower load platens, two pairs of friction shells, and two tangential strain sensors. The eight borehole jack cylinders are grouped into upper section and lower section corresponding to the respective loading platens and friction shells, and thus each section consists of four borehole jack cylinders. Fig.1 shows the photo of the borehole jack probe used for the borehole whose diameter is 98 mm. The probe is 676 mm in length and 96.6 mm in diameter.

The cross section view of the probe is shown in Fig.2. Semi-cylindrical load platens of the probe are covered by two pairs of half-pipe shaped friction shells. Before loading as

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shown in Fig. 2(a), the internal radius of the friction shells is 45.6 mm and it is smaller than the external radius of the load platens, 47.0 mm. The center of the curvature of the friction shells is 3.5 mm apart from the center of the borehole, and the center of the curvature of the load platens is 9.4 mm apart from the center of the borehole whose diameter is 98.0 mm. Such configuration makes clearance between the external surface of the friction shells and the borehole wall at the condition before loading. After loading, as Fig. 2 (b) shows, the friction shells are bent with the increase of the distance between the two load platens, and the internal radius of the friction shells becomes larger and finally equal to the external radius of the load platens. At the same time, the outside curvature of the friction shells turns equal to the curvature of the borehole wall.

Fig.1 Outward appearance of the borehole jack probe (676 mm in length and 96.6 mm in diameter) used for $\phi 98$ borehole.

Fig.2 Cross section view of the probe: (a) before loading (b) after loading

Fig.3 illustrates the borehole jack single-fracture probe and the fracture plane produced by the probe. During the loading process, the load platens transfer the pressure to the friction shells. Since the shape of the external surface of friction shells are saw-toothed, by bending of the friction shells, both normal stresses and frictional stresses apply on the borehole wall. A fracture is then generated along the direction of the opening section between the two semi-cylindrical load platens. The design of the probe is more effective than that of the conventional jack fracturing probe in the generation of tangential stress concentration at the opening sections of the borehole wall where a fracture is expected to be produced.

The upper section and lower section of the borehole jack cylinders are grouped in such a way as to leave a small 30 mm wide gap in the centre of the probe. The gap shown in Fig. 1 accommodates a pair of new specific tangential strain sensors that are applied on opposite sides of the opening sections of the borehole. As shown in Fig.4, the movement of the two tangential strain sensors is controlled by air pressure from a super-compact cylinder. The pins of the strain sensors will not press against the borehole wall until loading by the probe. The opening displacement of the fractures is detected as the displacement between the pins and it is measured by strain gauges on the bending beam.

Fig.3 Illustration for stress measurement by the borehole jack single-fracture probe.

Fig.4 Cross section view of the probe after loading with TSS (Tangential Strain Sensor) pressed against the borehole wall.

2 · 2 Principle of the borehole jack single-fracture method

The principal idea of the borehole jack single-fracture method is to detect reopening pressure of a fracture formed at an intended direction. When the stresses at the borehole wall exceed the tensile strength of the rock mass, a fracture is supposed to be formed. Repeated loading and recording of the jack pressure versus tangential strain allows determination of the fracture re-opening pressure. Fig.5 shows a typical recording of pressure versus strain for a borehole jack single-fracture method. Here the strain stands for the results measured by TSS, P_b is the break-down pressure, and P_r is the re-opening pressure of the fracture, as shown in Fig. 5.

The borehole jack single-fracture method presents a three-dimensional problem. However, since the length-to-diameter ratio of the probe is about 7 and measurements of the fracture are carried out at the middle of the probe, a plane strain condition could be assumed.

To determine rock stresses by the new borehole jack single-fracture method, it is assumed that $\sigma_{\theta r}$ is compressive and there is no residual opening of the fracture. Here $\sigma_{\theta r}$ means the tangential normal stress induced by rock stresses. The borehole wall fracture is assumed to be reopened when the tangential normal stress $\sigma_{\theta p}$ at borehole wall on the fracture plane induced by loading by the probe reaches the tangential normal stress $\sigma_{\theta r}$ induced by rock stresses, i.e.,

$$\sigma_{\theta r} = \sigma_1 + \sigma_2 - 2(\sigma_1 - \sigma_2) \cos 2(\theta_x - \psi) = \sigma_{\theta p} = k P_r \dots \dots \dots (1)$$

where σ_1 and σ_2 are far field principal stresses ($\sigma_1 > \sigma_2$) as shown in Fig. 6, θ_x is the angle of the fracture plane reckoned from x axis, ψ is the direction of σ_1 from x axis, and k is the ratio of $\sigma_{\theta p}$ to jack pressure P_r on the borehole wall at the fracture plane induced by the loading with the probe. P_r is the jack pressure when the fracture is re-opened. If three different values of the re-opening pressure P_r are obtained for three fractures at different directions, we can determine the three unknowns, i.e., σ_1 , σ_2 , and ψ .

3. Loading tests in a steel pipe and its numerical simulation

Due to the geometric complexity and non-uniform loading mechanism of the new borehole jack single-fracture probe, it is hard to calculate the state of stress distribution on the borehole wall by theoretical methods. There exist not only normal stresses on the borehole surface but also shear stresses caused

Fig.5 Idealized recording of pressure versus strain for borehole jack single-fracture method.

by the interaction between the friction shells and borehole wall. To study the stress distribution on the borehole surface caused by the new borehole jack probe, loading tests in a steel pipe were carried out. A three-dimensional finite difference method (FLAC3D: Fast Lagrangian Analysis of Continua in 3-Dimensions) was adopted to study the stress distribution at the internal surface of the steel pipe. The numerical results were compared with the measurement data around the external surface of the steel pipe for verification of the numerical simulation.

3 · 1 Steel pipe tests

The pipe used in the experiment measures 98 mm and 160 mm in the internal and external diameter, and 760 mm in length. Fig.7 shows the probe being ready to be inserted into the steel pipe. Strain gauges with length of 6mm are glued around the external surface of the steel pipe, and then the measured strains were converted to the stresses using the elastic constant of the steel pipe. The configuration of the instruments is shown in Fig.8. Ten strain gauges numbered 1 to 10 are glued to the first quadrant of the external surface of the steel pipe.

As shown in Fig. 2, the friction shells do not contact with

Fig.6 Designation of parameters and the coordinate system.

Fig.7 Loading tests in a steel pipe.

Fig.8 Configuration of the instruments in steel pipe tests.

the internal surface of the borehole until loaded by the load platens during loading process, which are designed intentionally to set the probe inside the borehole easily. To check the contact condition between the probe and the steel pipe, pressure-sensitive paper was inserted between the probe and the internal surface of the steel pipe. Fig.9 shows the photograph of the pressure-sensitive paper spread out after inserted between the friction shells of the upper section and the steel pipe under the loading pressure of 60MPa. The black lines indicate convex parts on the upper friction shell, and the two blank sections stand for the opening sections of the probe where fractures are supposed to be generated. The two white dots in the middle of the black lines are the traces of screws fixing the friction shell on the load platen. At least one friction shell contacts well with the steel pipe on the whole except in small regions at the right edge (the left edge is the center of the probe where TSS is installed). However, more careful manufacturing is required so that all of the friction shells work completely. In fact, plating process was forgotten for the internal surfaces of one pair of the friction shells, and the probe is now under remaking.

Fig.10 shows the stress distribution calculated from the strains measured at the external surface of the steel pipe under loading pressure of 60MPa. In the calculation, we used the following equation,

$$\sigma_{\theta} = E \varepsilon \dots \dots \dots (2)$$

where σ_{θ} is tangential stress in θ direction, E is the elastic constant of steel, 2.1×10^5 MPa, and ε stands for the measured strains. In Fig. 10, the tangential stress σ_{θ} on the external surface of the steel pipe is normalized by the loading pressure of the borehole jacks, P_i , while the horizontal axis stands for the angle measured counterclockwise from the opening section (as shown in Fig. 8).

It can be seen from the figure that the tangential stress

Fig.9 Photograph of the pressure-sensitive paper spread out.

Fig.10 Stress distribution calculated from measured strains at the external surface of the steel pipe.

at the external surface of the steel pipe is compressive at the opening section, and tensile at the perpendicular direction. The tangential stress changes from compressive into tensile at about 45 degree from the opening section.

3 · 2 Numerical study

Since only the stresses on the external surface of the steel pipe can be measured, in order to understand stress distribution on the internal surface of the steel pipe and obtain further information of the probe's loading mechanism, a numerical study of the new borehole jack probe is necessary. We already carried out a two-dimensional simulation of the probe⁸⁾, but found that it was inadequate for a thorough evaluation of the stress distribution due to its three-dimensional configuration. Therefore, a three-dimensional finite difference method named FLAC3D is adopted here to simulate the steel pipe test.

Fig.11 shows the model of the steel pipe with the borehole jack single-fracture probe inserted inside. The model is 760 mm long, 80 mm for the external radius which stands for the external surface of the steel pipe, and comprises about 280000 zones. Since the load platens and the friction shells are both made of steel and contact perfectly well after loaded, they are modeled as one body. The probe and the steel pipe are both modeled as non-yielding elastic continuums. FISH coding is used extensively in this simulation to form the proper shape of the mesh and adjust ratio of grid density to achieve the best modeling results, where FISH is a programming language embedded within FLAC3D

Fig.11 Mesh of FLAC3D model (The y axis is coincide with the borehole axis).

Fig.12 Contour of normal stress in Z direction under unit jack pressure.

to help researchers to define new variables and functions. For example, none of the primitive shapes in FLAC3D is suitable for the modeling of the geometry shape of the probe. In order to model the probe effectively and accurately, we create a special primitive shape using FISH coding. All grid points within this primitive shape are relocated to form the mesh of the probe by using a linear interpolation along radial lines⁹⁾.

Only one quarter of the probe is modeled since the geometry and loading are symmetrical with respect to x and z directions. The opening section is represented by the plane with $z = 0$. The boundary condition is applied by taking advantage of the planes of symmetry, i.e., all grid points are fixed in the x direction for the symmetrical plane with $x = 0$ and all grid points are fixed in the z direction for the symmetrical plane with $z = 0$. A unit jack pressure is applied for loading of all 8 borehole jacks, and the locations of them are shown as black semicircles in Fig. 11.

The contour of normal stress in z direction is plotted in Fig.12. The compressive stress distribution in the extents where unit load is applied by eight borehole jacks can clearly be seen. The stresses reach the maximum tensile stress at the opening section with a uniform distribution along the axis.

To verify the accuracy of the numerical simulation, the simulation results of tangential stresses along the external surface of the steel pipe are compared with the measured data. In Fig.13, we can see that the two results agree fairly well. For the numerical results, more samplings are taken close to the opening section, i.e., from 0 degree to 8 degree, to provide

Fig.13 Comparison between the measured and the numerical stress distributions at the external surface of the steel pipe; jack pressure P_i is compression (negative).

Fig.14 Tangential stress distribution at the internal surface of the steel pipe by numerical simulation.

a more accurate representation of high stress gradient at the external surface of the steel pipe.

The tangential stress distribution at the internal surface of the steel pipe at the middle of the upper friction shell is shown in Fig.14. The horizontal axis means the angle measured counterclockwise from the opening section at the internal surface of the steel pipe. As expected, the tangential stress reaches the maximum tensile stress at the opening section and then it decreases smoothly. The tangential stress changes from tensile stress to compressive stress at the angle of 56 degree from the opening section, and the magnitude of the compressive stress increases along with the angle. Based on this analysis, the stress concentration factor k shown in Equation (1) is considered 0.92 for loading in the steel pipe.

The distribution of the tangential stress at the internal surface is critical for generating and reopening of fractures at intended directions. All previous jack fracturing techniques had to consider the influence of a load platen half-contact angle, i.e., an extent where the load platen contact with the borehole wall, on the stress distribution and fractures were generated either at the edge of the bearing plates or at the middle of the opening section^{10, 11)}. From Fig.14, however, we can understand that the tensile stress concentration is generated significantly only at the opening section as expected. Furthermore, the tangential stress becomes compressive about 60 degrees away from the opening section, which means that the probe can be applied to measure in situ stress even at the location where there are existing fractures, as long as these fractures are located along the longitudinal direction in the compressive section by loading

Fig.15 Tangential stress distribution along diametrical directions every 15 degrees within the steel pipe.

of the probe.

To understand why the tangential stress distribution at the internal surface of the steel pipe is almost opposite to that at the external surface, Fig.15 plots the tangential stress distribution along diametrical directions every 15 degrees within the steel pipe at the same section as in Fig. 14. The horizontal axis stands for the sampling radius divided by the internal radius of the steel pipe. By studying this figure, we can understand that there exists positive bending moment at the opening section. The bending moment decreases to about zero at about 50 degree and turns negative afterwards.

Since the borehole jack single-fracture probe has three-dimensional geometry by using 8 borehole jacks, stress distributions along the axis in the longitudinal direction have to be studied as well. Fig.16 shows the tangential stress distribution along the longitudinal direction at the opening section of the internal surface of the steel pipe. The horizontal axis stands for the length of the steel pipe with the borehole jack probe inserted from the left side. From this figure it can be understood that the tangential stress normalized by unit loading of jacks varies slightly between 0.73 and 0.94 at the section where the probe is inserted, i.e., from 0 mm to 480 mm in length of the steel pipe, and then it decreases sharply to around zero from 500 mm to 760 mm in length where the steel pipe is not loaded by the probe. Based on the stress distribution at the longitudinal direction, we can assume that a fracture can be produced along the whole length of the borehole jack probe.

4. Conclusions

A new borehole jack single-fracture probe for deep stress measurements is developed. The new probe includes unique borehole jack loading system and new special tangential strain sensors to detect the opening of fractures directly.

Loading tests of the new probe in a steel pipe is carried out to study stress distribution on borehole surface induced by loading with the probe. The measurement data are compared with the numerical results and they agree fairly well. Through the test and numerical results, it was found that the probe generates high tensile stress concentration at the opening section where a fracture is expected to be formed, and the stress concentration factor, k , in Equation (1), is 0.92. The tangential stress turns compressive 60 degrees away from the opening section, which is important for applying the probe in fractured

Fig.16 Tangential stress distribution at the opening section along longitudinal direction of the steel pipe by numerical simulation.

rock mass since we can ignore effects of preexisting fractures in this compressive stress region during in situ stress measurement. In the longitudinal direction, the probe generates a relatively constant distribution of the tangential stress within the scope of influence of the probe.

The new developed borehole jack single-fracture probe presents the following advantages over the previous hydraulic or sleeve fracturing techniques. Firstly, a fracture can be generated at the intended direction based on the unique loading mechanism of the probe. Secondly, inaccuracies aroused by dealing with fluid pressure distribution in the fracture are not expected since no fluid is applied to the borehole wall. Thirdly, the opening of the fracture is measured directly by the tangential strain sensor; therefore the re-opening pressure of the fracture can be detected accurately.

The authors are going to carry out loading tests in 600 mm cubic specimens made of mortar and sandstone, in which artificial fractures at intended directions will be produced. Through these tests, the performance of TSS and reliability of this probe in stress measurement will be demonstrated. In situ stress measurement by this probe is planned to be compared with results obtained from hydraulic fracturing technique and other stress measurement methods. Through establishment of this new stress measuring method, a more accurate and economical method for deep underground stress measurement is expected to be realized.

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新型乾式破碎地圧測定法の鋼管試験の数値解析

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新たに開発されたボアホールジャッキ乾式一面破碎応力測定プローブの性能を検討するため、鋼管を用いた室内実験を行った。鋼管内壁の載荷状態を模擬した3次元数値解析を行い、その結果を鋼管外壁に貼り付けたひずみゲージの測定結果と比較し、数値解析の妥当性を確認した。その結果、ボーリング孔壁の亀裂造成位置には、大きな引張応力が作用するとともに、亀裂造成位置から離れた位置には圧縮応力が作用して既存亀裂の影響が表れにくいことなど、このプローブの有用性が明らかとなった。

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