Numerical Simulation of Borehole Slotter Layout Optimization

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Abstract. This paper briefs the basic principle, current methods and test process for measuring in-situ stress by the borehole slotter method. Studies are carried out to optimize the slot’s cutting depth and layout by means of 3D numerical simulation. Such simulation results show that when the original stress field is parallel to the slot, the required cutting depth to fully release the stress on both sides of the slot reaches its peak (16 mm). In order to avoid interaction between slots and enhance reliability, only one slot is arranged at a given drilling depth and the space between slots should generally be greater than 200 mm. Based on such results, the in-situ stress measurement was conducted by means of the borehole slotter method in an underground laboratory in Jinping. The tested rock mass is in stress concentration area in a tunnel face, and the acquired vertical component of the stress is found greater than the self-weight of the overlying rock mass. This field test shows that such test rock mass is under extremely high stress condition, which is in compliance with disked rock cores discovered during tunneling.

1. Introduction
The magnitude and orientation of in-situ stress has direct bearing on the layout and safety of large-scale tunnels and other underground structures. Therefore, precise and reliable measurement of in-situ stress within important rock masses has become a key technology which calls for immediate researches and implementation. Methods for such purpose proposed by the International Rock Mechanics Committee (ISRM, 1988) include borehole deformation measurement (BDM), overcoring borehole relief (OBR), hydraulic fracturing and stress recovery measurement (SRM) [1]. OBR can produce a full set of stress tensors of the tested rock mass with just one trial, while hydraulic fracturing has advantages of simple operation, deeper measuring depth and immunity from the mechanical parameters of the tested rock mass [2-5]. As a result, the above two methods are commonly used in engineering practices [6-8].

At present, a majority of the water conservancy and hydropower projects under construction or scheduled for implementation in west China are characterized by deep burial, high in-situ stress and complex structures. However, against extremely high in-situ stress conditions, OBR is inclined to face failures caused by disked rock cores, while hydraulic fracturing tends to be challenged by difficulties of ultra-high pressure equipment. Ge Xiurun, Academician of the Chinese Academy of Engineering, improved the commonly used in-situ stress measuring equipment and proposed a complete stress relief
method on local borehole wall [9]. Ai Kai, Senior Engineer of the Yangtze River Scientific Research Institute (YRSRI) put forward a partial stress relief method to measure the stress of the excavation rock surface under high stress condition [10]. Liu Yunfang expanded the use of the method and attained the elastic modulus of surrounding rock mass [11]. As the first scientific institute to have introduced the in-situ stress measuring method of borehole slotter (R. Corthesy, Guang He, D.E. Gill, et al. 1999) in China, YRSRI proved that such method works well for in-situ stress measurement under high stress condition [12, 13]. For the purpose of improved slot layout, this paper uses the finite element method to numerically simulate the process of stress relief at the borehole wall in-situ stress test, discusses the minimum cutting depth to fully release the stress, and discovers the effects of various slot depths under various stress boundary conditions on the strains on the upper side of the slot, along the borehole circle, and along the axial of the borehole. The layout of slot produced by the numerical simulation is used in the stress test in an underground laboratory in Jinping, China, which is under extremely high stress environment.

2. Technique Principles

2.1. Test Method

The borehole slotter method is based on the principle of the release of original in-situ stress. The arrangement of the test equipment is as shown in figure 1. A small-sized, air motor driven diamond saw blade can make several slots, which are parallel to the borehole axis and evenly distributed on the borehole wall perimeter, to fully release the normal stress on both sides of a slot. Variations of the normal stress on one side of a slot could then be read to understand the stress of the tested rock mass on the basis of elastic theory.

![Figure 1. Test equipment.](image)

1. Clamp mechanism piston, 2. Saw blade, 3. Strain sensor, 4. Slotter, 5. Supply pipes and cable, 6. Data acquisition, 7. Operating elements control desk, 8. Air motor.

The accuracy of the borehole slotter method is determined by the stiffness of the tested rock mass and the strain sensor’s sensitivity. According to the information provided by the manufacturer, the resolution of the strain sensor under normal conditions is about 1 micro-strain, and, as a result, the accuracy of the method is +/- 0.5 MPa when the measured rock’s elastic modulus is 40 GPa.

2.2. Test Theory

The tested rock mass is regarded as an isotropic linear elastic material, and the rock is assumed to be subjected to a 3D stress field with $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{yz}$, $\tau_{xz}$, and $\tau_{xy}$ acting in the local coordinate system.
system as shown in figure 2, in which the z-axis is parallel to the axis of the borehole. And θ is measured in the counter clockwise direction starting from the x-axis. After drilling, the stresses at the borehole wall at a point forming an angle θ are as follows:

\[
\sigma_{\theta\theta} = \sigma_{yy}(1-2\cos2\theta) + \sigma_{zy}(1+\cos2\theta) - \tau_{zy0}\sin2\theta
\]

(1)

\[
\sigma_z = 2\mu(\sigma_{y0} - \sigma_{z0}) - 2\tau_{zy0}\cos2\theta
\]

(2)

\[
\sigma_{zy} = 2\tau_{zy0}(\cos\theta - \sin\theta)
\]

(3)

\[
\sigma_{rr} = \sigma_{\theta\theta} = \sigma_{\theta z} = 0
\]

(4)

where \( \sigma_{\theta\theta}, \sigma_z, \sigma_\theta, \) and \( \sigma_{rr} \) are the tangential, axial and radial components of the borehole wall stress; \( \sigma_{yy}, \sigma_{zy}, \sigma_{zz}, \) and \( \sigma_{rx}, \sigma_{rz} \) are shear stress components; \( E \) is the elastic modulus, and \( \mu \) is the Poisson’s ratio. According to the Hooke’s law, the tangential, axial and shear strains of the borehole wall are:

\[
\varepsilon_{\theta\theta} = \frac{1}{E} \left[ (\sigma_{y0} + \sigma_{\theta0}) - 2(1-\mu^2)(\sigma_{y0} - \sigma_{\theta0})\cos2\theta - 4(1-\mu^2)\sigma_{y0}\sin2\theta - \mu\sigma_{y0} \right]
\]

(5)

\[
\varepsilon_z = \frac{1}{E} \left[ \sigma_z - \mu(\sigma_{y0} + \sigma_{\theta0}) \right]
\]

(6)

\[
\gamma_{z\theta} = \frac{4(1+\mu)}{E} (\tau_{zy}\cos\theta - \tau_{z\theta}\sin\theta)
\]

(7)

\[\text{Figure 2. Borehole coordinate systems.}\]

In field test, the slot is parallel to the borehole axis. Therefore, the shear stress and strain of the borehole wall are the normal stress and strain of the slot respectively.

During slotting, as the cutting depth increases, the normal stress of the slot is gradually released. The stress release rate is defined as \( \rho \). When \( \rho = 1 \), the stress is completely released. The variations of the normal strain and stress induced by slotting are as follows respectively:

\[
\Delta\sigma_{\theta\theta} = \rho \left[ \sigma_{y0}(1-2\cos2\theta) + \sigma_{zy}(1+\cos2\theta) - \tau_{zy0}\sin2\theta \right]
\]

(9)

\[
\Delta\varepsilon_{\theta\theta} = \frac{1}{E} \left[ \Delta\sigma_{\theta\theta} - \mu(\Delta\sigma_{\theta\theta} + \Delta\sigma_{rr}) \right]
\]

(10)
Equation (4) implies that $\sigma_{rr} = \sigma_{r\theta} = 0$. The variation of strain in the normal direction observed in the field test is $\Delta \varepsilon_{\theta\theta}$, which is a function of $\rho$ and $\Delta \sigma_{\theta\theta}$, $\Delta \sigma_{\theta\theta}$. The elastic modulus $E$ and the Poisson's ratio $\mu$ of the rock can be determined by indoor or outdoor mechanics tests. The equation (1) requires three independent unknown variants, i.e., $\sigma_{xx}$, $\sigma_{YY}$ and $\sigma_{XY}$, which requires three independent equations for original stress calculation or at least three slots with different $\theta$ in field test. The least square method is used to produce the 2D stress tensors on the cross section of the borehole within the tested rock mass.

$\rho$ cannot be determined during slotting. As a result, it’s necessary to study the minimum cutting depth of the slot to completely release the stress. Moreover, more than three slots need to be arranged on one tested rock mass, and every slot should be outside the influence zone of the rest slots. This makes it necessary to find out the best depth of slots and their influence areas with the help of the finite element (FEM) numerical simulation so as to optimize the layout of the testing slots.

3. Numerical Simulation of Borehole Slotter Test

Numerical simulations are widely used as a research means when it is difficult to do physical tests. Such simulation aims to study the relationship between the minimum cutting depth and $\rho$ so as to optimize the layout of slots.

3.1. FEM Model

Stresses are relieved locally by cutting slots into the borehole wall using a small-sized, air motor driven diamond saw blade. At least three slots are arranged on the wall of the borehole at a certain angle (usually 120° apart) and parallel to the axis of the borehole. For numerical simulation, every cutting step is 2 mm in the direction of the arrow as shown in figure 3 in the borehole wall. The numerical simulation is carried out by using the ABAQUS. The element type is C3D4 unit, and the model is divided into 165,395 elements and 29,390 nodes.

![Figure 3. FEM modelling.](image)

3.2. Rock Mechanics Parameters

The rock mass is assumed as an isotropic linear elastic material. Referring to the rock mechanics test results of marble specimens in an underground laboratory in Jinping (the “Laboratory”), the mechanical parameters of the rock mass are as follows: the deformation modulus $E_0$ is 45 GPa, and the Poisson's ratio $\mu$ is 0.26.

4. Slot Depth Optimization

4.1. Calculation Cases and Stress Boundary Conditions

In engineering practice, the original stress field of the rock mass is very complicated. The orientation of the maximum principal stress and that of the slot are different, and the minimum slot depth to completely release stresses varies. Therefore four calculation cases in table 1 are selected and studied.

In table 1, $\sigma_{z0}$ is the vertical stress (gravity), $\sigma_{x0}$ is the x-axis horizontal stress, and $\sigma_{y0}$ is the axial stress along the borehole. In case 1, the majority of the stress of the rock mass is the horizontal stress
perpendicular to the slot. In case 2, the majority of the stress of the rock mass is the horizontal stress parallel to the slot. In case 3, the rock mass is under the hydrostatic pressure, which means the three normal stress components are equal. In case 4, the majority of the stress of the rock mass is the vertical stress perpendicular to the slot. As shown in table 1, \( \sigma_{zz} \), \( \sigma_{xx} \), and \( \sigma_{yy} \) are vertical, horizontal along the X axis and along the tunneling axis respectively. The laboratory is located in the heart of the Jinping Mountain, and it is generally over 2,000 m below the ground. Therefore, it is assumed in all calculation cases that the burial depth is 2,000 m and the vertical stress component (gravity) is 54.7 MPa.

| Case No | \( \sigma_{z0}/\text{MPa} \) | \( \sigma_{x0}/\text{MPa} \) | \( \sigma_{y0}/\text{MPa} \) |
|---------|-----------------|----------------|-----------------|
| 1       | 54.7            | 1.2*\( \sigma_{z0} \) | 0.8*\( \sigma_{z0} \) |
| 2       | 54.7            | 0.8*\( \sigma_{z0} \) | 1.2*\( \sigma_{z0} \) |
| 3       | 54.7            | 1.0*\( \sigma_{z0} \) | 1.0*\( \sigma_{z0} \) |
| 4       | 54.7            | 0.8*\( \sigma_{z0} \) | 0.6*\( \sigma_{z0} \) |

4.2. Stress Evolution during Slotting

Obvious stress concentration zones and stress releasing zones appear in different parts of the borehole wall after the borehole is made. For the purpose of demonstration, figure 4 shows the evolution of stress components from the beginning of slotting to the final cutting depth, which is 30 mm in case 3 as an illustration. In such illustration, the cutting depth increases 2 mm for every step forward. Due to limited space, colored distribution of \( \sigma_z \) is shown when the slotting begins, and when the cutting depth reaches 6 mm, 18 mm, and 30 mm respectively.

![Figure 4](image-url)

According to figure 4, the stress concentration zone is obvious on both sides of the borehole wall after the borehole is made. As the cutting depth increases, the stresses around the slot are gradually...
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reduced, and the stress concentration zone shifts to the end of the slot. As shown in figure 4, when the cutting depth is 18 mm, the stress component of $\sigma_z$ at the upper and lower sides of the slot is basically stable. Due to the disturbance of slotting, the stress in a certain range around the slot are significantly lower than that in the undisturbed area around the borehole.

Figure 5 shows the evolution of the normal stress $\sigma_z$ of the middle upper node of the slot in case 3 before, during and after slotting. When the borehole is made, the stress component $\sigma_z$ in the central area of the slot displays obvious stress concentration. When the slot depth is 4 mm, the stress is partially released and reaches 3.74 MPa. When the slot depth is 8 mm, the stress is -1.1 MPa, which means the stress has turned into tensile stress. Then when the slot depth increases to 14 mm, $\sigma_z$ becomes basically stable at -1.0 MPa. In this figure, -1 and 0 on the horizontal axis means before slotting and when the slotting is done respectively.

Figure 5. Variation of $\sigma_z$ as the cutting depth increases.

4.3. Optimization of Slot Depth

The numerical simulation results show an evolution of the normal strain $\varepsilon_z$ in the middle upper side of the slot in all four cases similar to that of $\sigma_z$. As the cutting depth increases, $\varepsilon_z$ gradually goes down, and it generally becomes stable when the cutting depth reaches a certain depth. Figure 6 shows the evolution of $\varepsilon_z$ in case 2 and case 4. In case 2, $\varepsilon_z$ increases from 0 to -1.91e-3 after the borehole is done. This figure is 0.77e-3 and 0.81e-3 when the cutting depth increases to 6 mm and 14 mm respectively, and it remains stable at 0.81e-3 even when the cutting depth keeps increasing. Therefore, the evolution of $\varepsilon_z$ is similar to that of $\sigma_z$. Taking into consideration the evolution of $\varepsilon_z$ and $\sigma_z$, it can be considered that when the cutting depth reaches 16 mm, the stress is completely released. It means that the cutting depth should not be less than 16 mm in field test. In Case 4, $\varepsilon_z$ increases from 0 to -1.91e-3 during drilling, and when the cutting depth is 8 mm, $\varepsilon_z$ is 0.81e-3. Then with the increase of the cutting depth, $\varepsilon_z$ remains stable at 0.81e-3. It can be regarded that the stress is completely released when the cutting depth reaches 10 mm. It means that the depth of the slot should be more than 10 mm in field test.

Figure 6. Change of $\varepsilon_z$ as the cutting depth increases.
The cutting depth in case 2 should be more than 14 mm, which is the maximum among all the four cases, while such value in case 4 is 10 mm, the smallest. It can be concluded that when the majority of the stress is parallel to the borehole axis, the required cutting depth of the slot is relatively great. Therefore, in order to ensure the reliability of field test results, the cutting depth of the slot should be more than 14 mm to completely release stress.

5. Slot Spacing Optimization

From the simulation results of the previous section, case 2, in which the majority of the stress of the rock mass is horizontal stress parallel to the slot, requires the deepest cutting to release stress fully. For this reason, this case becomes the research object in this section to study the influence of the slot on the borehole perimeter and along the borehole axis to optimize the spacing of slots.

5.1. Slot’s Effects along the Borehole Axis

When slotting on the borehole wall, a certain band of influence zone along the axial direction near the slot will be formed as shown in figure 7. In order to avoid the overlapping effect, a slot should be placed away from the influence zone of other slots. Because case 2 requires the longest slotting to fully release stress, this section focuses on this case to find out the slot’s radius influence zone when the cutting depth ranges from 16 to 30 mm.

![Figure 7. Influenced band along the axis of borehole.](image)

![Figure 8. Distribution of $\varepsilon_z$ along the observation line at different slot depth.](image)
An observation line is arranged on one end of the slot as shown in figure 7 to find out such slot’s axial effect. The distribution of the normal strain $\varepsilon_z$ along the observation line starting from the end of the slot is used to study the scope of the slot’s influence. Figure 8 shows the variation of $\varepsilon_z$ on the observation line when the cutting depth is 16 mm, 24 mm and 30 mm respectively in case 2.

It can be seen from figure 8 that the value of $\varepsilon_z$ at the end of the slot is $4.5 \times 10^{-3}$. This value decreases as the axial distance increases. When such axial distance reaches 61 mm and goes beyond, the value becomes stable at $1.4 \times 10^{-3}$. Accordingly, slot spacing should be appropriately decided on the basis of cutting depth in field test. When the cutting depth is 16 mm, the distance between the ends of two cuts should not be less than 122 mm. When the cutting depth is 24 mm, its disturbance range is around 74 mm and the distance between the ends of two cuts should not be less than 182 mm. Generally, the space between slots in field test should be greater than the figure attained by simulation, or specifically, greater than 200 mm.

5.2. Slot’s Effect on Borehole Perimeter

In field test, at least three slots with different angle $\theta$ need to be arranged to obtain the two-dimensional stress tensors of the borehole cross section. The angle form by two slots is usually 120°. Therefore, it is necessary to study the slot’s influence on the borehole wall perimeter to avoid the mutual influence of slots and its harm to the reliability of the test results. Figure 9 shows the distribution of the normal strain $\varepsilon_z$ before cutting and when the cutting depth is 16 mm in case 2.

![Figure 9. Distribution of $\varepsilon_z$ in two situations.](image)

Comparison of figure 9(a) and figure 9(b) finds that when the cutting depth is 16 mm, the influence range on either side of the slot, will cover a 53° arc on the borehole perimeter in a symmetrical way. It means that with such stress, when the cutting depth is 16 mm, the angle formed by two slots should be more than 106°. Therefore, three slots can be arranged at a given drilling depth. However, in practice, in order to avoid the interaction between slots and ensure the reliability of the test, only one slot is arranged at a given drilling depth.

6. Engineering Application

6.1. Introduction to the Field Test

The Laboratory comprises four pairs (eight in number) of experiment tunnels and other auxiliary caves, close to the auxiliary construction tunnels for the diversion system in the second cascade of the hydropower station in Jinping, Sichuan, China. The laboratory is located in the D2b Baishan formation marble, and its burial depth is more than 2,000 m generally. Such outstanding in-situ stress environment presents high risk of rock burst during construction. In order to study the in-situ stress of the Laboratory, the borehole slotter in-situ stress test was carried out.
Drilling reveals that the drilled cores are gray-white thick layer of marble, and their lithology is relatively brittle. The cores obtained by drilling are generally short columns. During drilling, disked rock cores appear to a limited extent (figure 10). Only one slot is placed at one drilling depth meanwhile, according to the simulation results, the cutting depth of slots is 30 mm, and the distance between slots is 300 mm.

Figure 10. Photos of disked rock cores.

6.2. Test Results Analysis
Elastic parameters (E and μ) of the rock mass are required in the process of borehole slotter test. The elastic modulus of the rock is 52.0 GPa, and the Poisson's ratio is 0.22 based on laboratory test results. Table 2 shows the test results. In this table, $\sigma_A$ and $\sigma_B$ are the maximum and minimum principal stresses of the borehole cross-section respectively, and $\alpha$ is the maximum principal stress azimuth of the borehole cross-section. $\alpha$ equals to 0° when the azimuth is upward vertical, and it increase when the azimuth moves clockwise. Test results are as shown in table 2.

| Test depth/m | $\sigma_A$/MPa | $\sigma_B$/MPa | $\alpha/°$ |
|--------------|----------------|----------------|-----------|
| 9.4          | 94.5           | 80.3           | 155       |
| 14.0         | 64.7           | 59.7           | 133       |
| 15.4         | 85.5           | 75.5           | 144       |

Within the test depth, $\sigma_A$ is between 64.7 and 94.5 MPa, $\sigma_B$ is between 59.2 and 80.3 MPa, and $\alpha$ is between 133° and 155°. The majority of the in-situ stress of the rock mass at the test site is downward vertical.

The stress components on the borehole cross section could be arrived at by means of the principal stresses at the same place through equations (11)-(13):

$$\sigma_z = \left(\frac{\sigma_A + \sigma_B + \sigma_A - \sigma_B}{2}\right) \cos 2\alpha$$  \hspace{1cm} (11)

$$\sigma_x = \left(\frac{\sigma_A + \sigma_B - \sigma_A - \sigma_B}{2}\right) \cos 2\alpha$$  \hspace{1cm} (12)

$$\tau_{zx} = \frac{\sigma_A - \sigma_B}{2} \sin 2\alpha$$  \hspace{1cm} (13)

where $\sigma_z$, $\sigma_x$ and $\tau_{zx}$ are the vertical, horizontal and shear stress components of the borehole cross section. Table 3 provides the stress test results.
The density of the overlying rock mass is 2,650 kg/m$^3$, and the burial depth of the testing site is about 2,300 m. Then the gravity of the overlying rock mass is about 61.0 MPa. The test result shows that the vertical stress component is a little greater than the estimated self-weight of the overlying rock mass, and proves that the test is effective. The main reason is that the tested borehole is located in the stress concentration zone with relatively high stress. Disked rock cores as shown in figure 10 are easy to be found during drilling as evidence.

7. Conclusions
This paper studies the way to optimize the layout of borehole slotter method with the help of numerical simulation, and applies such method to field test. The main conclusions are as follows:

1. The results of 3D numerical analysis show that when the majority of the original stress field is parallel to the borehole axis, the stress on both sides of the slot could be released when the cutting depth of the slot reaches 16 mm; while the majority of the majority of the original stress field is perpendicular to the normal direction of slot, the stress on both sides of the slot could be released when the cutting depth of the slot reaches 10 mm. Therefore, in order to ensure the reliability of field test results, the cutting depth should be at least 16 mm in field tests.

2. When the cutting depth is 16 mm, the slot has symmetrical influence zones on the borehole perimeter, above and below the slot and each coving an angle of about 53°. The angle formed by two slots should be less than 106°. Three slots could be arranged at a given drilling depth, however, only one is arranged at such depth in order to avoid interaction of slots and enhance test reliability.

3. As the cutting depth of slot increases, the axial disturbance range of the slot increase. When the cutting depth of the slot is 16 mm, the distance between the ends of slots should not be less than 12 cm.

4. The GS-8 borehole of the 7# tunnel face in the underground laboratory in Jinping is located in the stress concentration zone, and the measured vertical component of the stress is larger than the estimated stress value based on the self-weight of the overlying rock mass. The test results show that the rock mass at the test site is in extra high stress environment, which is consistent with the occurrence of disked rock cores during drilling.

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