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*Research Article*

# Study on the Method for Measuring Stress on Rock Mass Excavation Surface under Extremely High Stress Conditions

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In view of the limitations of several existing stress measurement methods under extremely high stress conditions (stress – strength ratio $\sigma/Rc > 0.5$), this paper proposes a slot relief method based on partial deformation recovery to measure rock mass surface stress under extremely high stress conditions and justifies its viability with the help of an infinite element model. This method is then used to measure and study a research tunnel in West China's Jinping II Hydropower Station, where the maximum stress measured reached 80 MPa. In the process of measurement, this method needs neither complete borehole core nor ultrahigh pressure equipment. On the contrary, the test equipment is easy to carry and operate on, suitable for rock mass surface stress measurement under extremely high stress conditions, and able to provide in situ stress measurements for cavern rockburst prevention and slope management.

## 1. Introduction

More and more rock mass projects have been built in China. Highly tectonic movement is commonly seen in West China, where the issue of high in situ stress is involved in water and metal resource development. The maximum principal stress at a depth of 500 m in the Jinchuan mining area in northwest China's Gansu Province exceeds 30 MPa [1], and that at the dam site of the Ertan Hydropower Station in the southwest Sichuan province reaches 65 MPa [2]. The problem of high in situ stress faced by rock mass projects in high in situ stress areas is becoming increasingly prominent, especially in the construction period during which rockburst becomes increasingly dangerous. Previous studies show that the main determining factors of rockburst are the level of in situ stress and its relative ratio to the compressive strength of rock. When the stress-strength ratio ($\sigma/Rc$) in the rock is close to or greater than 0.5, and the rock mass is in a high stress envi-

ronment, rockburst is often difficult to avoid. The Laxiwa, Lijiaxia, Ertan, Tianshengqiao, and Lubuge hydropower projects and others completed in West China in the past 40 years, as well as the underground mining area of the Jinchuan Nickel Mine, have all encountered high in situ stress problems such as rockburst and spalling rib [3, 4]. These have posed a serious threat to the stability of cavern's surrounding rock and the safety of personnel and equipment. Even during the excavation of shallow dam foundation, layered exfoliation of surface rock mass caused by the release of high in situ stress will occur [5].

In situ stress is the most fundamental and most important load in rock mass engineering. It is also the initial condition for numerical calculation in a rock mass project and the basic factor for analyzing rock mass's failure and displacement characteristics. Therefore, it is of great significance to accurately understand the actual stress environment of a rock mass in high stress area through field testing and to

provide measurements for mitigating rockburst disasters and suppressing their occurrence.

## 2. Major Existing Methods for Measuring In Situ Stress and Their Limitations

Measuring in situ stress can directly reveal the stress state at a measuring point. The Swiss geologist Albert Heim puts forward the concept of in situ stress in rock mass at the beginning of the 20th century. Then, the Swedish scholar Hast invented the piezomagnetic stress meter in the 1950s and measured in situ stress at shallow depths in four mining areas in the Scandinavia. Afterwards, a group of in situ stress measurement methods have been developed. In the past half century, especially in the past 40 years, a variety of measurement methods and instruments have been developed as work in the area advances. Globally, there are more than a dozen major methods and hundreds of instruments up to now. The major methods include hydraulic fracturing, stress relief, stress recovery, borehole collapse, acoustic emission, and geophysical method [6–20].

In recent years, a series of large-scale deep underground projects have witnessed high stress, high ground temperature, high karst water pressure, and strong mining disturbance, which are characteristics of the deep rock and constitute a challenge to the theory and method for traditional in situ stress measurement. Therefore, it has become a major concern of researchers and engineers to improve and develop new theories, instruments, and technical methods for in situ stress measurement. Since the 1990s, in the face of in situ stress measurement in the depth of more than 1,000 meters, Cai of University of Science and Technology Beijing and his colleagues developed a measurement theory on the basis of accurate measurement and complete temperature compensation and established an in situ stress measurement system for deep rock [21]. Developing a three-dimensional in situ stress measurement method (BWSRM) and its logging robot, Ge and Hou proposed the principle of a three-dimensional in situ stress measurement method of the local wall stress relief in the borehole and applied in the test of a flat tunnel in the Jinping Hydropower Station [22]. Ma et al. developed a hydrofracturing in situ stress test system with a maximum test pressure of 100 MPa in view of the ultrahigh in situ stress characteristics of the diversion tunnel in the Jinping II Hydropower Station, and the highest rock mass fracturing pressure measured in the hole is 92.1 MPa [23]. In addition, the China Geological Survey successfully obtained measurements of 7000 m-deep in situ stress based on the inelastic recovery in situ stress test method (ASR method) of borehole cores, which provides a new idea for deep three-dimensional in situ stress measurement [24].

The four methods for testing rock stress recommended by the Committee on Testing Methods of the International Society of Rock Mechanics (ISRM-CTM) in 1987 are borehole diameter deformation testing, borehole wall strain testing, rock surface stress recovery testing, and hydraulic fracturing [6, 7]. These methods are widely utilized these days and can be used to measure stress of common magni-



Figure 1: Core discs.

tude. However, the unique geological environment and conditions of rock mass in high stress area make measuring in situ rock mass stress in such area a fundamentally different job because technical difficulties in high stress area make the existing relevant technical standards unapplicable and the above four methods unapplicable.

The borehole diameter deformation testing and borehole wall strain testing are based on borehole relief. They observe the strains in the borehole core before and after the relief and use the elastic theory to identify the stress of the rock mass. These methods require intact borehole core after the relief. However, under the high in situ stress, core discs are produced as shown in Figure 1 as a result of stress concentration in the vicinity of bore bit and release of stress on the core. Therefore, the strain of the relieved core cannot be obtained.

Hydraulic fracturing is a direct testing method, in which the borehole wall at a designated depth is fractured by hydraulic pressure provided by a hydraulic pump. By measuring the pressure and cracking orientation of each characteristic point in the process of fracturing, the magnitude and direction of in situ stress in rock mass near the measuring point can be acquired. This method requires a pressure device, and its pipeline shall be able to generate and withstand the pressure that causes the rock to break and sustain a flow rate (5 L/min) needed to reopen the fracture. In a high stress environment, 50 MPa for example, it is almost impossible for the fracturing equipment to reach a high pressure (greater than 100 MPa) while sustaining a flow rate of 5 L/min. The possibility is further undermined by extreme danger involved.

The stress recovery method is suitable for measuring low-magnitude stress of exposed rock mass surface or excavation surface of underground cavern. Its basic principle is to install measuring an element at selected test points, make a slot, and install a hydraulic pillow or jack, on which pressure will be increased until the reading of the measuring element returns to its value before the slot is made. At such moment, the pressure of the hydraulic steel pillow or jack is the stress in the normal direction. However, common pressure steel pillows cannot bear the high pressure needed by this test method under high stress condition.

As mentioned earlier, the testing methods widely used now have their respective limitations in high stress areas. The author thus puts forward a slot relief method based on partial deformation recovery to measure the surface stress of cavern and slope excavation face under extreme stress condition. In the process of testing, this method needs
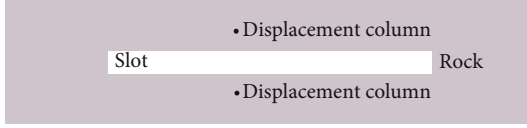
Figure 2: Test layout.

neither a complete borehole core nor ultrahigh pressure equipment. The equipment proposed by the author is light to carry and easy to operate on and can effectively measure in situ stress under extremely high stress. This method is useful for mitigating disasters caused by high stress in caverns and slopes.

## 3. Principle of Slot Relief Method

*3.1. Single Slot.* The slot relief method combines the principles of slot test and stress recovery test. By making a deep-enough crack, the stress on the rock mass surface along the slot's normal direction is completely released, and the difference in the normal displacement of the rock mass surface before and after stress release is obtained. The in situ elastic modulus of the rock mass is then acquired by means of partial deformation recovery and used to calculate the normal stress of the rock mass surface. The layout is as shown in Figure 2. The test process is divided into three parts, e.g., arrangement of measuring points, slot making, and partial deformation recovery, as shown in Figure 3.

The principle of the slot relief method can be demonstrated by Н. И. Мусхелищвили's theory. For a rectangular "relief groove" with a large length-width ratio and enough depth, the lateral stress on the rock mass surface is 0. The rock mass surface and a crack on it can be approximated to a finite-length crack in an infinite elastic plate [6]. After the slot is made, the normal stress on the rock mass surface is released, and the normal deformation of the rock surface on the slot's perpendicular bisector is as follows:

$$W = \frac{\sigma_n L}{2E\rho} \left[ 3 + \mu - \frac{2(1 + \mu)}{\rho^2 + 1} \right], \quad (1)$$

$$\rho = \frac{2y}{L} + \sqrt{\frac{4y^2 + L^2}{L^2}}, \quad (2)$$

where $L$ is the length of the slot. $y$ is the distance between the measuring point and the bisector of the slot. $W$ is the normal deformation of the rock mass at the deformation monitoring point after slotting. $\sigma_n$ is the initial normal stress of the slot before slotting. $E$ is the elastic modulus of the rock mass, which is arrived at with the help of partial deformation recovery and laboratory tests.

After slotting, the normal stress can be obtained by converting Equation (1) to the following:

$$\sigma_n = \frac{2W\rho E}{L[3 + \mu - 2(1 + \mu)/\rho^2 + 1]}. \quad (3)$$

In the test for elastic modulus by means of partial deformation recovery, a slot is made on the rock surface of the

cavern wall, a pressure steel pillow is buried then, and measuring elements are finally installed on both sides of the slot. Pressure is applied to the rock mass on both sides of the slot. The normal deformation of the rock mass surface is measured, and the rock mass deformation parameters are solved as an elastic plane problem. Equation Equation (1) also applies here.

*3.2. Measurement of Surface Stress.* The normal stress $\sigma_N$ of the slot is as follows:

$$\sigma_N = \sigma_x \sin^2\alpha_i + \sigma_y \cos^2\alpha_i - \tau_{xy} \sin 2\alpha_i (i = 1, 2, 3), \quad (4)$$

where $\alpha_i$ is the angle between the slot and the horizontal axis.

In theory, at least three independent slots shall be made and measured separately. The two-dimensional normal stresses of the cavern wall can be calculated by means of the results of the normal stresses of the above three slots.

It is suggested that such three slots be installed at 45°, 0° and 90°, respectively, to the horizontal direction. According to the following equations, the two-dimensional stresses on the cavern surface can be obtained.

$$\left. \begin{aligned} \sigma_x &= \sigma_{N2} \\ \sigma_y &= \sigma_{N3} \\ \tau_{xy} &= \frac{-(\sigma_{N2} + \sigma_{N3})}{2 + \sigma_{N1}} \end{aligned} \right\}, \quad (5)$$

where $\sigma_{N1}$, $\sigma_{N2}$, and $\sigma_{N3}$ are the initial normal stress of the joints, which form degrees of 45°, 0°, and 90° with the horizontal direction, respectively.

The principal stress is as the following:

$$\left. \begin{aligned} \sigma_{1,2} &= \frac{(\sigma_x + \sigma_y)}{2} \pm \sqrt{\frac{(\sigma_x - \sigma_y)^2}{4} + \tau_{xy}^2} \\ \alpha &= 0.5 \tan^{-1} \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \quad (\sigma_x - \sigma_y > 0) \\ \alpha &= 0.5 \tan^{-1} \frac{2\tau_{xy}}{\sigma_x - \sigma_y} + 90° \quad (\sigma_x - \sigma_y < 0) \end{aligned} \right\}. \quad (6)$$

*3.3. Expansion of Surface Stress Measurement Results.* The measurement of rock mass surface stress can be expanded to that of three-dimensional stresses in a circular caver. It is generally believed that as long as the surrounding rock of a circular cavern is complete, free from the impact of excavation blasting, and without large geological structure, it is feasible that the measurement method for two-dimensional stress can be applied to that of the three-dimensional stress. However, due to the differences in geological conditions of each measuring point and the impact of disturbances caused by excavation blasting to varying extent on the walls of a cavern, it is obvious that the result of such expansion is just an approximation and can only be used as a proof of the three-dimensional stress.
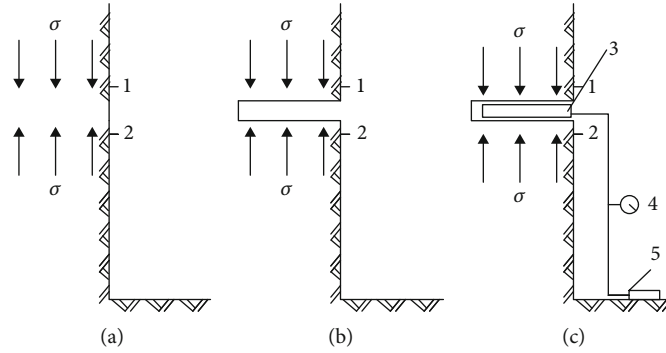
FIGURE 3: Test process. (a) Measuring point arrangement. (b) Slot cut. (c) Partial recovery deformation. 1-displacement column 1. 2-displacement column 1. 3-flat jack. 4-pressure gauge. 5-oil pump.

The surface stress recovery and surface stress relief can be used to the three-dimensional stress. Previous studies show that, in theory, the three-dimensional stress on a cavern wall can be obtained through the results of six independent slots. ISRM-CTM has recommended 8 slots in different directions in a tunnel for this purpose.

## 4. Simulation and Demonstration of Slot Relief

In order to optimize the testing plan and improve measurement accuracy, a variety of slots have been numerically simulated with the help of the finite element method in this paper.

A rock mass in the dimension of $2\,m \times 2\,m \times 1$ m is defined for calculation and analysis, and a slot is arranged in its center to ensure that the slot is in an infinite medium. The number of elements at the slot in the model has been increased. The rock material is homogeneous with isotropic linear and elastic features. We assume that the rock's elastic modulus is 30 GPa, and its Poisson's ratio is 0.2. The finite element mesh is as shown in Figure 4. The initial stress field of the model is considered as a uniform stress field of 50 MPa and is obtained by directly assigning the stress to the element and calculating. There is no constraint on the surface for displacement measurement while all its other surfaces have normal constraints.

Figure 5 shows the distribution of displacement when the slot is 0.8 m in length, and the normal stress is 50 MPa. Calculation shows that the maximum normal displacement on the slot's perpendicular bisector is 1.06 mm. For this magnitude of displacement, a multipoint displacement measurement can be used to replace the traditional strain measurement. This can meet the requirement of accuracy while it can be used in a wide scope.

In this paper, the finite element method is used to analyze and study the influence exerted by the slot with different lengths.

Figure 6 shows the relationship between the normal displacement on the slot's perpendicular bisector and the slot's length during the relief process, which is found to be a linear correlation. When the slot reaches 80 cm in length, the normal deformation of the slot has reached the millimeter level. Therefore, the length of the slot is suggested to be about
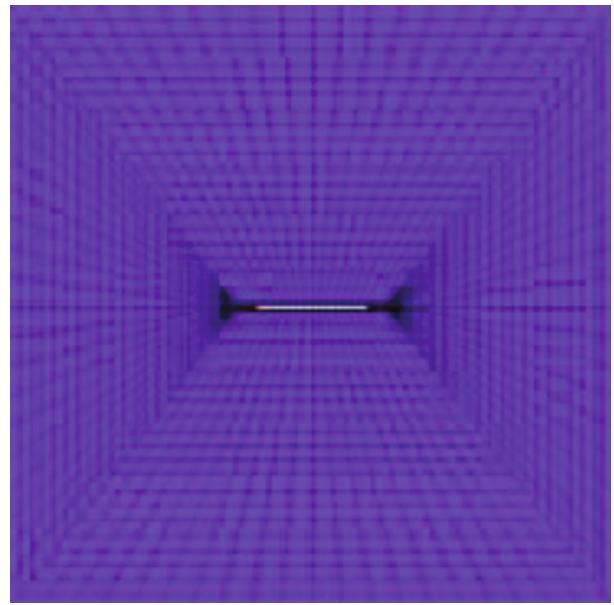


FIGURE 4: Finite element mesh.

80 cm under high stress condition. This meets the requirements of testing accuracy and facilitates the testing process.

In order to completely release the normal stress on the rock mass surface, the slot must be deep enough. Figure 7 shows the relationship between the slot's depth-to-length ratio ($D/L$, $D$ is the slot's depth) and the deformation relief rate (the ratio of a measuring point's deformation to its final deformation). When the slot depth is modest ($D/L < 0.4$), there is a linear correlation between the slot's normal deformation and its depth. As the slot goes deeper, the constraints of the surrounding rock become smaller. When $D/L$ reaches 0.5, the slot's normal deformation basically comes to an end, and its deformation relief rate stabilizes at 95%. Based on the above results, it is suggested that the slot depth in field test be 0.6 times its length to ensure full release of the normal stress of the rock mass surface.

Figure 8 shows the relationship between the rock mass's elastic modulus and the normal displacement of the slot's perpendicular bisector. They form an inversely proportional correlation.
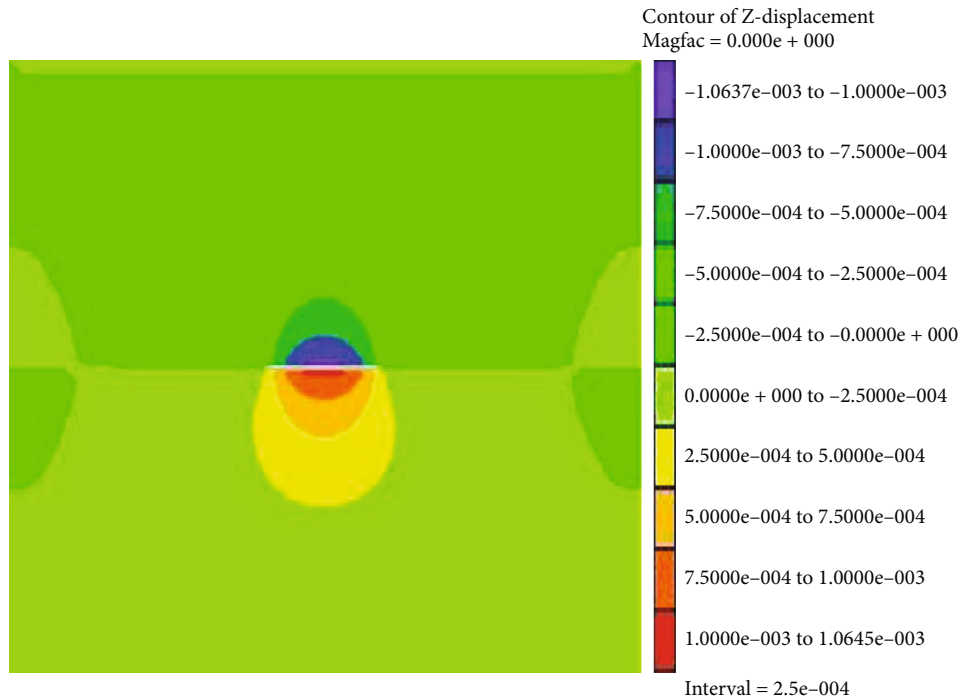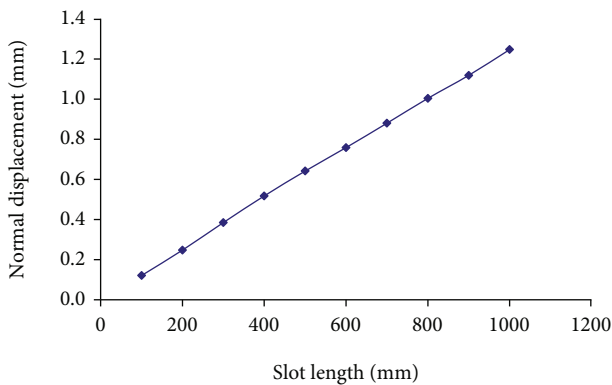
Figure 5: Distribution of rock mass displacement (m).



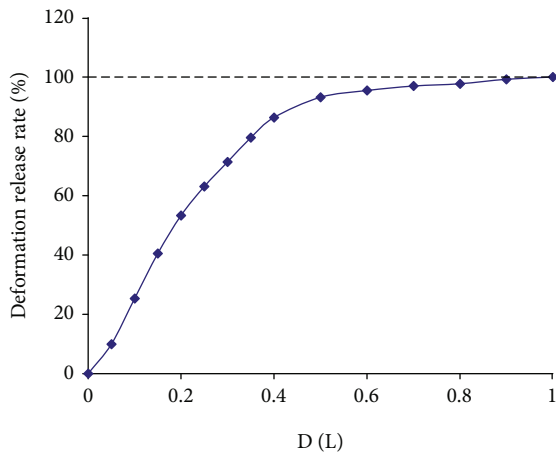Figure 6: Relation between slot length and normal displacement.



Figure 7: Relation between the slot's depth-to-length ratio ($D/L$) and its deformation release rate.

Figure 9 shows the distribution of displacement after slotting. Results of the finite element analysis show that the influence range in the normal direction is 1.5 times the slot's length while that of the lateral direction is 1.5 times the slot's depth.

Although the size of a test area is generally limited in field test, it is necessary to leave sufficient space between them to avoid mutual disturbance, with 3 times the slot length being the suggested spacing,

## 5. Engineering Application

*5.1. Slot's Layout and Making.* A test has been done in the No. 2 Test Branch (AK08+850 m) in the auxiliary tunnel A (NE125°) in the Jinping Hydropower Station in southwest China's Sichuan Province. Five slots in different directions have been arranged on the wall and floor of the test branch as shown in Figure 10. The surrounding rock of the test area is hard dolomite, and the thickness of the overlying rock is about 2,200 m.

After the test area is determined, a cavern is excavated by means of modest blasting of shockproof hole or smooth blasting to achieve minimum influence on the tunnel wall. Before the test, the wall in the selected test area was cleared of loose rocks caused by blasting. Parts that are flat and have no joints are selected for arranging slots.

Diamond bits and the row drilling method are used to make slots in two sequences as shown in Figure 10. After completing the row drilling and forming the slot, the surface of the slot is in a circular arc-shaped zigzag shape. In order to ensure that the pressure steel pillows fits well with the slot surface, a special tool is used to smooth the slot. The depth of the slot is 50 cm. The normal displacement is measured
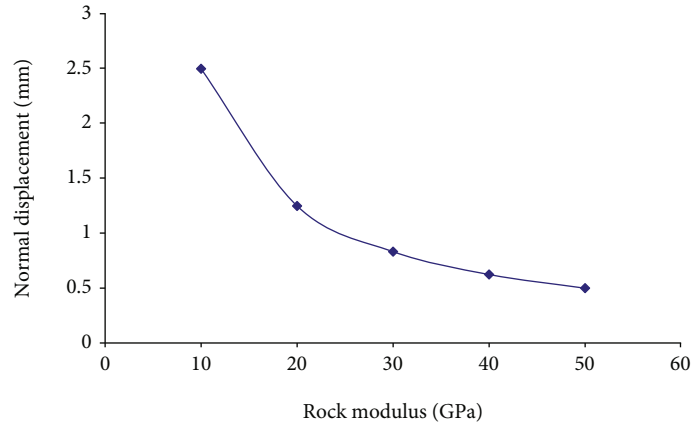
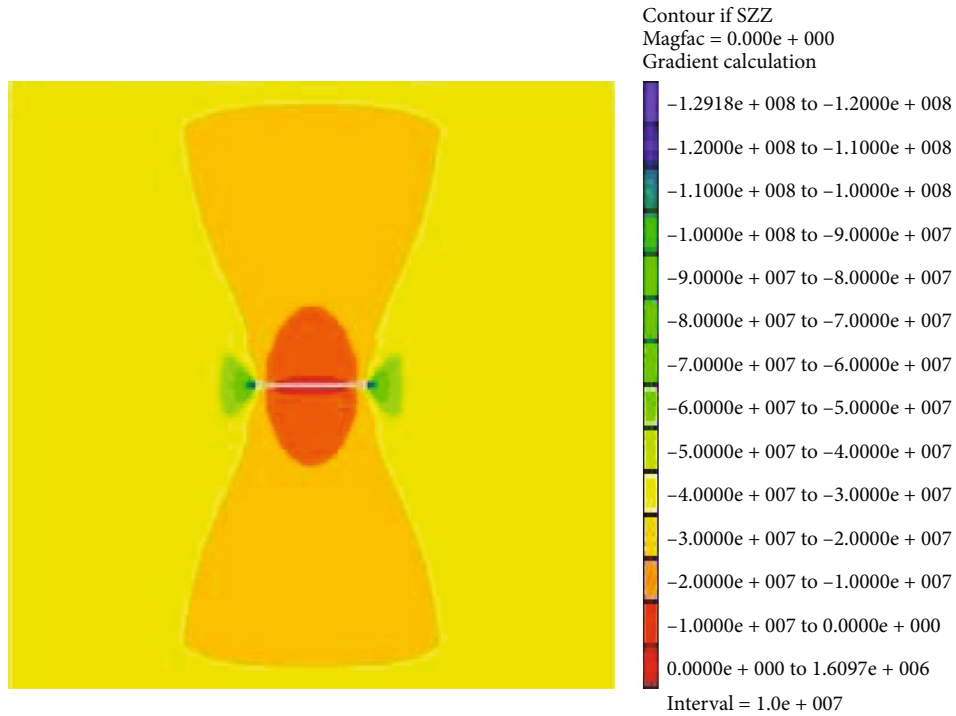FIGURE 8: Relation between rock modulus and normal displacement.



FIGURE 9: Contour map of stress after slotting (Pa).

by a multipoint displacement meter. Immediately after the slot of each stage is released, and after every 10 min reading, when the ratio of the reading difference between the adjacent 2 readings of all meters and the first reading under the slot release of the same stage and the last reading under the previous slot release is less than 5%, the lower slot is released.

*5.2. Results and Discussion.* In the process of slotting, the borehole cores' stress is released, and they become discs as shown in Figure 11. After slotting, the rock in the slot's area is freed from stress and thin sheets of paper-like rock fragments occur.

Deformations at each measuring point after slotting are as shown in Table 1, while the testing process curves are as shown in Figure 12.

It can be seen from Figure 12(a) that at the initial stage of slotting, the slot's is not deep enough, and there is a basically linear correlation between the normal deformation at a measuring point and the slot's depth. As the slot goes deeper, the normal constraint of the rock mass on the tunnel wall is gradually released, and constraints of the inside rock mass on measuring points on the wall reduce. When the slot depth reaches 40 cm (45% of the slot's length), the slot's normal deformation basically comes to an end and becomes stable. Such results are consistent with those of the finite element analysis.

As can be seen from Figure 12(b), the normal deformation on the slot's perpendicular bisector increases as the length of the slot increases, basically forming a linear correlation.
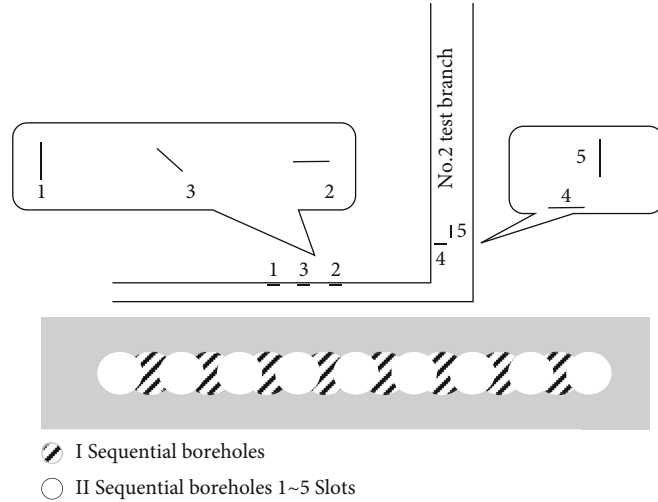
FIGURE 10: Layout of slots.



FIGURE 11: Borehole core after slotting.

Slotting is in nature a process in which the stress of rock mass under high stress conditions is unloaded. Upon the moment the slotting is finished, obvious elastic change is observed on the rock mass. As the stress of the rock mass surface diminishes and the stress inside undergoes adjustment and redistribution, the rock mass witnesses obvious expansion and continuous development of microcracks. Rock mass deformation leads to elastic rebound as well as deformation of cracks, whose direction is basically perpendicular to that of stress unloading. The full deformation of rock mass after unloading comprises elastic deformation and crack deformation [25].

The slot relief process is also one of unloading and fracturing of rock mass. As a result of strong expansion in the direction of stress unloading, deformation parameters gradually deteriorate [26]. According to the concept of effective stress and the principle of strain equivalence, it is known that

$$\bar{E} = E(I - D), \tag{7}$$

where $\bar{E}$ is the equivalent deformation modulus in the case of unloading and damages, $I$ is the unit matrix, and $D$ is the matrix for damage variables.

The deformation recovery test using pressure steel pillows can only obtain deformation parameters caused by damage after slotting. Therefore, laboratory tests are needed to determine the variables matrix of rock mass and its deformation parameters before damage.

Relatively high stress of rock mass, above 30 MPa according to estimation, exists in the test area in this paper. However, existing hydraulic pillows or other equipment are almost unable to provide such high pressure for stress recovery test, which is very dangerous. Therefore, the slot relief method based on partial stress recovery and laboratory rock mechanic test is used to determine the elastic modulus of rock mass and obtain its stress state in an indirect way.

The maximum pressure for stress recovery in the field test is 16 MPa. The recovery curve is as shown in Figure 13, and the elastic modulus of rock mass is calculated as shown in Table 1.

Based on the displacement value of elastic deformation obtained by the slot relief method and the elastic modulus obtained by partial stress recovery, the normal stress of the slot is calculated as follows:

The rock mass surface's principal stress value is arrived at by considering slots 1-3: $\sigma_1 = 64.3$ MPa, $\sigma_2 = 23.2$ MPa, and $\sigma_1$'s dip angle $\alpha = 82°$. This value is lower than that the wall of a circular cavern based on the estimated buried depth but is close to the estimation for a buried depth of about 2,200 m. It shows that when the cavern under the condition of high stress is excavated, the stress of the rock mass undergoes constant adjustment to the inside and finally reaches a balance of stress.

Slot 5 records the highest normal stress value at 80 MPa. This slot is situated in a branch tunnel with irregular geometric shape and in the vicinity of a tunnel corner, while close to the slot cracks occur in the rock mass. The in situ stress is estimated to have a complicated distribution. As a result, results of the test only represent the local stress.

The slot relief method adopted in this paper can meet the requirement for measuring rock mass surface stress under high stress conditions. The measurement of displacement and deformation of rock mass replaces the strain

TABLE 1: Test results of rock mass parameters.

| Slot no. | Deformation/(0.001 mm) | Slot's length/cm | Slot's direction | Elastic modulus/GPa | $\sigma_n$/MPa |
|---|---|---|---|---|---|
| $1^{\#}$ | 228 | 0.71 | 125∘∠90∘ | 70.1 | 23.9 |
| $2^{\#}$ | 552 | 0.65 | Horizontal | 70.3 | 63.6 |
| $3^{\#}$ | 602 | 0.90 | 125∘∠45∘ | 68.7 | 49.1 |
| $4^{\#}$ | 331 | 0.81 | 125∘∠90∘ | 68.7 | 31.0 |
| $5^{\#}$ | 904 | 0.79 | 215∘∠90∘ | 72.4 | 82.4 |



(a) Slotting from surface to inside (slot 3)



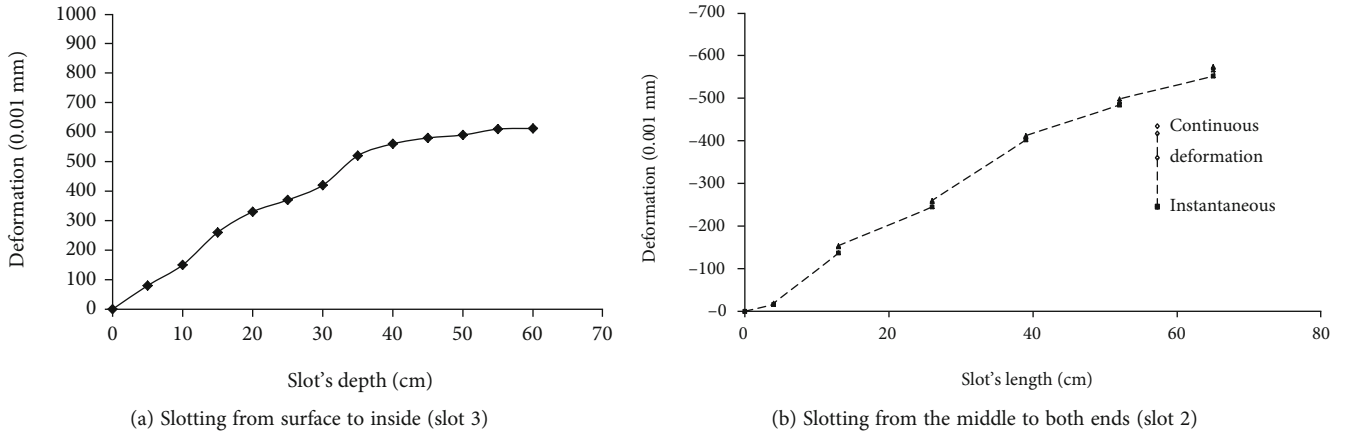(b) Slotting from the middle to both ends (slot 2)

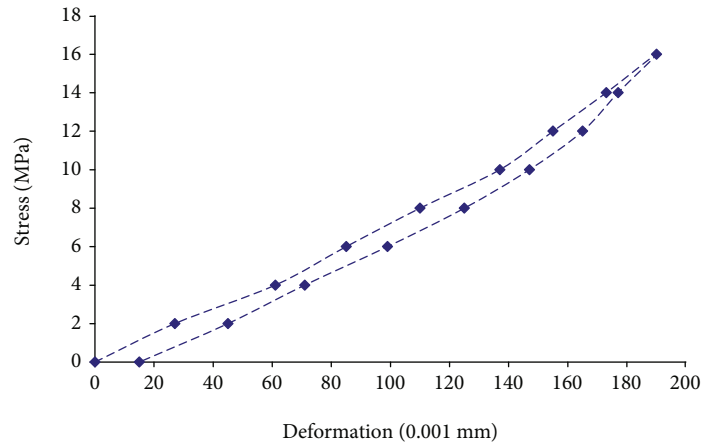FIGURE 12: Curve of typical stress relief process.



FIGURE 13: Curve of partial recovery.

measurement in traditional stress test, making it applicable in a wider range. The modulus of rock mass obtained by in situ stress recovery is more consistent with the constitutive relation and deformation mechanism of rock mass in the test area. This method uses equipment easy to carry and operate on and facilitates rapid stress test under extreme stress condition.

## 6. Conclusions

In view of limitations of several existing stress measurement methods under extreme high stress conditions (stress-to-strength ration > 0.5), this paper carries out simulation by the infinite element method and field research on the slot relief method based on partial stress recovery.

The finite element simulation demonstrates that under a high stress environment, the normal deformation of a 80 cm-long slot can reach the millimeter level, proving this method is feasible; the slot's depth should be more than 0.6 times its length to ensure complete release of normal stress; the elastic modulus of rock mass is inversely proportional to the normal displacement of the slot, and the distance between two slots should be no less than 3 times the length of a slot to avoid mutual influence.

The in-filed application of this method in the Jinping Hydropower Station shows that the slot relief method can meet the requirement for measuring rock mass surface stress under high stress conditions. The operation is simple and fast. The measured maximum stress is 80 MPa. The testing equipment meet the requirement of rapid stress test under extreme stress conditions.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

## References

[1] M. F. Cai, L. Qiao, B. Yu, and S. H. Wang, "Results and analysis of in-situ stress measurement at deep position of no. 2 mining area of Jinchuan mine," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 18, no. 4, pp. 414–418, 1998.

[2] H. G. Shi, "Rockburst analysis in Ertan hydropower plant's diversion tunnel," *Design of Hydroelectric Power Station.*, vol. 11, no. 1, pp. 35–40, 1995.

[3] S. J. Wang, "Century achievements and new hierarchical mission of rock mechanics and engineering in China," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 22, no. 6, pp. 867–871, 2003.

[4] J. J. Zhang and B. J. Fu, "Rockburst and its criteria and control," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 27, no. 10, pp. 2034–2042, 2008.

[5] H. Zhou, G. J. Wang, S. J. Fu, L. C. Zou, and S. H. Chen, "Finite element analysis of foundation unloading and relaxation effects of Xiaowan arch dam," *Rock and Soil Mechanics.*, vol. 30, no. 4, pp. 1175–1180, 2009.

[6] Y. F. Liu, *Geostress and Engineering Construction*, Hubei Scientific and Technological Press, Wuhan, 2000.

[7] M. F. Cai, L. Qiao, and H. B. Li, *Rock stress measurement principles and techniques*, Science Press, Beijing, 1995.

[8] E. R. Leeman and D. I. Hayes, "A technique for determining the complete state of stress in rock using a single borehole," in *Proceedings of the First International Congress on Rock Mechanics*, pp. 17–24, Lisboa, 1966.

[9] E. R. Leeman, "The determination of the complete state of stress in rock in a single borehole –Laboratory and underground measurements," *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts.*, vol. 5, no. 1, pp. 31–38, 1968.

[10] K. Sugawara and Y. Obara, "Draft ISRM suggested method for in situ stress measurement using the compact conical—ended borehole overcoming (CCBO)technique," *International Journal of Rock Mechanics and Mining Sciences.*, vol. 36, no. 3, pp. 307–322, 1999.

[11] X. R. Ge and M. X. Hou, "New approach to measure goestress-local borehole-wall complete stress relief method," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 23, no. 12, 2004.

[12] B. C. Haimson and F. H. Cornet, "ISRM suggested methods for rock stress estimation–part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF)," *International Journal of Rock Mechanics and Mining Sciences.*, vol. 40, no. 7-8, pp. 1011–1020, 2003.

[13] R. Cortheâsy, H. Guang, D. E. Gill, and M. H. Lei, "A stress calculation model for the 3D borehole slotter," *International Journal of Rock Mechanics and Mining Sciences.*, vol. 36, no. 4, pp. 493–508, 1999.

[14] X. P. Zhou and J. H. Wang, "The new method to measure geostress of rock mass," *Rock and Soil Mechanics.*, vol. 23, no. 3, pp. 316–320, 2002.

[15] Y. Wang, Y. Su, Y. Xia, H. Wang, and X. Yi, "On the effect of confining pressure on fatigue failure of block-in-matrix soils exposed to multistage cyclic triaxial loads," *Fatigue & Fracture of Engineering Materials & Structures.*, vol. 45, no. 9, pp. 2481–2498, 2022.

[16] B. Hu, G. Zhang, and G. Y. Li, "Determining 3D in-situ stress with a new borehole deformer by single overcore," *Rock and Soil Mechanics.*, vol. 27, no. 5, pp. 816–822, 2006.

[17] Y. F. Liu, J. B. Zhu, and Y. K. Liu, "Research on hollow inclusion triaxial strain gauge for geostress measurement," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 20, no. 4, pp. 448–453, 2001.

[18] Y. Wang, Z. Y. Song, T. Q. Mao, and C. Zhu, "Macro-meso fracture and instability behaviors of hollow-cylinder granite containing fissures subjected to freeze–thaw–fatigue Loads," *Rock Mechanics and Rock Engineering*, vol. 55, no. 7, pp. 4051–4071, 2022.

[19] Q. Niu, L. Cao, S. Sang et al., "Experimental study on the softening effect and mechanism of anthracite with $CO_2$ injection," *International Journal of Rock Mechanics and Mining Sciences*, vol. 138, no. 9, article 104614, 2021.

[20] Y. Wang, J. Q. Han, Y. J. Xia, and D. Y. Long, "New insights into the fracture evolution and instability warning predication for fissure-contained hollow-cylinder granite with different hole diameter under multi-stage cyclic loads," *Theoretical and Applied Fracture Mechanics*, vol. 119, article 103363, 2022.

[21] M. F. Cai, "Studies of temperature compensation techniques in rock stress measurements," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 10, no. 3, pp. 227–235, 1991.

[22] X. R. Ge and M. X. Hou, "A new 3d in-situ rock stress measuring method: borehole wall stress relief method(bwsrm) and development of geostress measuring instrument based on bwsrm and its primary applications to engineering," *Chinese Journal of Rock Mechanics and Engineering.*, vol. 30, no. 11, pp. 2161–2180, 2011.

[23] P. Ma, G. P. Zhao, and Y. Y. Zhang, "The preparation and application of ultrahigh pressure hydrofracturing geostress measurement system in rockmass," *Journal of Yangtze River Scientific Research Institute.*, vol. 29, no. 8, pp. 58–61, 2012.

[24] D. S. Sun, H. Song, and W. Lin, "Stress state measured at ~7 km depth in the Tarim Basin, NW China," *Scientific Reports*, vol. 7, no. 1, pp. 1–10, 2017.

[25] Y. H. Lu, Q. S. Liu, and H. Jiang, "Study of mechanical deformation characteristics of granite in unloading experiments of high stress," *Rock and Soil Mechanics.*, vol. 31, no. 2, pp. 337–344, 2010.

[26] Y. Wang, T. Mao, Y. Xia, X. Li, and X. Yi, "Macro-meso fatigue failure of bimrocks with various block content subjected to multistage fatigue triaxial loads," *International Journal of Fatigue*, vol. 163, p. 107014, 2022.