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Principle of *in-situ* 3D rock stress measurement with borehole wall stress relief method and its preliminary applications to determination of *in-situ* rock stress orientation and magnitude in Jinping hydropower station

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As a main constituent of geological body, the rock masses have distinct differences from other materials, one of which is that rock masses are initially stressed in their natural states. Hence, it is an extremely challenging and significant research project to know the present residual stress of the rock masses in the earth's crust. Although some regularities of distribution of *in-situ* rock stresses can be deduced, the basic means to study the state of rock stress is *in-situ* stress measurement. After a brief review of several measuring methods of *in-situ* 3D rock stress, a new one, borehole wall stress relief method (BWSRM) to determine the *in-situ* 3D rock stress tensor in a single drilled borehole was proposed. Based on the principle of *in-situ* rock stress measurement with BWSRM, an original geostress measuring instrument was designed and manufactured. Preliminary experiments for determination of *in-situ* stress orientation and magnitude were carried out at an experimental tunnel in Jinping II hydropower station in China, where the buried depth of overburden was about 2430 m. The results showed that it was feasible to measure the *in-situ* 3D rock stresses with BWSRM presented in this paper. The BWSRM has a broad prospect for *in-situ* 3D rock stress measurements in practical rock engineering.

rock mechanics and engineering, *in-situ* rock stress measurement, stress relief method, Jinping hydropower engineering

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1 Significance of *in-situ* rock stress measurement

In rock mechanics and engineering, it is important to conduct a research on *in-situ* rock stress measurement. As a main constituent of geological body, one difference between rock masses and other materials is that rock masses are initially stressed in their natural states. The *in-situ* rock stress is essentially an internal stress or an initial stress, which can also be regarded as a kind of residual stress from the viewpoint of geological history evolution.

Because of self-weight of rock masses and multiple geologically tectonic movements, there are internal stresses in the interior of the rock mass naturally. After long-term weathering, erosion, river cutting, uplifting and depression of the local earth's crust, tremendous changes of topography over time, etc., the residual stress state in some local region is complicated. It is an extremely challenging project to know the present residual stress state of the earth's crust.

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Although some regularities of distribution of *in-situ* rock stresses can be deduced, the basic means to study the stress state in the earth's crust is *in-situ* rock stress measurements by using different stress measuring methods and techniques.

From an engineering perspective, evaluating the characteristics of initial geostress field is one essential and critical task in the engineering construction areas because the *in-situ* rock stress is one source of basic loading in the process of construction and runtime of underground structures, such as tunnels, power plants, underground mining, and other underground buildings with various purposes. On the other hand, in dam foundation and slope engineering, open mining, oil and gas development, even petroleum production in deep well and secondary or tertiary oil recovery, it is also necessary to know the data of field geostress in the project areas. The theories, methods and technologies of *in-situ* rock stress measurement are leading research topics in rock mechanics and engineering.

For earth science, the significant role of the *in-situ* rock stress measurement is self-evident. It is of great significance to measure the *in-situ* rock stress in earth science. Although the theory of plate tectonic movement has been universally accepted in geosciences and engineering, the *in-situ* rock stress measurement is indispensable for studying some fundamental questions of geosciences such as exploring that how much driving force will cause the plate movement, understanding the relationship between the strained condition at the edge and center of various sizes of plates and tectonic movement, and so on. As a result, the geostress measurement is included in many international scientific deep drilling programs. For example, in the internationally renowned German Continental Scientific Drilling Program (KTB) [1, 2], a variety of geostress measurement methods were used to assess the *in-situ* rock stresses of the KTB main hole in a depth of 9100 m deep borehole.

2 Brief review of *in-situ* rock stress measurement methods

2.1 Overview of *in-situ* rock stress measuring methods

In general, the rock stress measuring methods can be classified into the following: hydraulic fracturing method [3, 5–9], stress relief method [4–11], flat jacking method [5–7], strain recovery method [5, 6], borehole breakout method [5, 6], differential strain curve analysis method [5, 6, 12], drilling induced tensile fracture method [13], acoustic emission method [14], and geophysical method [6]. Among them, the hydraulic fracturing method and the stress relief method with overcoring are usually employed for *in-situ* 3D rock stress measurement in rock engineering.

2.2 Introduction to hydraulic fracturing method

The fundamental principle of the hydraulic fracturing method is to separate a small segment from a whole borehole by using an upper packer and a lower one, respectively, and inject high-pressure liquid into the sealed-off borehole interval to induce and propagate tensile fractures in the borehole wall. The *in-situ* 3D rock stresses can be derived according to the characteristic curve of the hydraulic fracturing operation which is utilized to record the liquid pressures of initial fracture formation when or if fractures reopen.

The hydraulic fracturing method has the following advantages: 1) it does not need the overcoring; 2) it does not need delicate descent instruments; 3) it does not need physical or mechanical parameters of rock mass; 4) it can be used in different depths of a borehole; 5) the hydraulic fracturing operations are simple and easy to implement in shallow crust earth.

However, the hydraulic fracturing method requires that one of the principal directions of the *in-situ* rock stress tensor be aligned with the borehole's axis, which affects the reliability of measuring results under some engineering geological conditions. Therefore, one principal direction of the stress tensor is the borehole's axis in a vertical drilled borehole, namely the vertical direction, and its magnitude of this principal stress tensor component tensor is estimated by density of overlying rock masses and vertical depth of the stresses measurement site.

As a result, it is uncertain for the hydraulic fracturing method to determine the *in-situ* 3D rock stress tensor in rock masses with some geological structures such as the faults, the fractures, folds, or tilt. Even if the obtained results are modified by multi-borehole intersection or other methods, it is difficult to get the reliable *in-situ* 3D rock stress tensor. For horizontally bedded or stratified rock masses, the principal magnitude of *in-situ* rock stress tensor aligned with the borehole's axis is not always coincident with the above-mentioned stress calculation. In addition, its principal direction usually deviates from the vertical direction.

2.3 Overview of borehole stress relief method

The borehole stress relief method is referred to as overcoring, which is by far the most commonly used stress measuring method in rock engineering. The basic procedure of borehole stress relief method is as follows: First, a 130–150 mm diameter main borehole is drilled. Secondly, a homocentric 36–38 mm diameter pilot hole is drilled at the bottom of the main borehole. Thirdly, a probe for stress measurement is installed into the pilot hole. Then the main borehole is continued to relieve the rock stresses surrounding the probe which is used to sense and record the deformations of the borehole in course of stress relief operation. Finally, the *in-situ* rock stresses are calculated according to the obtained data. The general measuring steps of the conventional overcoring are shown in Figure 1. Many probes are developed and used for *in-situ* rock stress measurements with

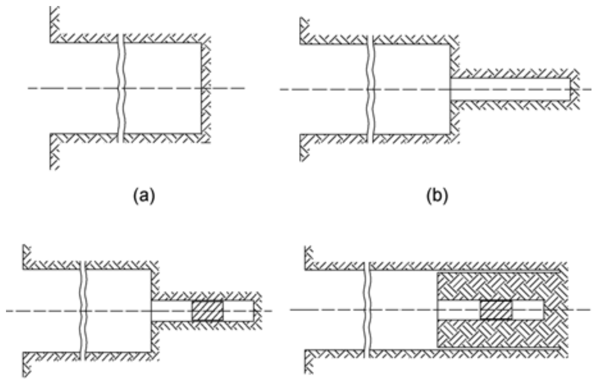

Figure 1 Measuring steps of stress relief method for overcoring. (a) Drilling a main borehole with 130–150 mm in diameter; (b) drilling a pilot hole with 36–38 mm in diameter; (c) installing a probe for stress measurement; (d) overcoring the probe.

overcoring. One of them is to measure the changes in diameter of the pilot hole. Another is the famous one, called triaxial cell with hollow inclusion, in which several strain rosettes are pasted onto the wall of the smaller borehole by special technical approaches, while the hollow inclusion itself has little influence on the deformations of the pilot hole. The most well-known probe is the Australian CSIRO triaxial cell with hollow inclusion [5, 8].

Although the stress relief method can be used to determine the magnitude and direction of two or three principal stresses, core breaking frequently occurs in deep measuring points. Consequently, it is only used in relatively shallow boreholes. Moreover, it is ineffective in areas with extremely high geostress because of the rock core disking.

From the discussions above on the *in-situ* rock stress measuring methods, it is shown that some of these methods, especially the 3D geostress measuring methods do not meet practical requirements in determination of either magnitude or direction of *in-situ* rock stress tensor. As a result, in rock mechanics and engineering, it is extremely necessary to develop a new approach to determining the 3D geostress tensor, which is self-contained in theory, feasible in actual operation and competent in deep borehole.

3 Postulations for borehole wall stress relief method (BWSRM)

Generally, the rock masses at the different parts of the earth's crust contain the geostress field information related to them. In addition, stresses and strains at any part of the rock mass are constrained by far-field stresses. As long as the relationship between the stress state of the measuring point and the corresponding far-field stresses is properly established, it is absolutely possible to determine the magnitudes and directions of three far-field principal stresses of the place where these measuring points are located according to the stress state information obtained from a certain number of measuring points in a local area. Even on the local surfaces of a deep drilled borehole wall, the regional stress field information is also included by them.

Considering the rocks surrounding the borehole as a homogeneous, continuous, isotropic and infinite linear elastic mass, a small section of a drilled borehole is selected as the measuring area, which is away from the influenced zones of the top and bottom of the borehole. The rock mass surrounding the borehole is subject to six far-field stress components. Based on the linear elastic rock mechanics theory, a relationship between normal strains at a point on the borehole wall surface and the components of the far-field *in-situ* 3D rock stress tensor can be derived, and the corresponding mathematical equation can be established. This basic relationship provides a solid foundation for determining the far-field stress state of the selected small section of the borehole through strain measurements. It is known that the *in-situ* 3D rock stress measuring method represents a point-wise estimate of a local stress tensor given by six independent components. According to the basic equation between a normal strain at a point on the borehole wall surface and the six components of the far-field *in-situ* 3D rock stresses tensor, no less than six independent equations can give the six stress components. Hence, at least six independent strain measurements at different measuring locations can be taken within this selected section. As a result, these strain measurements can be combined to make analysis and determine the far-field stress state corresponding to the selected small section of the borehole.

The simplest approach to obtaining more than six independent normal strains is to isolate several cylindrical rock core samples with a certain length from the borehole wall along the radial direction through annular cutting techniques by rock core drilling. Then the stored stresses can be completely relieved if the rock core sample is deep enough, while the strain responses are monitored by bonding an orthogonal triple-strain gage rosette (in three directions, each 45° apart) on each of them. Thus, three strain measurements can be obtained when a cylindrical core sample is completely relieved. As mentioned above, the rock properties surrounding the selected section of the borehole are consistent. In other words, it is subject to the same far-field stress. Thus the measured strains from these local surfaces are synthesized and analyzed to obtain the corresponding stress state of the far-field. This proposed method is referred to as the borehole wall stress relief method (BWSRM) to distinguish it from other borehole relief methods [15, 16].

4 Basic theoretical formula for *in-situ* 3D rock stress tensor with BWSRM

4.1 Coordinate systems of a drilled borehole

First, we define a Cartesian coordinate system, *oxyz*, and attach it to the drilled borehole with the *z*-axis aligned with the borehole axis, the x-axis horizontal and perpendicular to z and the y-axis perpendicular to x and z (Figure 2). Under the coordinate system $oxyz$, we let S_{xx}, S_{yy}, S_{zz}, S_{xy}, S_{yx}, S_{zx} be the components of the far-field *in-situ* rock stress tensor which are defined here as the average stress state in a few cubic meters of rock surrounding the drilled borehole at a distance far enough for the borehole not to influence this stress state greatly. We define a borehole cylindrical coordinate system, $or\theta z$, which is corresponding to the Cartesian coordinate system, $oxyz$ (Figure 2), and define σ_r, σ_θ, σ_z, $\tau_{r\theta}$, $\tau_{\theta z}$, τ_{zr} as the radial, tangential, longitudinal and shear stress components respectively. The Young's modulus of the rock material is denoted by E and Poisson's ratio by ν.

4.2 Relationship between strain tensor components at a point on borehole wall and the far-field stress components

In an isotropic, homogeneous, and linear elastic rock material, the stress components on the wall surface of the drilled borehole can be expressed as follows [17]

$$\sigma_r = \tau_{r\theta} = \tau_{zr} = 0, \tag{1}$$

$$\sigma_\theta = \left(S_{xx} + S_{yy}\right) - 2\left(S_{xx} - S_{yy}\right)\cos 2\theta - 4S_{xy}\sin 2\theta, \tag{2}$$

$$\sigma_z = -2\nu\left(S_{xx} - S_{yy}\right)\cos 2\theta - 4\nu S_{xy}\sin 2\theta + S_{zz}, \tag{3}$$

$$\tau_{\theta z} = 2\left(S_{yz}\cos\theta - S_{zx}\sin\theta\right). \tag{4}$$

Let ε_θ, ε_z, $\gamma_{\theta z}$ be the tangential, longitudinal and shear strain components of a point on the drilled borehole wall surface. According to Hooke's law the expressions of them are

$$\varepsilon_\theta = \frac{1}{E}\Big[\left(S_{xx} + S_{yy}\right) - 2\left(1-\nu^2\right)\left(S_{xx} - S_{yy}\right)\cos 2\theta - 4\left(1-\nu^2\right)S_{xy}\sin 2\theta - \nu S_{zz}\Big], \tag{5}$$

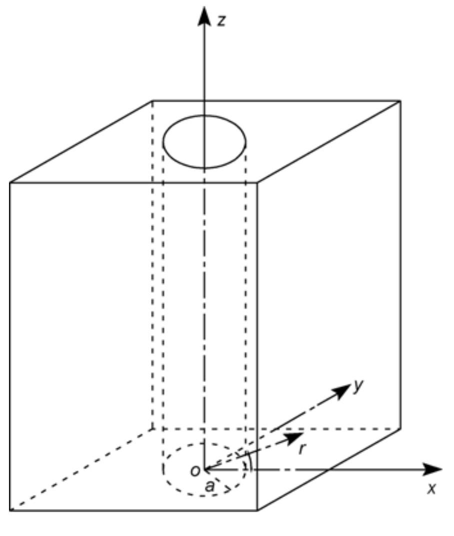

Figure 2 Coordinate system of a drilled borehole.

$$\varepsilon_z = \frac{1}{E}\Big[S_{zz} - \nu\left(S_{xx} + S_{yy}\right)\Big], \tag{6}$$

$$\gamma_{\theta z} = \frac{4(1+\nu)}{E}\left(S_{yz}\cos\theta - S_{zx}\sin\theta\right). \tag{7}$$

4.3 Relationship between normal strain at a point on the borehole wall surface and the far-field stress components

Define ε_φ as the normal strain at a point making an angle φ from the tangential direction (Figure 3). Then the normal strain ε_φ is related to the local strain components ε_φ, ε_z and $\gamma_{\theta z}$ as

$$\varepsilon_\varphi = \varepsilon_\theta\cos^2\varphi + \varepsilon_z\sin^2\varphi + \gamma_{\theta z}\cos\varphi\sin\varphi. \tag{8}$$

By substituting eqs. (5), (6) and (7) into eq. (8), the normal strain ε_φ is related to the far-field *in-situ* stress tensor components as follows

$$E\varepsilon_\varphi = A_1S_{xx} + A_2S_{yy} + A_3S_{zz} + A_4S_{xy} + A_5S_{yz} + A_6S_{zx}, \tag{9}$$

where

$$A_1 = \left[1 - 2\left(1-\nu^2\right)\cos 2\theta\right]\cos^2\varphi - \nu\sin^2\varphi, \tag{10a}$$

$$A_2 = \left[1 + 2\left(1-\nu^2\right)\cos 2\theta\right]\cos^2\varphi - \nu\sin^2\varphi, \tag{10b}$$

$$A_3 = -\nu\cos^2\varphi + \sin^2\varphi, \tag{10c}$$

$$A_4 = -4\left(1-\nu^2\right)\sin 2\theta\cos^2\varphi, \tag{10d}$$

$$A_5 = 2(1+\nu)\cos\theta\sin 2\varphi, \tag{10e}$$

$$A_6 = -2(1+\nu)\sin\theta\sin 2\varphi. \tag{10f}$$

Eq. (9) gives the basic relationship between the strain value of a point on the drilled borehole wall surface and the far-field *in-situ* stress tensor surrounding the borehole.

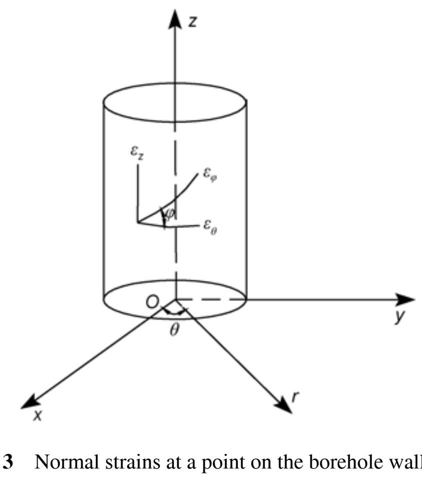

Figure 3 Normal strains at a point on the borehole wall surface.

4.4 Estimate of *in-situ* 3D rock stress tensor by the least square method under borehole Cartesian coordinate system

For the *in-situ* rock stress measurement with BWSRM, a small section of the drilled borehole is first selected as the measuring area. If choosing three lines parallel to borehole axis on the borehole wall (their circumference angles denoted by θ_1, θ_2 and θ_3, respectively), the differential angles for these three lines are advisable for 110–130 degrees. Choose one measuring point at each line, and paste an orthogonal triple-strain gage rosette on the measuring point, namely, $\varphi = 0°, 45°, 90°$ at each point. A certain interval in the axis direction between these measuring points on the three lines is required to avoid interfering with each other during the stress relief operation. Here, the stress relief is conducted by drilling annular slots into the surrounding rock mass along the radial direction. After stress relief, no less than six independent normal strain values can be obtained. Because there are six unknown variables to be solved, it is usually to estimate the *in-situ* 3D rock stress tensor components by the least square method. Thus, the stress tensor is given under the borehole Cartesian coordinate system.

If m measurement locations are selected around the drilled borehole wall, and an orthogonal triple-strain gage rosette (in three directions 45° apart) is glued onto the borehole wall at each of the m measurement locations, n normal strain measurements ($n=m\times t$) can be obtained. For a given strain rosette, strain gage t ($t=1, 2, 3$) corresponds to the angle φ ($\varphi=0°, 45°, 90°$). Denote the normal strain in gage i as ε_i, and let

$$[\boldsymbol{g}] = E\cdot\begin{bmatrix}\varepsilon_1 & \varepsilon_2 & \cdots & \varepsilon_n\end{bmatrix}^{\mathrm{T}}, \tag{11}$$

and $S_1=S_{xx}$, $S_2=S_{yy}$, $S_3=S_{zz}$, $S_4=S_{xy}$, $S_5=S_{yz}$, $S_6=S_{zx}$. According to eq. (9), the strain ε_i in strain gage i is linearly related to the *in-situ* rock stress components in the $oxyz$ borehole coordinate system as

$$E\varepsilon_i = A_{i1}S_1 + A_{i2}S_2 + A_{i3}S_3 + A_{i4}S_4 + A_{i5}S_5 + A_{i6}S_6. \tag{12}$$

With substitution of θ and φ corresponding to the normal strain ε_i into eqs. (10a–f), the coefficients $A_{i1},\cdots, A_{i6}$ in eq. (12) are obtained. Eq. (12) can be written in matrix form as below

$$[\boldsymbol{A}][\boldsymbol{S}] = [\boldsymbol{g}], \tag{13}$$

where

$$[\boldsymbol{S}] = \begin{bmatrix}S_1 & S_2 & S_3 & S_4 & S_5 & S_6\end{bmatrix}^{\mathrm{T}},$$

$$[\boldsymbol{g}] = E\cdot\begin{bmatrix}\varepsilon_1 & \varepsilon_2 & \cdots & \varepsilon_n\end{bmatrix}^{\mathrm{T}},$$

$[\boldsymbol{A}]$ is a coefficient matrix of ($n\times6$). All the elements in matrix $[\boldsymbol{A}]$ can be determined by substituting θ and φ corresponding to the normal strain ε_i into eqs. (10a–f). The superscript T stands for transposition of a matrix. If $n>6$, the best fit *in-situ* 3D rock stress tensor component matrix $[\boldsymbol{S}]$ can be obtained by the least squares method from the following equations

$$[\boldsymbol{A}]^{\mathrm{T}}[\boldsymbol{A}][\boldsymbol{S}] = [\boldsymbol{A}]^{\mathrm{T}}[\boldsymbol{g}], \tag{14}$$

or,

$$\sum_{j=1}^{6} K_{kj}S_j = G_k, \quad (k=1,\ 6), \tag{15}$$

where

$$K_{kj} = \sum_{i=1}^{n} A_{ki}A_{ij}, \tag{16}$$

$$G_k = \sum_{i=1}^{n} A_{ik}g_i. \tag{17}$$

By solving the contradictory eqs. (14) or (15), the matrix of far-field 3D rock stress tensor under the borehole coordinate system can be obtained in the following forms

$$[\boldsymbol{\sigma}]_{xyz} = \begin{bmatrix} S_{xx} & S_{xy} & S_{zx} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{zx} & S_{yz} & S_{zz}\end{bmatrix}. \tag{18}$$

4.5 *In-situ* 3D rock stress tensor matrix under the global coordinate system

If the matrix of *in-situ* 3D rock stress tensor represented as eq. (18) under the borehole Cartesian coordinate system needs to be expressed under the global coordinate system, the coordinate transformation rules are required. At present consider the geometry of a drilled borehole in a global coordinate system $OXYZ$ inclined with respect to the borehole Cartesian coordinate system $oxyz$ (Figure 4), where the

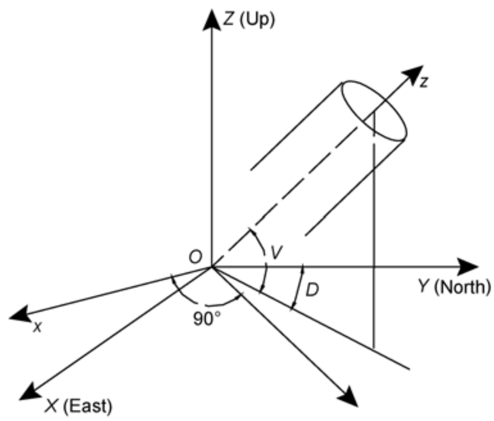

Figure 4 Orientation of a drilled borehole in the global X, Y, Z coordinate system.

orientation of the borehole and the *x*-, *y*-, and *z*-axes are defined with respect to the *X*, *Y*, *Z* coordinate system by two angles *D* (borehole azimuth) and *V* (borehole rise) such that x-axis lies in the *X*, *Y* plane.

In the global coordinate system, the *in-situ* 3D stress field has components σ_{XX}, σ_{YY}, σ_{ZZ}, τ_{XY}, τ_{YZ} and τ_{ZX}. Let $[\boldsymbol{\sigma}]_{XYZ}$ be the stress tensor matrix in the global coordinate system such that

$$[\boldsymbol{\sigma}]_{XYZ} = \begin{bmatrix} \sigma_{XX} & \sigma_{XY} & \sigma_{ZX} \\ \sigma_{XY} & \sigma_{YY} & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{YZ} & \sigma_{ZZ} \end{bmatrix}. \tag{19}$$

By coordinate transformation, the *in-situ* rock stress tensor matrix under the global coordinate system can be obtained as below

$$[\boldsymbol{\sigma}]_{XYZ} = [\boldsymbol{L}]^{\mathrm{T}}[\sigma]_{xyz}[\boldsymbol{L}], \tag{20}$$

where

$$[\boldsymbol{L}] = \begin{bmatrix} l_x & m_x & n_x \\ l_y & m_y & n_y \\ l_z & m_z & n_z \end{bmatrix}, \tag{21}$$

$[\boldsymbol{L}]$ is a (3×3) transformation matrix. The components of this matrix depend on the direction cosines of the *x*-, *y*-, and *z*-axes with respect to the global coordinate system *OXYZ*, and can be written as follows

$$\begin{aligned} & l_x = \cos D, \ \ m_x = -\sin D, \ \ n_x = 0, \\ & l_y = \sin V \sin D, \ \ m_y = \sin V \cos D, \ \ n_y = -\cos V, \\ & l_z = \cos V \sin D, \ \ m_z = \cos V \cos D, \ \ n_z = \sin V. \end{aligned} \tag{22}$$

The application of an invention patent for the principle of *in-situ* 3D rock stress measurement with BWSRM has been accepted and authorized by the State Intellectual Property Office of the People's Republic of China (Patent No. ZL01126815.8).

5 Implementation of *in-situ* 3D rock stress measurement with BWSRM

The rock stress measurement with BWSRM was carried out in a drilled borehole with 150 mm in diameter. The measuring areas selected from a drilled borehole are not to be affected by structures or buildings near the borehole. Besides, it is necessary to keep lithology intact and identical in properties in the measuring areas.

Three lines parallel to borehole axis were chosen on the borehole wall of the selected measuring segment, the angles between them along the circumference were recommended as 110°–130°. On each line, a local surface with 30 mm in diameter was considered as a measuring point, and an orthogonal triple-strain gage rosette was glued onto it. Three local measuring points and the arrangement for each strain rosette were shown in Figure 5. The intervals between these three local surfaces were not to affect each other when the stress relief operation was conducted.

The stress relief operation was carried out by using the core bit with 34 mm in outer diameter and only 2 mm in thickness. Therefore, the relieved cylindrical core's diameter was about 30 mm, and the annular slot's width was 2 mm. The stress relief operation was shown in Figure 6. The drilling depth *h* was related to the diameter of the relieved rock core sample *d*[16, 18]. It was shown that all the stored stresses were completely released when *h*/*d*=1.2, which is in agreement with numerical simulation results (in Figure 7, where the position of strain rosette pasted is at θ=0°, $S_{xx}:S_{yy}=1:2$).

In the course of stress relief with BWSRM, the real-time curves between changes of micro-strain values on the relieved surfaces and the drilling depth were monitored. Then, according to the obtained parameters, such as the change of

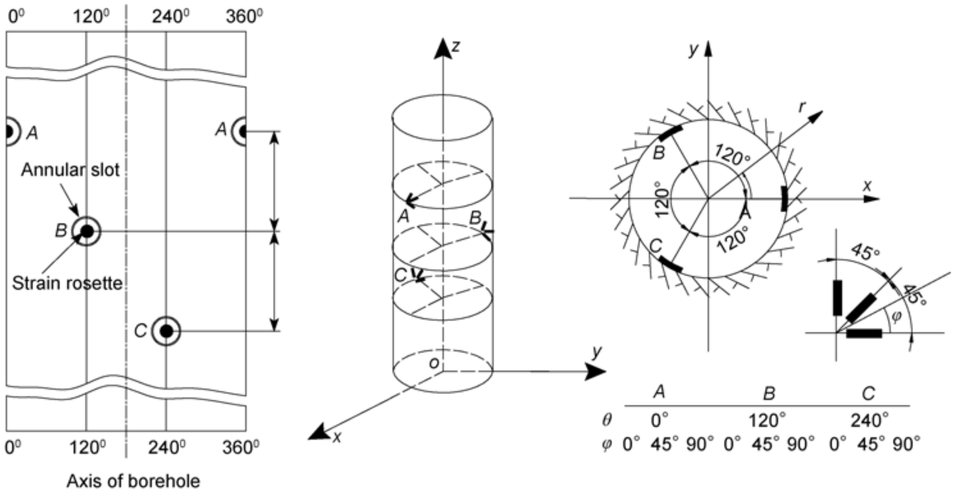

Figure 5 Schematics for the measuring points around a drilled borehole and arrangement of strain rosettes.

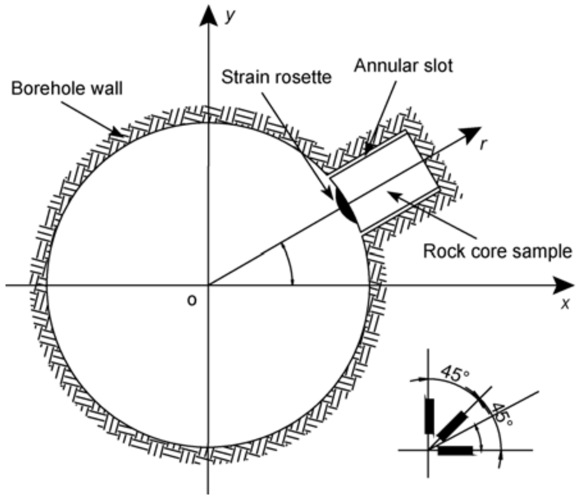

Figure 6 Schematic of local borehole wall stress relief by core drilling.

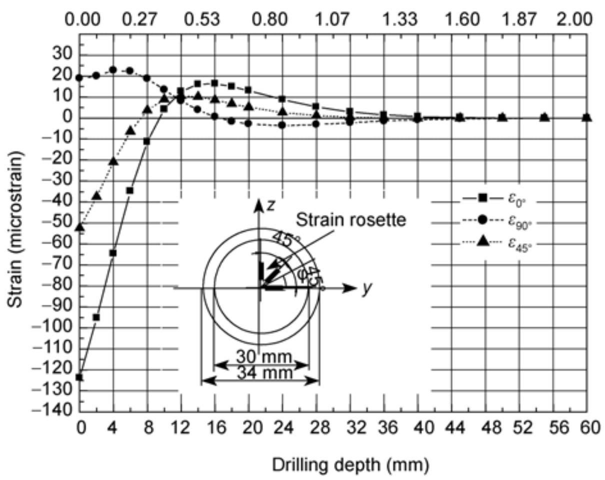

Figure 7 Response curves of the strains vs. depth of an annular slot advance.

strain values, borehole azimuth and rise, the *in-situ* 3D rock stress tensor under the global coordinate system could be determined based on the theoretical formula with BWSRM mentioned in the previous sections. However, it was not easy to utilize the *in-situ* rock stress measurement with BWSRM in a drilled borehole. An original *in-situ* stress measuring instrument with intelligent characteristics was indispensable.

6 Development of the measurement instrument of *in-situ* 3D rock stress with BWSRM

As mentioned in the previous sections, the design and manufacture of a new geostress measuring instrument is a key to the implementation of the *in-situ* 3D rock stress measurement with BWSRM. The developed 3D geostress measuring instrument based on the principle of BWSRM mainly consists of the following parts: end connection unit, anchoring and positioning unit, stress relief and strain gauging unit, integrated circuit module, monitoring and automatic control unit, etc. The designed measuring instrument has functions as follows: scanning and observing the drilled borehole wall, self-anchoring and fastening on the borehole wall, polishing and air-drying the local surfaces of the borehole wall to be relieved, spraying adhesive and gluing the strain gauge rosette onto the polished surfaces; relieving the stresses by drilling annular slot around strain rosette, real-time monitoring and recording the micro-strain value on the surface of the rock core to be relieved, cutting off wires attached to the strain rosette, retrieving the drilling tools automatically, etc. The whole process of the *in-situ* rock stress measuring operation can be completely achieved by the computer.

The drilling tool used for cutting annular slot is driven by a specially manufactured motor with a power of 400 W. It is about 3–4 min for this drilling tool to cut an annular slot with 40 mm in depth into rocks such as granite and marble. There are seven motors with different powers and sizes installed in the measuring instrument of *in-situ* 3D rock stress with BWSRM. Among these motors, the minimum power is only 2 W. The most critical keys include polishing the local surface of the borehole wall and automatically sticking art of the strain rosette onto it. One characteristic for this instrument is the automatically sticking art of the strain rosette onto the borehole wall. The built-in resistance strain recovery unit has high precision, reliability and stability.

The type of the *in-situ* 3D rock stress measuring instrument with BWSRM used in Jinping II hydropower station in China, is named as BWSRM-H01. The appearance of BWSRM-H01 is cylindrical, and its outer diameter is 148 mm. It spans about 720 mm and weighs about 21 kg (see Figure 8). It took about seven years to design, manufacture, shake down test, and modify the instrument before it fell into a pattern. Each main component of the BWSRM-H01 was strictly verified in laboratory. Moreover, the prototype BWSRM-H01 had been tested on a special platform in laboratory for nearly one year after it was assembled. After that, the test at the construction site of Jinping II hydropower station in China was a great success when it was used for the first time to measure the *in-situ* 3D rock stresses in a branch tunnel with buried depth of 2430 meters.

7 Preliminary application to *in-situ* 3D rock stress measurement with BWSRM at Jinping II hydropower station in China

From August to September in 2010, the *in-situ* 3D rock stress measurement with BWSRM was carried out at the construction site of Jinping II hydropower station, which was located on the Great Jinping River Bend of the Yalong River, Sichuan Province, China. According to the geological

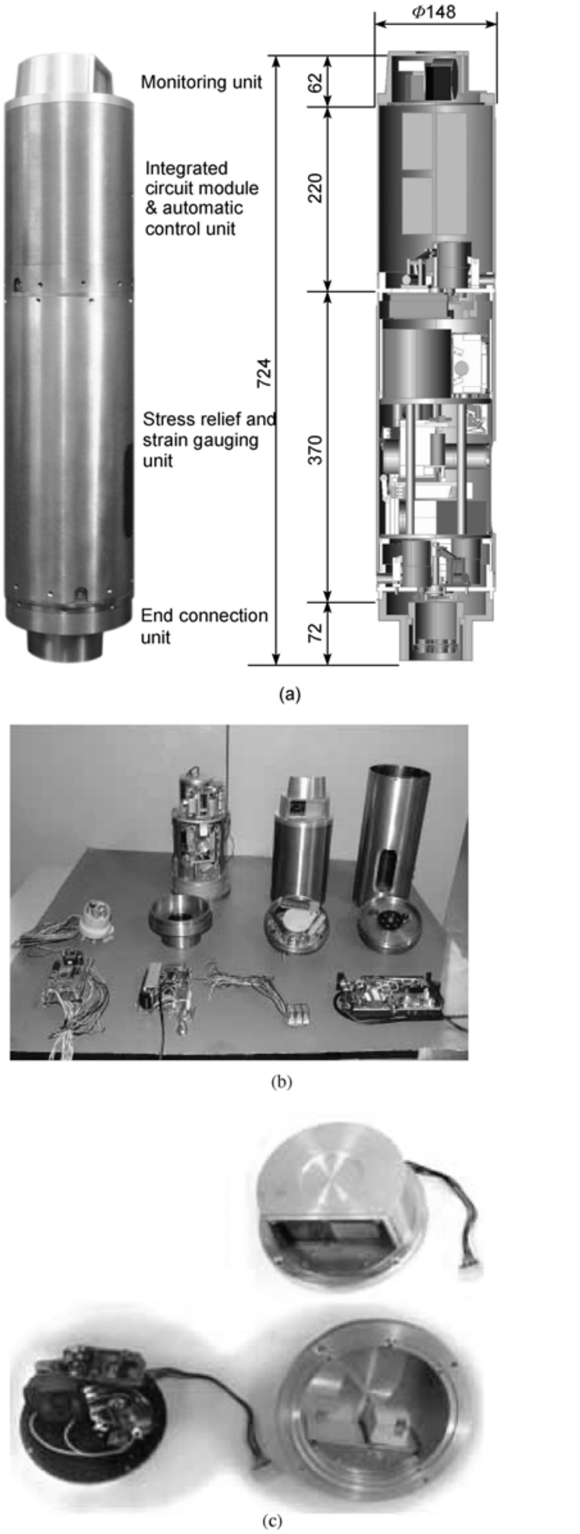

Figure 8 Photographs of BWSRM-H01. (a) Configuration and structure of BWSRM-H01; (b) photograph of the main units for BWSRM-H01; (c) photograph of scanning units.

conditions and configuration of the experimental tunnels of Jinping II hydropower station, the testing boreholes for the *in-situ* rock stress measurement with BWSRM were arranged on the side wall of the experimental tunnels with a deep overburden. The axis of the testing borehole had a 3° rise relative to horizontal plane.

The Jinping II hydropower station consists of a sluice dam located upstream the Great Jinping River Bend, with the tailrace water from Jinping I hydropower station which is diverted through the Jinping Mountain via four 16.7 km long, 13 m diameter tunnels [19]. A powerhouse is constructed within the mountains on the downstream side of the 150 km long Great Jinping River Bend where a 310 m head of water is used for power generation. The Jinping II hydropower station with a total capacity of 4800 MW has eight hydro-generator units of 600 MW. There are also two other tunnels used for transportation named auxiliary tunnels A and B. These tunnels cross through the Jinping Mountain with a maximum overburden of up to 2525 m. Because of the complex topography and geological setting, there exist some complicated engineering geological problems such as high geostress, rockburst, wall spalling, serious underground water distributions, and so on. It is of paramount importance for designer and contractor of the Jinping project to obtain the reasonable data of the *in-situ* rock stress measurement, especially the geostress data at the vertical burial depth of 2400 m under the Jinping Mountain in the area of underground powerhouse. In this area, the *in-situ* rock stress measurement was done previously by the hydraulic fracturing method and other available conventional methods. However, no reliable data were achieved. Therefore, there were no geostress data to be compared with the result obtained by the *in-situ* 3D rock stress measurement with BWSRM when the field test was finished. The construction site of Jinping II hydropower station was shown in Figure 9. The spatial distribution of underground tunnels and caverns was shown in Figure 10.

There were four experimental tunnels in Jinping II hydropower station. All of them were located in auxiliary tunnel A. The field test was carried out at experimental branch tunnel C with a section of 3.0 m×2.2 m (width×height), which was located in experimental branch tunnel No.2 with a section of 3.0 m×2.2 m (width×height). The vertical buried depth of test site was about 2430 m, which was BaiShan group marble (T_{2b}). The drilled testing boreholes for *in-situ* rock stress measurement with BWSRM were located in the experimental branch tunnel C. The boreholes were 150 mm in diameter, and 20 m in length. Testing borehole No.1 was drilled parallel to the axis of experimental branch tunnel C on its bottom, while testing boreholes No.2 and No.3 were drilled perpendicular to the axis of experimental branch tunnel C on its side wall. All the testing boreholes have a 3° rise relative to the horizontal plane. The locations of the testing boreholes were shown in Figure 11.

The geostress test was accomplished by using the developed instrument of *in-situ* 3D rock stress measurement with BWSRM described in the previous sections in accordance with the predetermined program. The test was first finished

Figure 9 Photograph of the construction site of Jinping II hydropower station in China.

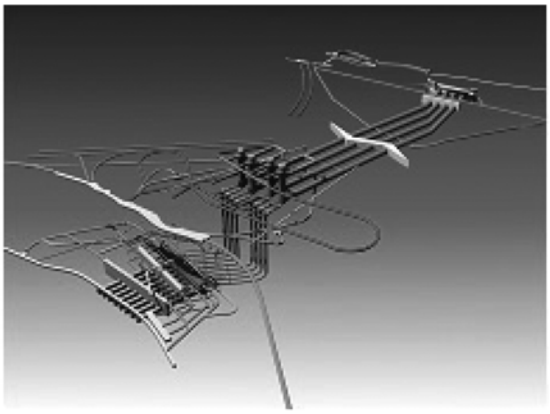

Figure 10 Schematic of spatial distribution of underground tunnels and caverns in Jinping II hydropower station in China.

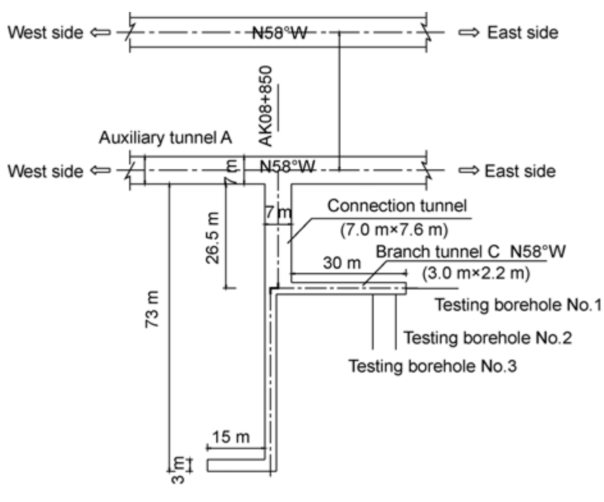

Figure 11 Schematic of testing borehole site.

in testing borehole No.1. The selected testing section with no fissures or breakout had a depth of 6.94–7.71 m in testing borehole No.1. The curves of micro-strain value vs. the relieved annular slot depth in one of the stress reliefs were given in Figure 12. They represented the characteristics of the relieved strains on a local surface of the borehole wall in the course of stress relief operation. In order to obtain the elastic modulus and Poisson's ratio used in rock stress calculation, the rock cores retrieved from the testing boreholes were prepared into cylindrical samples with diameter of 50 mm and length of 100 mm. The elastic modulus and Poisson's ratio were determined by several groups of rock samples from uniaxial and triaxial compression experiments in lab. A loading and unloading curve of a rock sample obtained by using MTS testing machine under the confining pressure of 45 MPa was shown in Figure 13, from which the elastic modulus E was 68.0 GPa, and Poisson's ratio ν was 0.11. It should be pointed that the rock samples were not yielded when they were loading and unloading under different confining pressures. The principal components of *in-situ* 3D rock stress tensor were obtained by the calculation program for BWSRM and shown in Table 1. The spatial distributions of the principal stress components were also shown in Figure 14.

The measured *in-situ* 3D rock stress tensor has the following characteristics: 1) the principal stress component mostly close to vertical direction is just the minimum principal stress. It is about 15° deviated from the vertical direc-

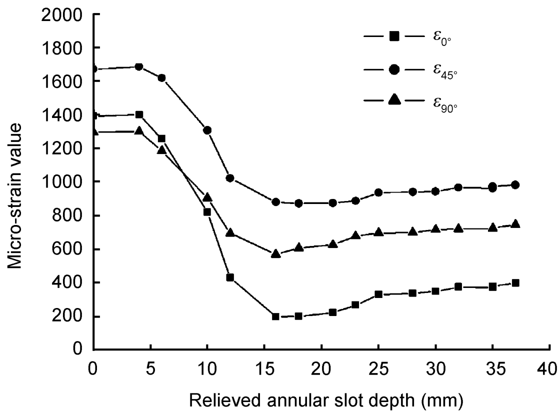

Figure 12 Curves of micro-strain value vs. the relieved annular slot depth in the course of stresses relief.

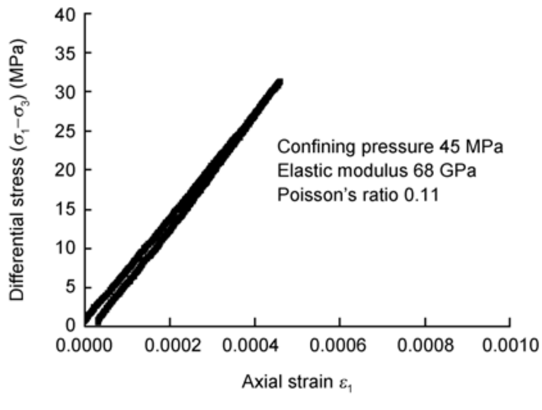

Figure 13 Triaxial loading and unloading test curve under confining pressure 45 MPa for marbles.

Table 1 Principal components of *in-situ* 3D rock stress tensor in experimental branch tunnel C of Jinping II hydropower station

The principal stresses	Magnitude (MPa)	Azimuth angle (°)	Obliquity angle (°)	Elastic modulus (GPa)	Poisson's ratio
σ_1	63.09	125.6	0.5		
σ_2	57.66	215.5	15.2	68.0	0.11
σ_3	38.65	37.4	74.8		

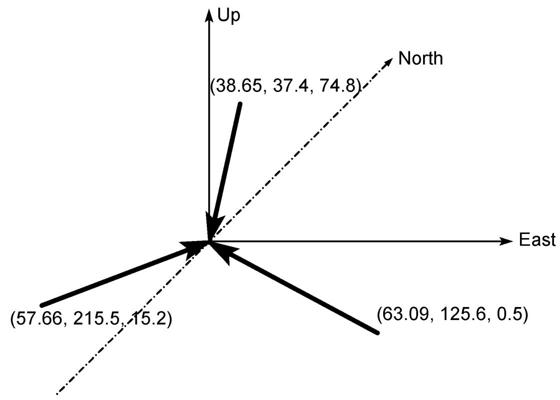

Figure 14 Spatial distribution of the principal *in-situ* 3D rock stresses tensor components σ_1, σ_2, σ_3 in experimental branch tunnel C of Jinping II hydropower station.

tion. The azimuth angle of it is 37.4°. The magnitude of this minimum principal stress is only 38.65 MPa, which is far less than that estimated by the self-weight of the overlying rock mass (about 63 MPa). It is consistent with distribution regulations of the rock stresses at deep depth, namely the vertical stress is the minimum principal stress, and is not equal to the weight of overlying rock masses. The direction of it is deviated from the vertical. 2) The first principal stress is very close to the second one. The difference between them is only 5.43 MPa, which is only 8.26% of the average value (60.37 MPa) of σ_1 and σ_2.

The influences of the elastic modulus E and Poisson's ratio ν on geostress tensor calculation were also analyzed. It can be concluded that 1) if ν equals 0.11 and keeps constant, all of the magnitudes of the three principal stress components increase or decrease as E increases or decreases by 5 GPa, whereas their azimuth and obliquity angles stay the same. 2) if E maintains constant and ν increases, all of the magnitudes of the three principal stresses increase. Moreover, they decrease as ν decreases, although the changes are not very obvious. On the other hand, the variation of ν also has effect on the azimuth and obliquity angles of the principal stresses. It requires comprehensive analysis of many measurement data of *in-situ* rock stress to obtain the distributions of the geostress field in a region. In addition, it is necessary to use the different measuring methods of *in-situ* rock stress to study the rock stress state of the measuring points, to evaluate and compare them. As a result, the reasonable and scientific conclusions can be drawn about the distributions of the geostress field of a region. The *in-situ* 3D rock stress measurement with BWSRM is relatively preliminary. The data obtained with BWSRM need to be complemented and made perfect in the future. Moreover, it is also important to compare the *in-situ* rock stress measuring data by BWSRM with those by other methods.

8 Conclusions

From the testing results of the *in-situ* 3D rock stress measurement with BWSRM, the following conclusions can be obtained:

1) The feasibility and rationality of the measuring method of *in-situ* 3D rock stresses measuring method have been verified.

2) The developed *in-situ* 3D rock stress measuring instrument with BWSRM is also successful, effective, and reliable.

3) The BWSRM has broad prospects for the *in-situ* 3D rock stress measurements in practical rock engineering.

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