In-situ Rock Stress – Lu, Li, Kjφrholt & Dahle (eds)
©2006 Taylor & France Group, London, ISBN 0-415-40163-1

A new approach for measuring the in situ 3D rock stress tensor in drilled borehole

X.R. Ge
Institute of Geotechnical Engineering, Shanghai Jiaotong University, Shanghai, People's Republic of China
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, People's Republic of China

M.X. Hou
School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, Shanghai, People's Republic of China

S.L. Wang
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, People's Republic of China

ABSTRACT: A new method for measuring in situ 3D rock stress tensor based on a special approach for stress relief on the local surfaces of a drilled borehole wall is proposed. The special approach for stress relief is achieved by drilling three cylindrical rock core samples surrounding the local surfaces of a drilled borehole wall using core drilling or annular cutting techniques. This new method can be used to measure the in situ 3D rock stress tensor with no need of overcoring along a borehole axis (traditional borehole overcoring does) and no requirement of simplifying assumptions concerning principal stresses magnitude and orientation (hydraulic fracturing does) when calculating the complete rock stress tensor. A new stress measuring instrument is designed and under manufacturing now for this purpose. Numerical simulation for stress relief under the biaxial load is analyzed using finite element method (FEM). The range of influence area caused by cutting annular slot is also studied. These results are helpful for designing prototype test and further developing the new stress measuring instrument.

1 INTRODUCTION

It is well known that rock masses are initially stressed in their natural state. Knowledge of in situ stresses is of importance to solve the problems related to rocks in civil and mining engineering, oil and gas recovery, geophysics and geosciences. The in situ stress measurements are one of the accesses to study the state of rock stress. One of the earliest measurements of in situ stresses using stress relief methods was conducted by Lieurance from the US Bureau of Reclamation in Denver in 1932 (Cai 1995). Since then, the researchers have achieved outstanding results in their innovative work concerning rock stress measurements, partial stress measuring methods and equipments have been widely applied to the practical rock engineering. On the other hand, however, because of the complex nature of rocks and rock masses, rock stresses are difficult to be determined accurately. The theoretical modeling of in situ rock stresses calculation and the development of in situ stress measuring techniques associated with these models have attracted extensive research interest over the years.

Now it is easy to obtain a large body of literature on the subject of in situ rock stress measurements. A general overview of the rock stress and its measurement is presented by Amadei and Stephansson (1997), which reflects the state of the art in rock stress measurements in 1990s. Generally speaking, the methods for measuring the 3D in situ stresses in boreholes are the following kinds: borehole overcoring (Leeman 1966, Sugawara et al. 1986), hydraulic fracturing (Fairhurst 1964, Haimson 1978), acoustic emission (AE) method (Holcomb 1993), and 3D borehole slotter (Yeun & Bock 1988, Corthésy et al. 1999). The borehole overcoring method is by far the most commonly used stress measuring methods in rock engineering. It can be used to determine the magnitude and direction of two or three principal stresses without any assumption regarding the in situ stress field. The borehole overcoring method has been used in vertical water-filled boreholes even those with a depth of 510 m (Liu, 2000). But the overcoring method is limited by core breaking easily happening in deep measuring points. The success rate with it rarely exceeds 50% (Herget 1993).

The Hydraulic fracturing is the most dominant method of in-situ rock stress measurement at great depths. Using very specialized techniques, the deepest reliable hydraulic fracturing stress measurements at a depth of 9 km ever made were reported by scientists at the KTB borehole (German Continental Deep Drilling Project) in Germany (Brudy et al. 1997). Unfortunately, the hydraulic fracturing method often requires an assumption that one of the principal directions of the stress tensor is coincident with the borehole axis. This assumption affects the reliability of the stress measuring results to some extent. Another limitation of the hydraulic fracturing technique is that it fails in some geological structures such as the faults, the fractures, and folds, while for tectonic movement and geodynamics, the in situ stress measurements of this kind of sites are important. Therefore as one of the approaches selected to measure the complete rock stress tensor, the hydraulic fracturing method still need to be improved.

The AE method is based upon the Kaiser's effect of the rock medium to determine the rock stresses in rock masses, and as a matter of fact, the rock stresses deduced from the Kaiser effect of AE at a measuring point are the largest previously experienced stress level. So the AE method can not be used to determine the current in situ stress state, and only serves as a supplementary technique for borehole stress measurements. As to the borehole slotter, although very good agreement has been found between stress measurements with it and stress measurements with other techniques (Amadei & Stephansson 1997, Corthésy et al. 1999), it can only be used at the dry borehole and the borehole depth beyond 30 meters is not permissible (Amadei & Stephansson 1997), which restrict its applications to the practical rock engineering to some degree.

In this paper, we put forward a new method to determine the in situ 3D rock stress tensor in a single drilled borehole. This new method is based on a special approach for stress relief on the local surfaces of a drilled borehole wall. Here, we refer to this method proposed as BWSRM to distinguish it from other borehole relief methods. This article elaborates the calculation model for determination of the complete rock stress tensor, studies the theoretical and technical feasibility of BWSRM for the measurement of the 3D rock stress tensor in a single drilled borehole, describes the numerical simulation on the process of stress relief using FEM. Results from FEM analyses of the stress and strain distributions around an annular slot on the borehole wall are given. This numerical modeling also gives complementary information concerning the range of influencing area of an annular slot along and around the drilled borehole wall. These results are helpful for designing prototype test and further developing the new stress measuring instrument based on BWSRM. At present, the new stress measuring instrument for this purpose has been designed and is under manufacturing now.

2 STRESS STATE AROUND A DRILLED BOREHOLE

This section presents the basic theory to determine the complete rock stress tensor in a single drilled borehole. In order to explain the principle of BWSRM for measuring the rock stresses, we still assume the rock as an ideal continuous medium. From a practical point of view, this simplified model is rational. Let first define a Cartesian coordinate system, $oxyz$, attached to the drilled borehole with the z-axis aligned with the borehole axis, the x-axis is horizontal and perpendicular to z and the y-axis is perpendicular to x and z (Fig. 1). Let S_{xx}, S_{yy}, S_{zz}, S_{xy}, S_{yz}, 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 enough for the borehole not to influence this stress state greatly.

Define a borehole cylindrical coordinate system, $or\theta z$, which is corresponding to the Cartesian coordinate system, $oxyz$ (Fig. 1). Define σ_r, σ_θ, σ_z, $\tau_{r\theta}$, $\tau_{\theta z}$, τ_{zr} respectively as the radial, tangential, longitudinal and shear stress components. Denote by E and ν the Young's modulus and Poisson's ratio of the rock material respectively. In an isotropic,

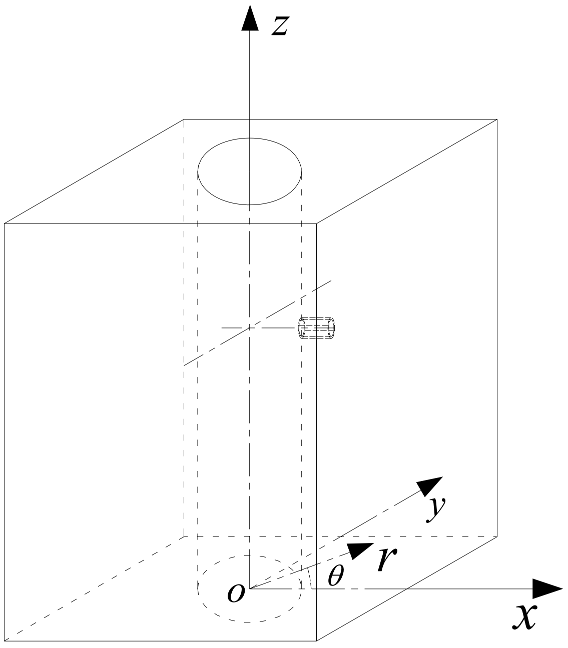

Figure 1. Borehole coordinate system.

homogeneous, linear elastic material, the stress components on the wall surface of the drilled borehole can be written as (Hiramatsu & Oka 1968):

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

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

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

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

Now defining ε_θ, ε_z, $\gamma_{\theta z}$ as the tangential, longitudinal and shear strain components of a point on the drilled borehole wall surface, then the expressions of them according to Hooke's law are:

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

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

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

Thus, if denoting by ε_φ the normal strain at a point making an angle φ from the tangential direction (Fig. 2), then the normal strain ε_φ is related to the local strain components ε_θ, ε_z and $\gamma_{\theta z}$ as

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

Substituting Eqs. (5), (6) and (7) into Eq. (8), the normal strain ε_φ is related to the in situ stress field as follows:

$$E\varepsilon_\varphi = A_1 S_{xx} + A_2 S_{yy} + A_3 S_{zz} + A_4 S_{xy} + A_5 S_{yz} + A_6 S_{zx} \tag{9}$$

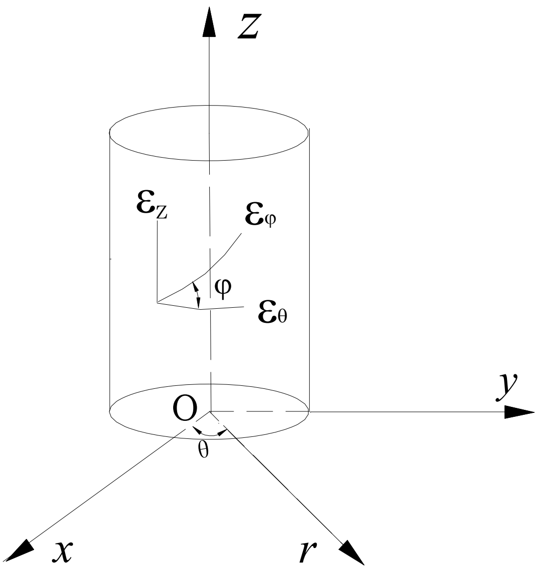

Figure 2. Normal strains at a point on the borehole wall surface

where

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

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

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

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

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

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

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 in rock surrounding the borehole. According to Eq. (9), a new stress relief method to determine the rock stress tensor is described below.

3 AN APPROACH FOR MEASURING THE IN SITU 3D ROCK STRESS TENSOR IN DRILLED BOREHOLE

3.1 *Principle of stress measurements with BWSRM*

We know that the in situ 3D rock stress measuring method represents a point-wise estimate of a local stress tensor given by six independent components. In a drilled borehole, we can select a short section of the whole borehole wall surface as a measuring point to estimate the local stress tensor. For example, one can select a local borehole section with no more than 1m in length. We consider that the far-field in situ stress tensor components are constant in this section, and the rock properties are uniform. Therefore, 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 analyses. The in situ 3D rock stress tensor components can be calculated with at least six independent strain measurements performed on the several local surfaces of the borehole wall within the selected short section.

In order to obtain strain measurements, a special stress relief approach is applied here. As analyzed in the previous section, if a cylindrical rock core sample with a certain length is isolated from the borehole wall along the radial direction through core drilling

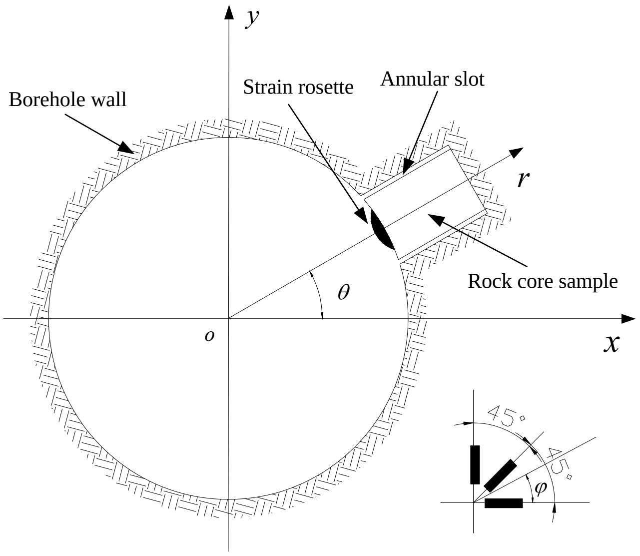

Figure 3. Scheme of local borehole-wall stress relief by core drilling

or annular cutting techniques (Fig. 3), the stored stresses can be completely relieved when the depth of the rock core sample is deep enough, while the strain responses be monitored by bonding strain gages on it. The relationship between the relieved strain and the far-field in situ stress tensor components can be determined from Eq. (9). In this process, the rock core sample is locally unloaded. The loading/unloading curves on rock core samples can be obtained in the lab. According to the loading/unloading curves, this unloading process can be considered as a linear elastic behavior. From Figure 3, for a given θ position, an orthogonal triple-strain gage rosette (in three directions 45^0 apart) is glued onto the borehole wall, then an annular slot is cut around the rosette using a diamond core bit. Three strain measurements can be obtained when the cylindrical core sample is completely relieved. In the same way, one can get more strain measurements in the other positions. After at least six independent strain measurements are made on the selected borehole wall surfaces of this section, the six compo nents of in situ rock stress tensor, S_{xx}, S_{yy}, S_{zz}, S_{xy}, S_{yz}, S_{zx}, can be theoretically calculated from six independent equations in term of Eq. (9).

It is denoted that those borehole wall surfaces for stress relief should be close to each other and not point to the same orientation, of which the purpose is to keep the lithologic characters identical between the local borehole wall surfaces for stress relief and the in situ stress field information included, and to minimize the influence of heterogeneity, thus combining the measured strains from these local surfaces to make analyses and give the stress state at several measurement point. It is because all the information of the in situ complete stress tensor (i.e. six stress components) can be obtained at several measuring locations within a local section in a single drilled borehole using the above mentioned local borehole-wall surfaces stress relief approach that we call this method as Borehole-wall Stress Relief Method (BWSRM).

3.2 *Estimate of in situ 3D rock stress tensor*

As mentioned above,the in situ 3D rock stress tensor can be determined using BWSRM from at least six independent strain measurements according to Eq. (9). In practice, however, it is preferable to perform more than the minimum number of measurements and estimate the best fit in situ 3D rock stress tensor components with the least squares approach. In the following, the mathematical developments are given.

After m measurement locations are selected around the drilled borehole wall, and an orthogonal triple-strain gage rosette (in three directions 45^0 apart) is glued onto the borehole wall at each of the m measurement locations, then n normal strain measurements ($n = m \times 3$) can be obtained. For a given strain rosette, strain gage t (t=1, 2, 3) corresponds to the angle φ (φ=0^0, 45^0, 90^0), respectively. For a given θ_k position (k=1, m), let us identify the normal strain in gage i (i=3×(k-1) +t) as ε_i. According to Eq. (9), the strain ε_i in strain gage i is linearly related to the in situ stress components in x, y, z borehole coordinate system as

$$E\varepsilon_i = A_{i1}S_1 + A_{i2}S_2 + A_{i3}S_3 + A_{i4}S_4 + A_{i5}S_5 + A_{i6}S_6 \quad (11)$$

where $S_1 = S_{xx}$, $S_2 = S_{yy}$, $S_3 = S_{zz}$, $S_4 = S_{xy}$, $S_5 = S_{yz}$, $S_6 = S_{zx}$. The A_{ij} (i=1, n; j=1, 6) denote the terms including different angles θ and φ, and can be determined from Eqs. (10). For example, for a given θ_k position, if t=2 (φ=45^0), then i=3×(k-1) +2, the A_{ij} (j=1, 6) can be calculated according to Eqs. (10):

$$A_{i1} = \frac{1}{2}\left[1 - 2\left(1-\nu^2\right)\cos 2\theta_k\right] - \frac{1}{2}\nu \quad (12a)$$

$$A_{i2} = \frac{1}{2}\left[1 + 2\left(1-\nu^2\right)\cos 2\theta_k\right] - \frac{1}{2}\nu \quad (12b)$$

$$A_{i3} = \frac{1-\nu}{2} \quad (12c)$$

$$A_{i4} = -2\left(1-\nu^2\right)\sin 2\theta_k \quad (12d)$$

$$A_{i5} = 2\left(1+\nu\right)\cos\theta_k \quad (12e)$$

$$A_{i6} = -2\left(1+\nu\right)\sin\theta_k \quad (12f)$$

Eq. (11) relates the in situ stress tensor components with the measured strains at the borehole wall at each of the n strain measurements around the drilled borehole. All six components of the in situ rock stress tensor can be found in Eq. (11) from at least six independent strain measurements. Eq. (11) can also be rewritten in a matrix form as follows:

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

where

$$[S]=[S_1 \quad S_2 \quad S_3 \quad S_4 \quad S_5 \quad S_6]^T;$$

$$[g]=E\cdot[\varepsilon_1 \quad \varepsilon_2 \quad \cdots \quad \varepsilon_n]^T;$$

$[A]$ is a $(n\times 6)$ coefficient matrix, the elements of which can be determined by Eqs. (10) with substituting relative values of angles θ and φ. The superscript T stands for transposition of a matrix. If $n>6$, the best fit in situ 3D rock stress tensor components can be obtained by the least squares method from the following equations:

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

or

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

Where

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

$$G_k=\sum_{i=1}^{n}A_{ik}g_i \tag{16b}$$

As demonstrated in this section, the 3D rock stress tensor with respect to the borehole x, y, z coordinate system can be calculated by the special local borehole wall surface stress relief approach.

Now considering that the geometry of a drilled borehole in a global X, Y, Z coordinate system inclined with respect to the borehole x, y, z coordinate system (Fig. 4), the orientation of the borehole and that of 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. The direction cosines of the x-, y-, and z-axes are equal to

$$l_x=\cos D \qquad m_x=-\sin D \qquad n_x=0$$

$$l_y=\sin V\sin D \qquad m_y=\sin V\cos D \qquad n_y=-\cos V$$

$$l_z=\cos V\sin D \qquad m_z=\cos V\cos D \qquad n_z=\sin V \tag{17}$$

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

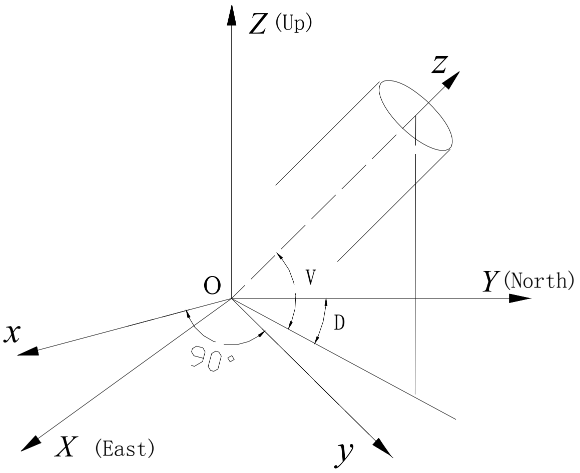

Figure 4. Orientation of a drilled borehole in a global X, Y, Z coordinate system.

$$[\sigma]_{XYZ}=\begin{bmatrix}\sigma_X & \tau_{XY} & \tau_{ZX}\\ \tau_{XY} & \sigma_Y & \tau_{YZ}\\ \tau_{ZX} & \tau_{YZ} & \sigma_Z\end{bmatrix} \tag{18}$$

Let $[\sigma]_{xyz}$ be the stress tensor matrix in the borehole coordinate system such that

$$[\sigma]_{xyz}=\begin{bmatrix}S_{xx} & S_{xy} & S_{zx}\\ S_{xy} & S_{yy} & S_{yz}\\ S_{zx} & S_{yz} & S_{zz}\end{bmatrix} \tag{19}$$

Then the stress tensor matrix $[\sigma]_{XYZ}$ is related to $[\sigma]_{xyz}$ as follows:

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

where $[L]$ 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 X, Y, Z coordinate system defined in Eqs. (17). Matrix $[L]$ can be written as follows:

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

From the Eq. (20), the 3D rock stress tensor in the global X, Y, Z coordinate system can be calculated .

3.3 *Development of BWSRM in situ rock stress measuring instrument*

As mentioned above, we can see that the in situ 3D rock stress tensor can be determined with BWSRM in the following procedures: firstly select an ideal short section of the drilled borehole wall surface as a measuring point; relieve locally the stresses of the rock masses by drilling three cylindrical rock core samples into the borehole wall using the core drilling techniques at the different positions and monitor the strain responses along the different directions before and after stress relief; then calculate the in situ complete rock stress tensor components with the least squares approach according to the equations relating the measured strains to the in situ far-field stresses; finally determine the in situ 3D rock stress tensor in a global coordinate system and its principal stress orientations and/or intensities.

It can also be seen that BWSRM differs from the conventional borehole overcoring techniques in that overcoring is entirely replaced by drilling several cylindrical rock core samples surrounding a drilled borehole wall, so it can be utilized with no need of drilling a pilot hole along a borehole axis. Moreover, only a length of rock core sample of as little as 40 mm is required for complete stress relief (discussed in section 4). This means that the rate of core breaking happening with it can be decreased. As a result, BWSRM may offer an innovative approach to stress measurements at great depths. On the other hand, BWSRM can be applied with no requirement of simplifying assumptions concerning principal stresses magnitude and orientation when calculating the complete rock stress tensor. It overcomes some limitations of hydraulic fracturing stress measuring techniques.

Based on the above discussion, a proposed scheme for the arrangement of strain gage rosettes of BWSRM in situ rock stress measuring instrument is shown in Figure 5. Three triple-strain gage rosettes are directly glued onto the rock surface around and along the borehole wall with 120^0 apart. These rosettes are in three parallel circumferences. At each circumference, only one strain rosette is arranged, while along the borehole axis, the successive strain rosettes are arranged at an an equal interval three or four times larger than the outer diameter of the annular slots formed by subsequently drilling. This arrangement of strain gage rosettes consists in the following factors: (1) conduct them in the smallest volume possible and to minimize the scatter caused by heterogeneities so as to combine these strain measurements to calculate the in situ rock stress tensor; (2) avoid drilling the rock core sample in the influence area of other ones. Meanwhile, this arrangement is beneficial to the design and manufacture of triaxial strain cell.

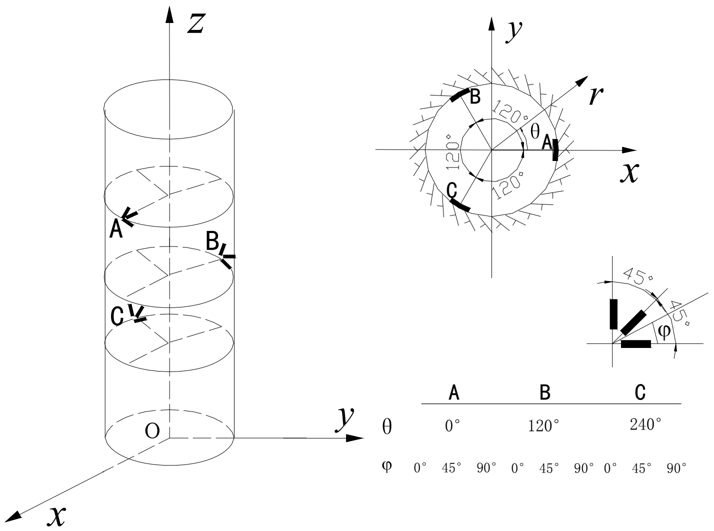

Figure 5. Scheme for the arrangement of strain gage rosettes around a drilled borehole.

According to the above scheme for the arrangement of strain gage rosettes, nine strain measurements from three rock core samples are available when the whole stress measuring process is finished. There are nine stain measurements, three of them being parallel to the borehole axis and three in the circumferential direction and three in 45^0, however, only six unknown variables are needed. This fact leads to redundant measurements. Therefore the six in situ stress tensor components are to be estimated with a least squares method. If denoting by θ_k (k =1,2,3, $\theta_1=0^0$, $\theta_2=120^0$, $\theta_3=240^0$) the different positions bonding the strain rosettes on the borehole wall, φ_t (t=1,2,3, $\varphi_1=0^0$, $\varphi_2=45^0$, $\varphi_3=90^0$) the arrangements of strain gages in a rosette, then $n=9$, $i=3(k-1)+t$ in Eq.(11). For example, if $k=1$($\theta_1=0^0$), and $t=1$ ($\varphi_1=0^0$), then $i=1$, one can calculate the coefficients A_{1j} (j =1,6) from Eqs. (12). In the same way, if $k=3$($\theta_3=240^0$), and $t=2$($\varphi_2=45^0$), then $i=8$,the coefficients A_{8j} (j =1,6)can be determined from Eqs.(12). According to the same notation, one can give the coefficient matrix $[A]_{9\times 6}$ in Eq. (13) as follows:

$$[A]=\begin{bmatrix} -1+2\nu^2 & 3-2\nu^2 & -\nu & 0 & 0 & 0 \\ -\frac{1+\nu}{2}+\nu^2 & \frac{3-\nu}{2}-\nu^2 & \frac{1-\nu}{2} & 0 & 2(1+\nu) & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 2-\nu^2 & \nu^2 & -\nu & 2\sqrt{3}(1-\nu^2) & 0 & 0 \\ 1-\frac{\nu(1+\nu)}{2} & -\frac{\nu(1-\nu)}{2} & \frac{1-\nu}{2} & \sqrt{3}(1-\nu^2) & -1-\nu & -\sqrt{3}(1+\nu) \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 2-\nu^2 & \nu^2 & -\nu & -2\sqrt{3}(1-\nu^2) & 0 & 0 \\ 1-\frac{\nu(1+\nu)}{2} & -\frac{\nu(1-\nu)}{2} & \frac{1-\nu}{2} & -\sqrt{3}(1-\nu^2) & -1-\nu & \sqrt{3}(1+\nu) \\ -\nu & -\nu & 1 & 0 & 0 & 0 \end{bmatrix} \tag{22}$$

By performing a number of elementary operations on the matrix A, it can be found that its rank is six. It means that a maximum of six independent equations can be obtained from Eq. (13). Then the six in situ stress components can be calculated with the least squares approach.

The main advantage of BWSRM is that it can be used to determine the complete stress tensor in one drilled borehole only. The new instrument for BWSRM is developing now. This new instrument can be used into a 156mm diameter drilled borehole.

Laboratory tests on automatic sticking art of rosette onto the borehole wall and on the circumferential cutting art for stress relief have been carried out. The core drilling techniques are also researched and tested on rock specimens such as granite rock, marble rock, and red sand rock. The lab experiments supply some beneficial results for designing this new instrument. On the other hand, by reviewing the state-of-the art of the in situ stress measuring methods, it can be seen that the existing stress measuring methods and techniques can not perfectly meet the needs of practical engineering and theoretical research in geosciences, especially in the 3D rock stress measurements. So it is necessary to develop this new stress measuring technique. We are trying to develop a new in situ stress measuring instrument with intelligent characteristics, which maybe lead to a leap in the development of stress measuring techniques.

4 NUMERICAL SIMULATION

As mentioned above, the in situ stress measuring method is based on a point-wise estimate of local stress tensor within a measuring section. Three annular slots are needed for determination of the 3D rock stress tensor requires at different locations along and around the drilled borehole wall. Because these strain measurements are combined, the three cylindrical rock core samples should be drilled in the smallest volume possible to minimize the errors caused by heterogeneities of the rock. On the other hand, the rock core samples can not be drilled in the range of influence area of other ones to reduce the errors arising from stresses disturbances. The numerical simulation on stress relief using linear elastic FEM is made to determine the required length of a cylindrical rock core sample after it entirely isolated from the stress field in the surrounding rock masses, and to estimate the range of the influence area of cutting the annular slots.

Here we mainly illustrate the results that the slot position is located at x (+)-axis position (Fig. 6) for the biaxial load case ($S_{xx} : S_{yy} = 1{:}2$). The mechanical model and a section of the borehole wall ($x = a$) which is parallel to the y, z plane are shown in Figure 6. The numerical dimensions can be considered as that the borehole is located in an infinite, isotropic, homogeneous, and linear elastic medium. The borehole's diameter is 156 mm; the cylindrical core's diameter is 30 mm; and the annular slot's width is 2 mm. The annular slot is simulated by retrieving rock material.

4.1 *Stress relief curves*

Providing that a triple-strain rosette is glued onto the surface of a borehole wall (Fig. 7), and it records the strain changes through the whole stress relief. The response curves of the strains verse the depth of the annular slot advance are plotted (Fig. 8), where Young's modulus of the rock material is 40GPa and Poisson's ratio is 0.25. It is shown that the stresses are nearly zero when the depth of the annular slot is 36 mm, the ratio of depth relieved and diameter of the rock core is 1.2. Therefore the stored stresses on the rock core surface aren't entirely relieved until the ratio of the length of rock core sample and its diameter is no less than 1.2 under linearly elastic unloading.

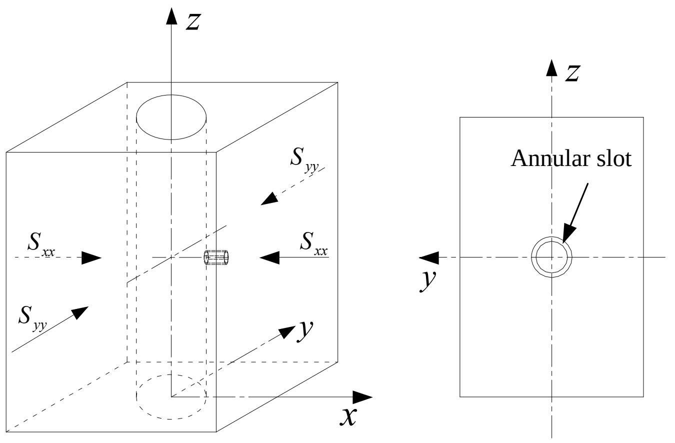

Figure 6. Position of rock core sample relieved on the drilled borehole wall.

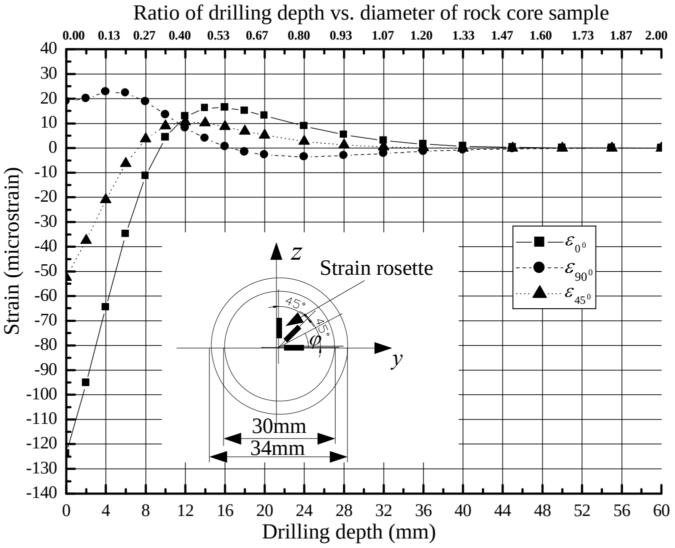

Figure 7. Response curves of the strains vs. depth of an annular slot advance.

4.2 *Core drilling influence area*

Figure 8 shows the normal stress (σ_y component) profile at the drilled borehole wall along borehole axis. The different stress profiles correspond to the depth of annular slot advance (or depth of drilling-bit advance). Along the borehole axis, the range of the influence area can be considered as about 110mm on each end measured from the center of annular slot. It means that the successive cylindrical rock core samples can be drilled at an interval three

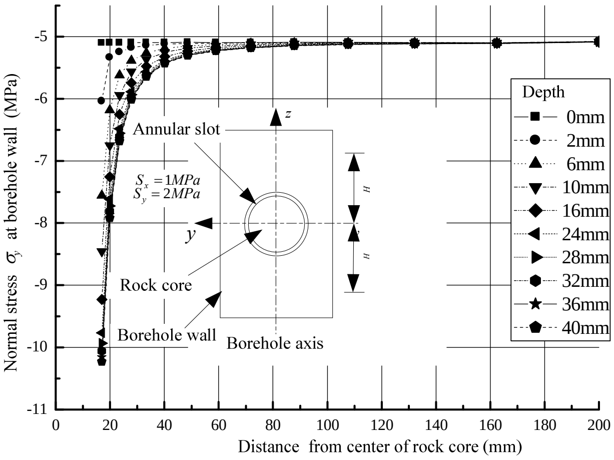

Figure 8. Normal stress component at the borehole wall along the borehole axis for different drilling depths

times larger than the outer diameter of the annular slot (center to center) along the borehole axis if their respective influence areas do not overlap.

5 CONCLUSIONS

A new method (BWSRM) for measuring the in situ 3D rock stress tensor is proposed in this paper. The principle of stress measurements with BWSRM is presented in a single drilled borehole. The main advantages of BWSRM are that it only requires short rock core lengths, and does not need for a pilot hole along the borehole axis. An innovative instrument based on BWSRM is developing now. It fits in 156 mm diameter water-filled or water-free boreholes. Laboratory tests on automatic sticking art of the rosette onto the borehole wall and on the circumferential cutting art for the stress relief have shown that this method proposed in this paper is reliable, but this research is still made in the lab. It’s feasibility in practical rock engineering needs to be verified in the future.

ACKNOWLEDGEMENTS

The authors wish to thank The National Natural Science Foundation of China (grant no. 50579037) and the “985” Project of Shanghai Jiaotong University for financing this research.

REFERENCES

Amadei, B. & Stephansson, O. 1997. *Rock stress and its measurement*. London: Chapman & Hall.

Ask, D. 2006. New development in the Integrated Stress Determination Method and their application to rock stress data at the ÄspÖ HRL, Sweden. *Int. J. Rock Mech. & Min. Sci.43*: 107-126.

Brudy, M., Zoback, M.D., Fuchs, K., Rummel, F. & Baumgärtner, J. 1997. Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: implications for crustal strength. *Journal of Geophysical Research* 102(B8): 18,453-18,475.

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

Corthesy, R., Guang, He, Gill, D.E. & Leite, M.H. 1999. A stress calculation model for the 3D borehole slotter. *Int. J. Rock Mech. Min. Sci* 36(3): 493-508.

Fairhurst, C. 1964. Measurement of in situ rock stresses with particular references to hydraulic fracturing. Rock Mech. Eng. Geol.2: 129-147.

Haimson, B.C. 1978. The hydrofracturing stress measuring method and recent field results. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.1*5: 167-178.

Haimson, B. 1989. Hydraulic fracturing stress measurements. Introduction to Part I and II. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.26*: 445, 563.

Herget, G. 1993. Rock stresses and rock stress monitoring in Canada. In Hudson, J.A. (ed.), Comprehensive rock engineering, Oxford: Pergamon Press, vol.3: 473-496.

Hiramatsu, Y., Oka, Y. 1968. Determination of the stress in rock unaffected by boreholes or drifts from measured strains or deformations. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*5: 337-353.

Holcomb, D.J. 1993. General theory of the Kaiser effect. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*30: 929–935.

Hughson D.R., Crawford A.M. 1986. Kaiser effect gauging: a new method for determining the pre-existing in-situ stress from an extracted core by acoustic emission. In: Proceedings of the International Symposium on Rock Stress and Rock Stress Measurement, Stockholm, pp. 359-368.

Lavrov, A. 2003. The Kaiser effect in rocks: principles and stress estimation techniques. *Int. J. Rock Mech. Min. Sci.* 40: 151-171.

Leeman, E. R. & Hayes, D. J. 1966. A technique for determining the complete state of stress in rock using a single borehole. In Proc. 1st Cong. Int. Soc. Rock Mech. (ISRM). Lisbon, Lab. Nac. De Eng. Civil, Lison, Vol.II: 17-24.

Liu, Y. F. 2000. Rock stress and engineering construction. Wuhan: Hubei Scientific and Technological Press.

Michichiro K., Fujiwara T. 1985. Study on estimating geostresses by the Kaiser effect of AE. In: Proceedings of the 26th US Symposium on Rock Mechanics, Rapid City, pp. 26-28.

Sugawara, K. et al. 1986. Hemispherical-ended borehole technique for measurement of absolute rock stress. In Proc. Int. Symp. On Rock Stress and Rock Stress Measurements, Stockholm, Centek Publ., Luleå, pp. 207-216.

Van Heerden, W.L. 1976. Practical application of the CSIR triaxial strain strain cell for rock stress measurement. In Proc. ISRM symp. On Investigation of Stress in Rock, Advances in stress measurement, Sydney, The Institution of Engineers, Australia, pp. 1-6.

Yeun, S.C.K., Bock, H.F. 1988. Analytical evaluation for the design and operation of new recoverable 3D stressmeter for rock. In Proc. 5th Australia - New Zealand Conf. on Geomechanics, Sydney, pp. 207-213.

Zoback, M.D., Apel R. et al. 1993. Upper-crustal strength inferred from stress measurements to 6 km depth in the KTB borehole. Nature 365: 633-635.