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Mineral Resources Extraction

Exploration of Measurement Methods of 3D In-Situ Stresses in Rock Masses

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Abstract: This paper gives an overview of the measurement methods for the 3D in-situ stresses. Rock masses in the Earth's crust are stressed in a natural stress state, which has six components in three dimensions. They are called "in-situ stresses" or "field stresses" with three principal stress components. Reliable estimate of the in-situ stresses in the rock mass is essential and vital for proper planning and design, underground excavation, mineral resource exploitation and ground stability control in geotechnical, mining and petroleum engineering. The basic principles of the measurement methods, including overcoring, hydraulic fracturing, back analysis, borehole slotting, flat jack, geophysical, and borehole breakout, are introduced. The advantages and limitations are discussed and compared. Methods that measure borehole deformation and strains during overcoring appear most common and are the only methods for the complete 3D stresses. Other measurement methods generally provide results of the orientations and/or magnitudes of some components of the in-situ stresses, mostly the maximum and the minimum stresses in the plane perpendicular to the borehole. In some methods the vertical stress is assumed as a principal stress.

Keywords: in-situ stresses, magnitude, orientation, 3D stresses, principal stress, maximum and minimum stresses, measurement methods

1 Introduction

In-situ stress state is of great interest in geotechnical, mining and petroleum engineering. It is one of the most basic parameters in underground engineering projects. In-situ stress field is disturbed when an underground engineering structure, e.g., tunnel, shaft, stope, haulage, well, and so on, is created because the stressed solid material is removed. A stress redistribution will occur in the vicinity of the engineering structure. If this new stress state exceeds the strength of the rock mass, it may cause rock failure. Hence the in-situ stresses are among the key factors that affect the stability of an engineering structure. In mining engineering, the stress state is also influenced by the opening geometry, opening shape, excavation sequence and orientation of underground excavations. Accordingly, the in-situ stress field plays an important role in helping underground excavation, mine design, support system selection and rock failure prevention. In petroleum engineering, the stress state is crucial in various stages of well planning, drilling, production and wellbore stability control (Aadnøy and Looyeh 2011). Table 1 lists the activities that require the information of the in-situ stresses in mining and petroleum engineering.

Table 1. Activities requiring information of the in-situ stresses in mining and petroleum engineering practices (after Amadei and Stephansson 1997)

Field	Mining engineering	Petroleum engineering
Activities	• Stability analysis and failure prevention of underground opening • Design of opening shape and geometry • Determination of excavation methods, sequence and orientation • Design of mine layouts • Prediction and prevention of rock bursts • Selection of support systems	• Forecasting and control of wellbore stability • Well planning • Improvement of well drilling safety • Selection of casing • Management of reservoir production

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In underground, the pe-existing stress state is in three dimensions (3D), forming a stress field (Hoek and Brown 1980, Zou 2015). The state of stress at a point within a rock mass can in general be represented by nine stress components defined in an x, y, z coordinate system, as shown in Figure 1. From equilibrium principles, we have $\tau_{xy} = \tau_{yx}$, $\tau_{yz} = \tau_{zy}$, $\tau_{xz} = \tau_{zx}$. Thus, this 3D stress field has six independent stress components {σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{zx}} in terms of the x, y, z directions. The 3D stress field can also be represented by three principal stresses {σ_1, σ_2, σ_3} which are perpendicular to each other (Figure 1).

The in-situ stresses are impacted by several factors including the weight of overlying materials, geologic structures, tectonic stress, residual stress and thermal stress (Herget 1988). The complexity of the relations between these factors and the in-situ stresses usually affects reliable estimation of the in-situ stresses (Sarwade et al 2009). Moreover, compared with rock mass properties, the state of in-situ stresses in the rock mass is difficult to measure. All stress measurement methods need to disrupt the rock to create a response that can then be measured and analyzed (Goodman 1989).

The existing methods for measuring the in-situ stresses can be divided into the following main groups: borehole-based methods, drill core-based methods, methods performed on rock surfaces, geological observation methods and geophysical methods. This paper gives an overview of the commonly used methods for in-situ stress measurements. The basic principles, advantages and disadvantages of these methods are discussed and compared.

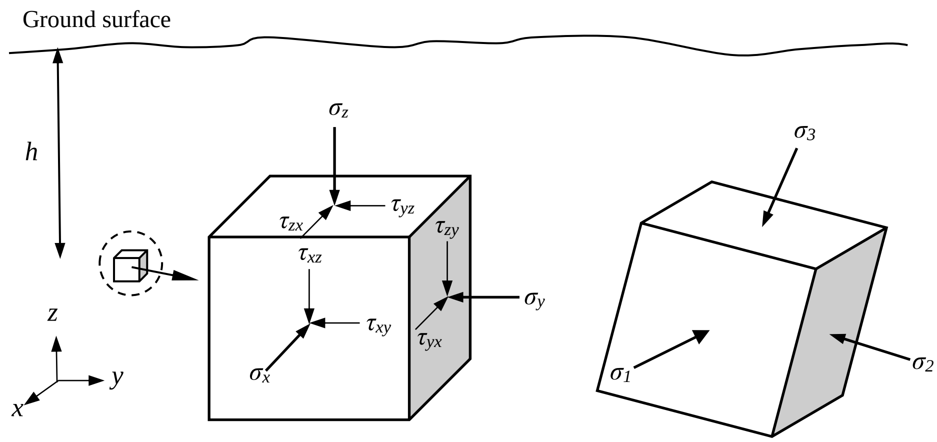

Figure 1. Three dimensional in-situ stresses underground

2 Overcoring Methods Measuring the Complete 3D In-situ Stresses

Overcoring method is used to estimate the complete 3D stresses underground, particularly in mining and geo-technical engineering. In this case, strains or deformations around a borehole during overcoring, which provide complete stress relief, are measured and analyzed. This method requires physical access to the location where stresses are to be measured and allowance of complete stress relief by overcoring.

With the overcoring method, a larger-diameter borehole is drilled in the rock mass to the desired depth where stresses are to be determined. Then a small concentric pilot hole is advanced from the bottom of the borehole. A measurement instrument (stress cell or deformation cell) is installed in the pilot hole. Subsequently the larger borehole is extended by overcoring, completely relieving stresses around the cell within the cylinder of rock. The changes in strains around the borehole wall or diametric deformations across the borehole are simultaneously recorded. Based on the measured strains or displacements, the in-situ stress components acting on the overcored rocks can be calculated by using formula derived from the theory of linear elasticity for continuous, homogenous and isotropic rocks (Fairhurst 2003). Figure 2 demonstrates the typical steps of overcoring method and the cross-section view of stress measurement by overcoring.

2.1 Strain cells

There are typically two kinds of measuring instruments for strain changes, CSIR cell and CSIRO cell. A major advantage using these cells is that they allow the 3D state of stress to be determined from one single borehole. The CSIR triaxial strain cell contains three rosettes of strain gages at 120° apart. In each rosette, four electric wire resistance strain gages are glued onto the wall of the borehole in different directions (Vreede 1981). The CSIRO cell has similar configuration as the CSIR cell. It also consists of three rosettes 120° apart, each of which has three- or four-component strain gages (Sarwade et al 2009).

There are six unknown components for the 3D in-situ stresses. Nine (or twelves) strain measurements are made from different locations around the borehole wall. This makes redundant equations available. There are two angles, η and θ, which are used to define the stain gauge orientations, as shown in Figure 3. Figure 4 demonstrates the procedure for establishing the relationship between the measured strains and the six components of the in-situ stresses.

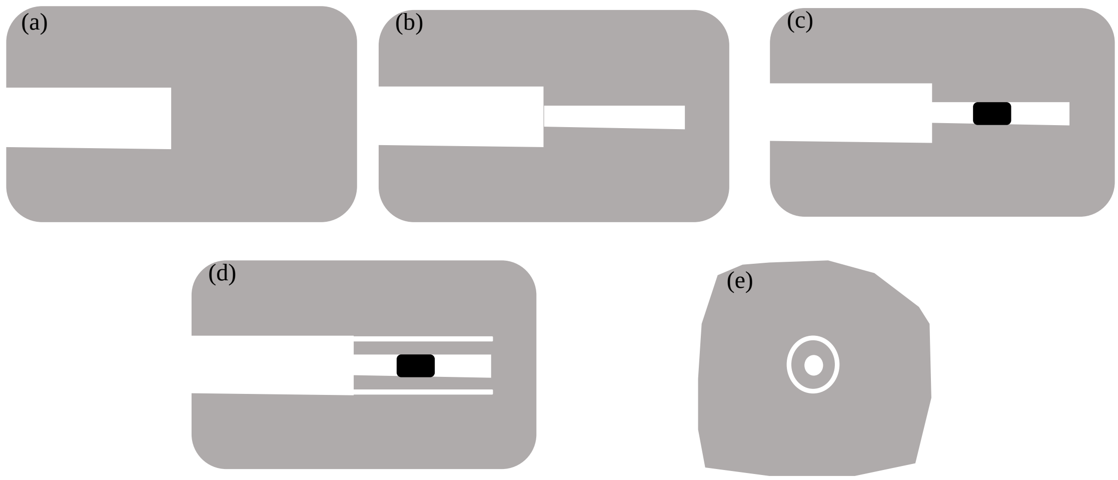

Figure 2. Sketch of typical steps for overcoring method. (a) a larger-diameter borehole drilled to the desired measurement depth; (b) a small pilot hole advanced from the bottom of the borehole; (c) a measurement instrument installed in the pilot hole; (d) the larger borehole extended by overcoring to completely relieve stresses; (e) cross-section view of stress measurement by overcoring

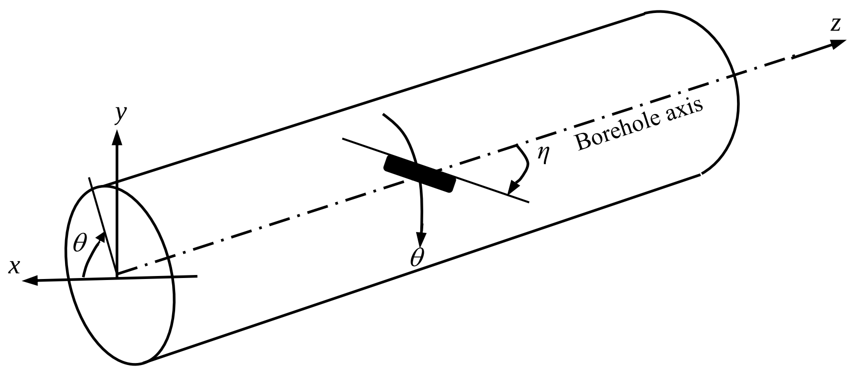

Figure 3. Strain gauge orientations in borehole

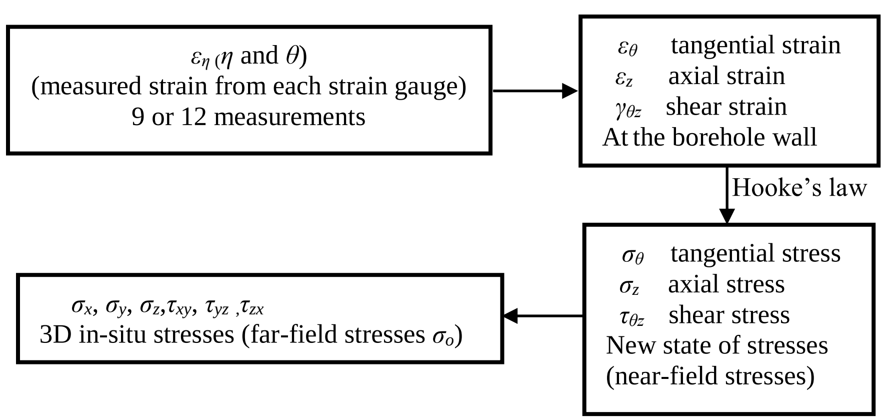

Figure 4. The relationship between the measured strains and the 3D in-situ stresses

The set of equations allowing the calculation of the 6 stress components from strain measurements can be written in a simplified matrix format:

$$\begin{aligned} \varepsilon_\eta &= [c]\{\sigma_o\} \\ &= [c_1 \quad c_2 \quad c_3 \quad c_4 \quad c_5 \quad c_6]\{\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{xy} \quad \tau_{yz} \quad \tau_{zx}\} \end{aligned} \tag{1}$$

where ε_η is a strain gage reading, $\{\sigma\}$ is the in-situ stress matrix to be determined, and $[c]$ is the coefficient matrix depending on the rock properties, the stain gage orientation angles θ and η. The elements of $[c]$ are defined below:

$$\begin{aligned}
c_1 &= \{[k_1 - 2(1-\upsilon^2)k_2\cos 2\theta]\sin^2\eta - \upsilon\cos^2\eta\}/E \\
c_1 &= \{[k_1 + 2(1-\upsilon^2)k_2\cos 2\theta]\sin^2\eta - \upsilon\cos^2\eta\}/E \\
c_3 &= (\cos^2\eta - \upsilon k_4\sin^2\eta)/E \\
c_4 &= -4(1-\upsilon^2)k_2\sin 2\theta\sin^2\eta/E \\
c_5 &= 2(1+\upsilon)k_3\cos\theta\sin 2\eta/E \\
c_6 &= -2(1+\upsilon)k_3\sin\theta\sin 2\eta/E
\end{aligned} \tag{2}$$

where, E and υ are Young's modulus and Poisson's ratio, respectively. For CSIRO cell, k_i (i = 1, 4) depends on the Poisson's ratio of the epoxy, the inner radius of the cell, the Poisson's ratio of the rock, the ratio between the inner and outer radii of the cell, and the ratio between the shear modulus of the epoxy and the shear modulus of the rock. When CSIR cell is employed, all k_i = 1.0.

2.2 USBM deformation cell

Two prevalent deformation cells are the US Bureau of Mine cell (USBM) and the Sigra in-situ stress tool (IST). The principle for both cells is the same. The USBM instrument has a three-component borehole deformation gage. The diametrical deformations are measured in three directions (60 degree apart) in the same diametral plane, as depicted in Figure 5.

With only one borehole, the three stress components σ_x, σ_y and τ_{xy} in the x, y plane normal to the borehole axis and one stress component σ_z parallel to the borehole axis can be expressed as Eqn (3) and two stress components of $\{\sigma\}$ are missing. Therefore, at least two nonparallel and non-perpendicular boreholes are necessary to calculate the complete 3D in-situ stresses.

$$u_d = 2u_{r=r_o} = \frac{2r_o}{E}\left[1+2\cos 2\theta(1-\upsilon^2) \quad 1-2\cos 2\theta(1-\upsilon^2) \quad -\upsilon \quad \theta(1-\upsilon^2)\right]\{\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{xy}\} \tag{3}$$

where u_d is the diametrical deformation, r_o is the radius of the borehole and θ is measured from the x axis counter clockwise.

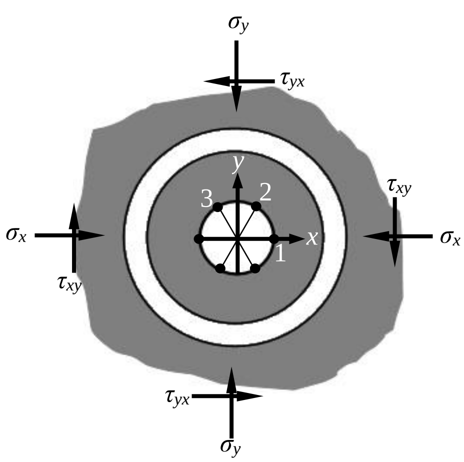

Figure 5. Diametrical deformation measurements at 0°, 60°, 120° from x-axis

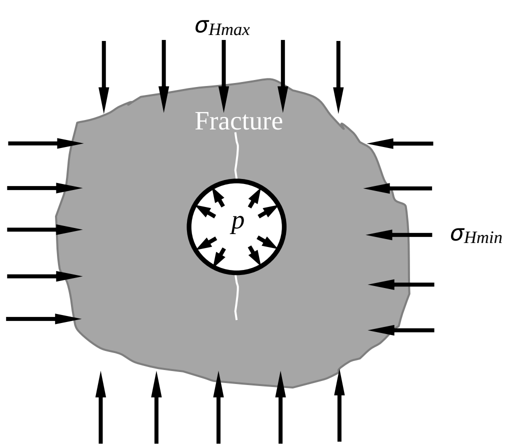

Figure 6. Fracture induced in a vertical well by hydraulic fracturing method

The overcoring method is probably the only method for measuring the complete 3D stresses (all magnitudes and orientations). It is a mature method in fundamental theory and practical use. However, there are some limitations: 1) it is very expensive because of the need for large overcoring equipment and labor; 2) it requires physical access to the measurement location, which is not applicable to small deep well in petroleum engineering; 3) it may give scattering results of the stress state due to small rock volume involved; 4) the rock mass is assumed to be homogeneous, isotropic and elastic and the results can be affected by local rock properties.

3 Methods Measuring Stress Components in a Plane

3.1 Hydraulic fracturing

Hydraulic fracturing is a method originated in the oil industry from oil well stimulation (Goodman 1989, Wang 2009). The basic principle of this method is to correlate the shut-in and reopening pressures during fracturing with the maximum and minimum stresses in a plane perpendicular to the borehole axis. An isolated section of a borehole is sealed off with inflatable straddle packers on either side of the section and then is slowly pressurized with a fluid. As the fluid pressure increases in the borehole, the initial compressive stresses on the borehole wall are reduced and at some points become tensile. Pressurization continues until the borehole wall ruptures through tensile failure (Brady and Brown 2004). At the initiation of fracturing, the stress reaches $-T_0$ (T_0 is tensile strength) and down-hole fluid pressure is p_{c1} (the fracture initiation pressure). Fractures are initiated simultaneously in diametrically opposite positions on the borehole periphery. If fluid pumping continues, the crack will propagate. The fracture develops in a direction parallel to the maximum stress, as shown in Figure 6. The orientation of the initiated fractures thus coincides with the orientation of the maximum stress in a plane perpendicular to the borehole axis. Simultaneously, the fluid penetrates the rock mass and the pressure acts on the walls of the fracture. The fluid pressure falls in the test section. Eventually the pressure down the hole will fall to a steady value p_s. This is called "the shut-in pressure". The magnitude of the minimum principal stress component can be determined directly from the recorded shut-in pressure. This allows a direct measurement of the minimum principal stress. After relaxation of the pressure and its subsequent repressurization, the peak borehole pressure achieved p_r is less than the initial fracturing pressure p_{c1}. This pressure is named "the reopening pressure". The maximum stress in a plane perpendicular to the borehole axis can be derived from Eqns (5) and (6).

$$p_S = \sigma_{H\min} \tag{4}$$

$$-T_0 = 3\sigma_{H\min} - \sigma_{H\max} - p_{c1} \tag{5}$$

$$T_0 = p_{c1} - p_r \tag{6}$$

In this method, it is assumed that the rock mass is continuous and elastic, at least in the zone of influence of the hole and the hydraulically induced fractures (Brady and Brown 2004).

In petroleum industry, min-frac test can also be applied to estimate the magnitude and direction of the maximum and minimum stresses in the plane perpendicular to a well. The difference is that in this test a liquid with a relatively small volume is injected. It is carried out before the major hydraulic fracturing treatment (Fjar et al 2008).

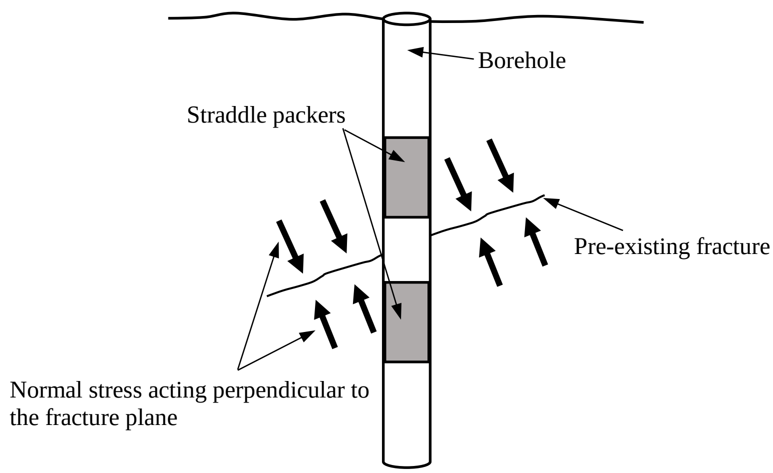

Figure 7. Schematic diagram of HTPF

3.2 Hydraulic tests on pre-existing fractures (HTPF)

Hydraulic tests on pre-existing fractures (HTPF) can also be applied in a well (Cornet and Valette 1984). In conventional hydraulic fracturing, new fractures are created in the borehole wall by a pressurized liquid, whereas for HTPF the existing fractures in the borehole walls are re-opened by a pressurized liquid. The average normal stress acting perpendicular to the fracture plane is considered equal to the recorded shut-in pressure (Figure 7). The average normal stress acting on the ith fracture plane is related to the in-situ stresses in a plane perpendicular to the borehole axis by Eqn (7) (Cornet and Valette 1984, Cornet 1986):

$$\sigma_{ni} = \gamma z_i \cos^2\theta_i - \frac{1}{2}\sin^2\theta_i[S_1 + S_2 + (\alpha_1 + \alpha_2)z_i + (S_1 - S_2)\cos 2(\varphi_i - \lambda) + (\alpha_1 - \alpha_2)z_i \cos 2(\varphi_i - (\lambda + \eta))] \tag{7}$$

where σ_{ni} is the normal stress acting on the ith fracture plane, θ_i is the angle between the normal n_i to the ith fracture plane and the vertical axis, φ_i is the orientation of the horizontal projection of n_i with respect to the north, γ is the weight of the overburden per unit length, and z_i is the depth of test location. S_1, S_2, α_1, α_2, λ, and η are unknown parameters related to the stress tensor.

Since no new fractures are induced, HTPF relies on existing fractures (Lin et al 2018). The key for this method is a sufficient number of fractures with varying dip and strike. Sometimes it is not easy to find these fractures. Moreover, it is essential to know the precise locations and orientations of fractures prior to the tests. This method is time consuming (Stacey and Wesseloo 2002). Theoretically, it may be possible to estimate the 3D in-situ stresses. However, the authors are not aware of any publication describing the explicit relationships between the average normal stress perpendicular to a fracture plane and all of the six independent components of the 3D in-situ stress state.

The major advantage of the above fracturing methods is that they can be applied to deep boreholes for in-situ stress estimation. They normally provide the information of the magnitudes and orientations of the maximum and the minimum stresses in the measurement plane.

In practice the vertical stress is usually assumed as a principal stress with an acceptable error and is proportional to the rock density and the depth below the surface. Thus the vertical stress and the two stresses determined from fracturing tests in a vertical borehole are sometimes used as an approximation of the three principal stresses of the in-situ stress field.

3.3 Borehole slotting

Borehole slotting is based on the principle of local stress relief in a borehole, in which slots are cut into the borehole wall and the strain relieve adjacent to the slots is measured. In this method a properly-sized borehole is drilled first and then a half-moon shaped radial slots are sawn parallel to the borehole axis with a specially-designed device (Figure 8a).

Directly next to the slot a specifically developed contact strain sensor that is part of the slotter is pressed with a specific force to the borehole wall during the slotting. It is used to measure the tangential strain at the borehole wall in the near vicinity (within a 15° arc) of the slot before, during and after cutting the slot. Figure 8b shows Finite Element simulation results of tangential stress relief at varying locations next to a slot and varying slotting depths. For points of the borehole surface close to the slot (θ < 15°), 100% stress relief occurs at slot depth of 22 mm.

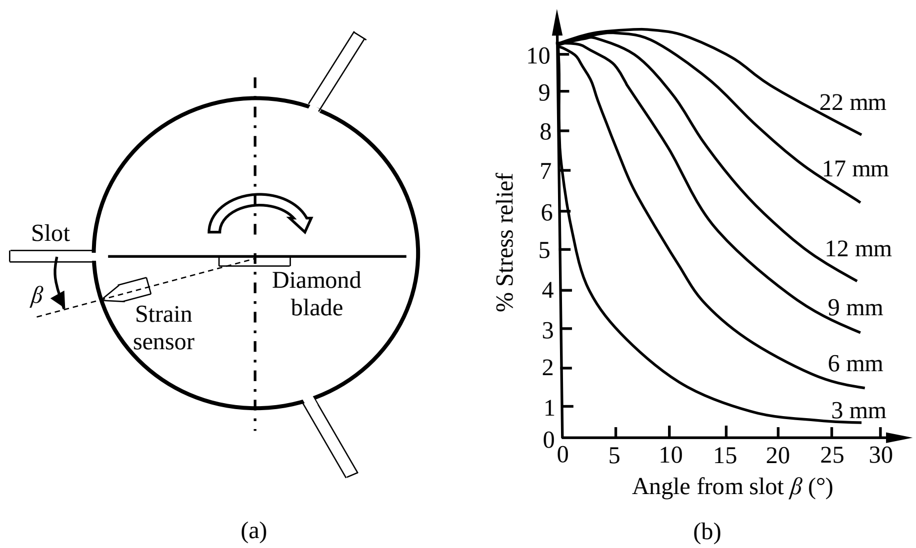

Figure 8. (a) Cross-section view of borehole slotting set-up and (b) tangential stress relief next to a slot at a borehole surface from Finite Element simulation (after Bock and Foruria 1983)

The measured strains are converted into stresses under a plane strain condition using the theory of linear elasticity. Normally, a minimum of three longitudinal cuts (usually 120° apart) in three different directions is necessary to determine the 2D in-situ stresses in the plane perpendicular to the borehole, Eqn (8):

$$\varepsilon_\theta = \frac{1-\upsilon^2}{E}\left[1-2\cos 2\beta \quad 1+2\cos 2\beta \quad -4\sin 2\beta\right]\left\{\sigma_x \quad \sigma_y \quad \tau_{xy}\right\} \qquad (8)$$

where ε_θ is the tangential strain measured in different direction.

The significant advantage with the method is that it does not require any overcoring (Ljunggren et al 2003). However it can only estimate the three stress components in the plane perpendicular to the borehole axis.

3.4 Flat jack

Flat jack is one of the oldest methods of stress measurement. In many aspects they can be classified as partial surface relief methods. If there is an access to a rock face, stress can be measured using this method. A slot (planar or circular) is cut on rock surface to disturb the equilibrium of a rock mass. Reference pins or strain gages placed in the near vicinity across the slot are employed to measure the deformation caused by slot cutting. Then a device such as a jack is inserted into the slot and pressurized until the deformation has vanished. The cancellation pressure of the jack required to null the deformation approximates the stress normal to the plane of jack (Figure 9). In each flat jack test, one stress component is determined. It also should be pointed out that the measured stress is not the in-stiu stress, instead, the average excavation-induced stress within the range of the cutting depth *D*.

This method can also be applied for estimation of the 2D in-situ stresses in the plane perpendicular to the borehole axis. If a borehole wall is cut with the flat jack parallel to the hole axis, the tangential stress σ_θ around the hole can be measured at that location with this method. If three measurements are made in different locations around the hole, there are three tangential stresses $\sigma_{\theta 1}$, $\sigma_{\theta 2}$ and $\sigma_{\theta 3}$. If the borehole is perpendicular to the *x*, *y* plane, the in-situ stress components σ_x, σ_y and τ_{xy} in the *x*, *y* plane are related to the three measured tangential stresses by Eqn (9) (Amadei and Stephansson 1997):

$$\begin{Bmatrix}\sigma_{\theta 1}\\ \sigma_{\theta 2}\\ \sigma_{\theta 3}\end{Bmatrix} = \begin{bmatrix}1-\cos 2\theta_1 & 1+\cos 2\theta_1 & -4\sin 2\theta_1\\ 1-\cos 2\theta_2 & 1+\cos 2\theta_2 & -4\sin 2\theta_2\\ 1-\cos 2\theta_3 & 1+\cos 2\theta_3 & -4\sin 2\theta_3\end{bmatrix}\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix} \qquad (9)$$

where θ is measured from the x axis counter clockwise.

Several major assumptions are made in the analysis of this method: 1) the rock mass is uniform and isotropic; 2) the stress relief process is assumed to be completely reversible; 3) flat jacks are assumed to be aligned with the stress parallel to the surface of the opening.

3.5 Back analysis of excavation or drilling

Back analysis is a practical engineering tool to evaluate geo-mechanical parameters of underground structures based on field measurements of some key parameters, such as displacements, strains and stress changes and to optimize designs. This method has been applied over the last few decades to estimate the in-situ stress state and the mechanical properties of the surrounding rock masses in geotechnical and mining engineering (Sakurai 2017).

In 1966, a back-analysis method of calculating the average ground stress components from measurements of the deformation of a circular hole was presented by Panek (Panek 1966). In the same year, Suzuki developed the measuring instruments for borehole deformation considering the roundness and roughness of the inner surface of a borehole for applying in field stresses calculation (Suzuki 1966). Back analysis was used in Kirsten (1976) in determination of rock mass elastic moduli from deformation measurements and then introduced to identify elastic parameters and earth pressure in a tunnel lining by Gioda in 1980 (Gioda 1980). Back analysis of measured displacement of tunnels based on a finite element formulation was used to determine the initial stresses by Sakurai and Takeuchi in 1983 (Sakurai and Takeuchi 1983). Kaiser and Zou in 1990 developed a stress change fitting technique for in-situ stress determination based on back-analysis principle (Kaiser et al 1990, Zou and Kaiser 1990). The stress changes can be measured during the excavation of a drift by installing stress cells in the undisturbed rock mass ahead of the advancing face of the drift (Figure 10). Based on this technique, Wiles and Kaiser did further work. They combined readings from both CSIRO, CSIR and other borehole strain cells with displacement measurements from convergence gauges, extensometers, inclinometers and tiltmeters to determine the in-situ stresses (Wiles and Kaiser 1994a and 1994b). Zou (1995) proposed a back-analysis inverse method using relative and convergence displacements and boundary element method to estimate the effective field rock properties and in-situ stresses. Sakurai (1997, 2003, 2017) did further work with this method in rock engineering with numerical modelling.

When an excavation is made, or an excavation enlarged, in a rock mass, stress changes/displacements are induced by the nearby excavation in response to the action of the in-situ stresses.

1) Back analysis of nearby excavation with strain cells

The major difference between overcoring and back analysis method is that overcoring process relieves completely the stresses around a strain cell, therefore the measured strain changes are directly from the in-situ stresses ($\sigma_o \rightarrow 0$, $\Delta\sigma = \sigma_o$). Whereas back analysis method uses the excavation of a nearby opening to partially relieve the stress around a strain cell, accordingly the measured strain changes are not directly from the in-situ stresses but they are related indirectly ($\sigma_o \rightarrow \sigma_n$, $\Delta\sigma = \sigma_n - \sigma_o$) (Figure 10) and the in-situ stresses are calculated through a back analysis process.

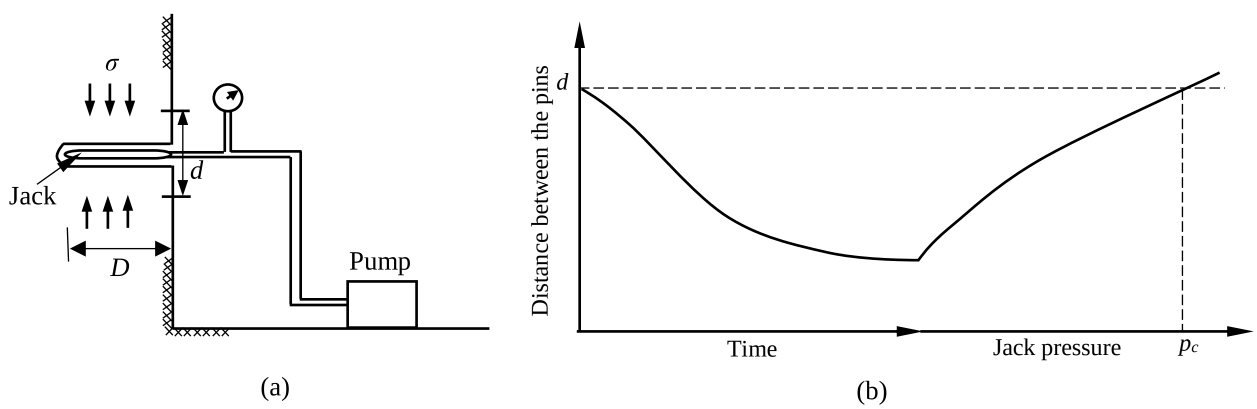

Figure 9. (a) Flat jack set-up and (b) the record of distance between the pins in the flat jack test (after Goodman 1989)

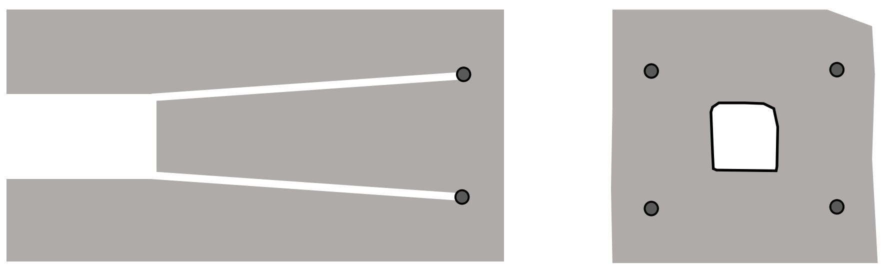

Figure 10. Field measurement of stress changes by excavation

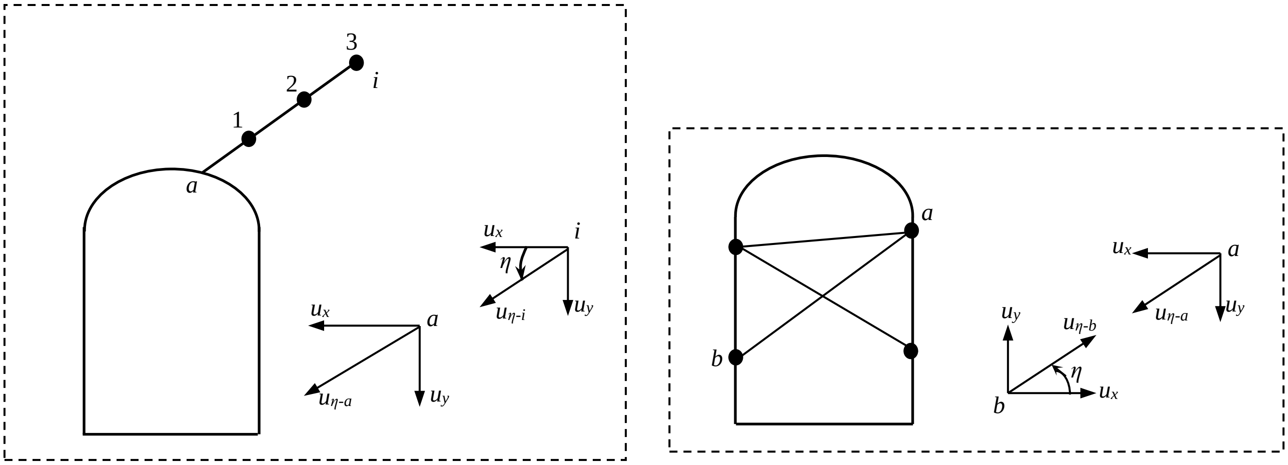

Figure 11. Relative movement measurement and convergence measurement and their calculations (after Zou 1995)

Overcoring method is very expensive, and the measurement results often vary widely from location to location. Compared with overcoring, back analysis by excavation is relatively inexpensive when it is done during excavation and gives the stress state in a relatively large volume of rock.

2) Back analysis of nearby excavation with deformation measurement instruments

The deformation of the rock mass around the opening is the immediate effect of excavation. It is relatively easy to measure. It can be measured on the opening surface or inside the rock mass. Figure 11 shows the relative movement measurement and convergence measurement for calculation of the in-situ stresses. In order to obtain the complete solution for all six components of the 3D stress field, a pair of non-perpendicular excavations are required.

The relationship between the stress changes/ displacements and the in-situ stresses can be represented by a simple equation:

$$\{\Delta\sigma\} = [M_1]\{\sigma_o\} \tag{10}$$

$$\{u\} = [M_2]\{\sigma_o\} \tag{11}$$

where $\{\Delta\sigma\}$ is a matrix of stress changes, $\{u\}$ is a matrix of displacements, $\{\sigma_o\}$ is a matrix of the in-situ stresses, and $[M_1]$ and $[M_2]$ are coefficient matrices, which are functions of the geometry of the opening, location of measurement points and the rock properties.

If the stress changes or displacements induced by excavations can be measured, then the in-situ stresses can be calculated (back analysed) by solving the above equations:

$$\{\sigma_o\} = ([M_1]^T[M_1])^{-1}[M_1]^T\{\Delta\sigma\} \tag{12}$$

$$\{\sigma_o\} = ([M_2]^T[M_2])^{-1}[M_2]^T\{u\} \tag{13}$$

where superscript T and -1 denote transpose and inverse of a matrix, respectively.

The method of back analysis of nearby excavation is based on the assumption of linearly elastic behaviour. If the opening is circular, analytical solution can be obtained. If the opening has irregular shape, it is necessary to use a numerical stress simulation technique such as the Boundary Element Method (BEM) or Finite Element Method (FEM).

Lin and Zou (2016) developed a practical back analysis method for estimation of the 2D stresses in petroleum field from well deformation with consideration of different permeability of rock formation, i.e., highly permeable, low permeable and non-permeable. They are presently focused on further research for estimation of the complete 3D stresses using borehole deformation and have proposed to make two sets of measurements in two strategical sections in a well and combine the data in a global system through mathematical transformation.

This back analysis method for determining the in-situ stresses from well deformation is expected to have the following advantages:

- it can be used for measuring the 2D in-situ stresses in a plane perpendicular to the well axis in a small deep well in petroleum industry and has showed potential to determine the complete 3D stresses;
- it assesses average stresses over a large volume of rock mass;
- it only needs drilling and deformation measurement, making it more versatile in application;
- it is less expensive than overcoring method.

3.6 Geophysical methods

Borehole acoustic logging and surface seismic survey, which are used in petroleum industry, are the possible methods to estimate the in-situ stresses (Fjar et al 2008). They are based on wave propagation in an elastic medium.

Borehole acoustic logging is a well logging tool that provides a formation's interval transit time, designated as Δt, which is a measure of a formation's capacity to transmit elastic waves. Seismic survey is for mapping the large subsurface structures. Elastic waves are generated by an artificial vibroseis at the surface and received by a series of sensors on the surface.

There are two approaches to assess the horizontal stress field. One principal component of the in-situ stress field is supposed to be vertical and equal to the weight of the overburden. The two others are considered to be horizontal.

The basic principle for the first approach is to measure the dynamic rock mass properties by borehole acoustic logging or surface seismic survey, correlate them to the static rock mass properties through laboratory tests on rock samples and estimate the stress magnitude based on an established relationship. In the borehole acoustic logging and surface seismic survey, the primary wave (compressional or P-wave) and secondary wave (shear or S-wave) would be received at different times after the waves propagates through the rock formation and back to the receivers. The P-waves arrive first and S-waves are the second arrival because of the higher velocity of P-wave. S-wave generally have higher energy and amplitude. These characteristics enables separation of S-wave from P-wave and allows measurement of the interval transit time for P-wave and S-wave, respectively (Serra 2004).

There is a direct relationship between wave velocities or travel time and the dynamic elastic properties of rock mass (Hearst et al 2000, Fjar et al 2008).

$$E_{dyn} = \frac{\rho}{\Delta t_s^2}\left(\frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}\right)\times 10^9 = \frac{\rho V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}\times 10^{-3} \quad (14)$$

$$\upsilon_{dyn} = \frac{\Delta t_s^2 - 2\Delta t_p^2}{2(\Delta t_s^2 - \Delta t_p^2)} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (15)$$

where E_{dyn} is dynamic Young's modulus (*MP*a), υ_{dyn} is dynamic Poisson's ratio, ρ is bulk density (g/cm^3) (obtained through density logging), Δt_s is shear sonic transit time ($\mu s/m$), Δt_p is compressional sonic transit time ($\mu s/m$), V_s is shear sonic velocity *(m/s)*, and V_p is compressional sonic velocity (*m/s*).

Subsequently, by laboratory tests, the quantitative correlations between dynamic and static elastic parameters can be established (Fjar et al 2008). The two horizonal principal stress components may be derived from empirical models, which relate the magnitudes of the maximum and minimum principal in-situ stresses to the static mechanical properties of the rocks, E and υ (Jin and Chao 2016, Yin et al 2018).

In the second approach, Tang and Cheng (2004) indicated that the maximum stress orientation can be estimated using cross-dipole acoustic logging. The fast shear polarization coincides with the maximum stress axis. They also indicated that the stress magnitude may be determined in theory using the stress-induced shear-wave anisotropy effect but difficulty in practice.

3.7 Borehole breakout

Borehole breakout has been developed as a reliable measurement technique for stress orientations. It is based on the rock failure at the borehole wall. When a borehole is drilled in the ground, the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the surrounding rock (i.e. the borehole wall). The maximum concentration is in the direction of the minimum field stress. If the circumferential stress around the borehole exceeds the compressive rock strength, borehole breakouts occur by crushing failure and thus are oriented parallel to the minimum stress (σ_{Hmin}) (Figure 12a). Breakage of the rock results in two diametrically opposed zones of enlargement. The borehole breakout can be detected by using borehole logging tools, such as optical (borehole camera), mechanical (caliper log), acoustic (televiewer) or electrical resistivity (formation microscanner or FMS) methods (Reinecker et al 2003, Tingay et al 2008).

On the other hand, when the circumferential stress is reduced to tension due to borehole mud pressure and exceeds the tensile strength of the borehole wall, drilling-induced fractures form and are oriented parallel to the maximum horizontal stress (σ_{Hmax}) (Figure 12b).

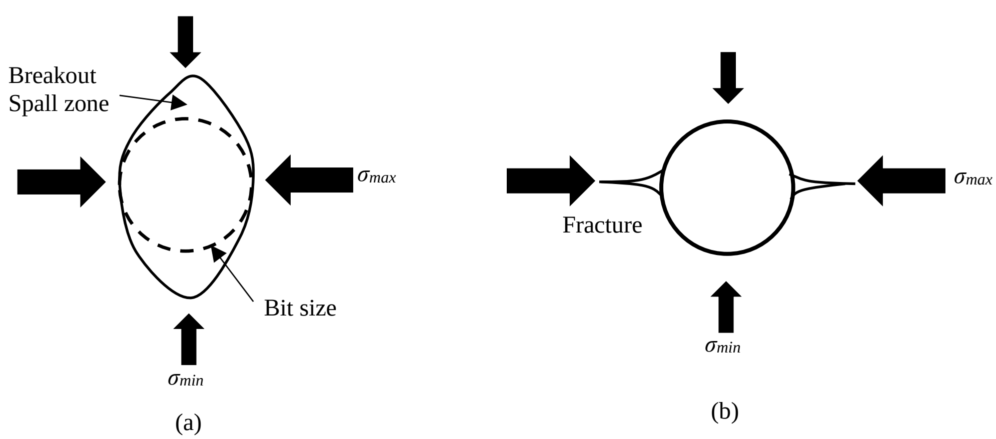

Figure 12. (a) Schematic cross-sections of borehole breakout and (b) drilling-induced fracture

This method is quick to use and cost effective. It may be applicable for revealing the stress information at great depth which other methods may not reach. The major limitations of the method are that it only works if breakouts exist and that it applies only for obtaining the orientations of the principal stresses in a plane perpendicular to the borehole axis. This method cannot determine the magnitudes of the in-situ stresses.

3.8 Fault slip data and earthquake focal mechanism analysis

Apart from the borehole breakout, geological observation can also provide information for the orientation of in-situ stresses (Goodman 1989). It can be divided into two groups: methods based on the orientation, distribution, deformation and fracturing of geological features; and methods based on the first motion of earthquakes.

Geological structures have been used as indicators of paleostresses because their features have a close relationship with the in-situ state of stress in the rock mass (Wang 2014). It is also assumed that vertical stress is one of the principal stresses. Figure 13 shows the relationship between principal stress directions and different types of fault.

In the first case of a normal fault, the minimum horizontal stress points perpendicularly to the fault trace and faulting in the rock will be parallel to the maximum horizontal stress. The second case corresponds to a reverse/thrust fault. The minimum horizontal stress points horizontally to the fault trace. In the case of strike-slip fault, fracturing of the rock will be parallel to the vertical stress. it is caused by a state of stress in which σ_{Hmax} is inclined about 30° with the fault trace, clockwise or counter-clockwise as dictated by the sense of motion on the fault.

Sometimes dikes and flank volcanoes formed around larger craters can give indication for the direction of the minimum horizontal stress. Some dikes represent hydraulic fractures, in which case they lie perpendicular to the minimum horizontal stress.

Another analysis approach comes from the first motion interpretation of earthquakes (. In the case of a fault-related event it refers to the orientation of the fault plane that slipped and the slip vector is also known as a fault-plane solution. Fault plane solutions are useful for defining the fault motion. Then this can give the information on the directions of the horizontal principal in-situ stresses.

It should be noted that most geological structures were formed a long time ago and the results of stress may not be the current state. Furthermore, the results are on a regional scale, not specific to a local area and it can not be used to determine the in-situ stress magnitude.

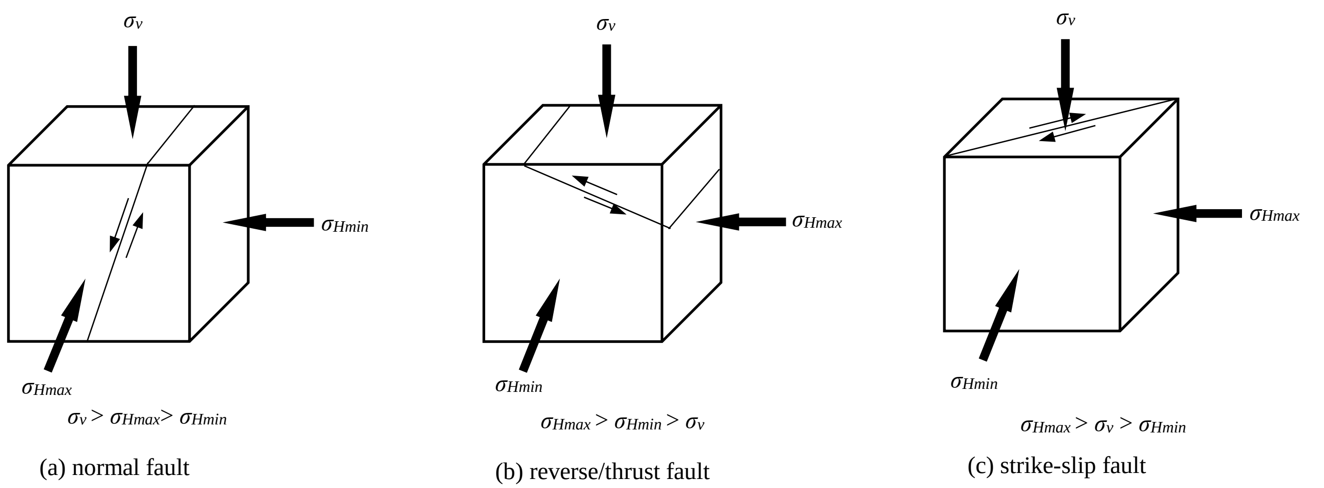

Figure 13. Illustration of fault types and directions of the inferred stresses (after Amadei and Stephansson 1997)

4 Comparison and Summary

Based on the above review of various methods for in-situ stress measurement, a comparison and summary of these methods are given below and also summarized in Table 2.

Currently only overcoring method can be used to determine the complete 3D in-situ stresses underground. It is widely used in mining and geotechnical engineering and have been practised for many years. However it requires physical access to the location where stresses are to be measured and allowance of complete stress relief by overcoring. Thus, they are not suitable for application in small deep wells. It may give scattering results due to a small rock volume involved.

Other methods may be able to estimate the orientations and/or magnitudes of some components of the in-situ stresses. Hydraulic fracturing and mini-frac tests are widely used in petroleum engineering. They can provide the information of the magnitudes and orientations of the maximum and the minimum stresses in the plane perpendicular to the borehole axis in a large rock volume. HTPF determines the average normal stress acting perpendicular to the plane of the pre-existing fracture. A sufficient number of fractures with varying dip and strike are needed to estimate the in-situ stresses in the plane perpendicular to the borehole axis. Borehole slotting is a localized complete stress relief method and doesn’t require overcoring. So compared with overcoring, the test procedure is simple. However it is only for estimation of the in-situ stress in the plane perpendicular to the borehole axis in a small rock volume. Flat jack is a partial stress relief method and conducted at the surface of excavation. The average excavation-induced stress perpendicular to the jack plane is determined in each test. The 2D stresses (not necessarily the in-situ stress) in the plane normal to the jack are estimated with three tests by cutting boreholes on the surface of the opening. Back analysis utilizes the response (stress change, strain change, displacement) of the rock mass during or after excavation to calculate the in-situ stresses based on elastic theory. Numerical modeling may be adopted in the back analysis procedure for non-circular opening. It involves a large volume of rock and can be applicable in a small deep well. This method is currently applied to evaluate the 2D in-situ stresses in the plane perpendicular to borehole axis and possible for the complete 3D stresses in a borehole. Geophysical methods relate the rock mechanical properties obtained from well logging and seismic measurement data to the in-situ stress field. They generally give the information of the maximum and minimum horizontal stresses with the assumption that the vertical stress is one of the three principal stresses.

Borehole breakout is a stress-related phenomenon, which gives the indication of the orientations of principal stresses in a plane. With geological observation method, the vertical stress component is generally assumed to be a principal stress and the orientations of the horizontal principal in-situ stresses can be inferred. The results from this method are less accurate.

Table 2. Comparison of in-situ stress measurement methods

Method	Principles and Characteristics	Advantages	Disadvantages
Overcoring	• Complete stress relief, • Widely used in mining and geotechnical engineering, • The rock mass is assumed to be homogeneous and isotropic and linear elastic theory is applied, • Rock volume involved is borehole size, • Determine the complete 3D stresses when strain cells are used, • Possible to determine the complete 3D stresses by drilling 2 non-perpendicular holes when deformation cell is used.	• Determine the complete 3D stresses – magnitudes and orientations, • A mature method in fundamental theory and practical use.	• Requires physical access, • Not applicable to petroleum engineering in small wells, • Assess the stresses at measurement location.
Hydraulic fracturing and mini-frac	• Rock fracture induction, • Used in mining, geotechnical and petroleum engineering, • The rock mass is assumed to be continuous and elastic at least in the zone of influence of the hole, • Involves a fairly large rock volume, • Determine the magnitudes and orientations of maximum and minimum stresses in the plane perpendicular to the borehole axis.	• Give a direct estimate of the maximum and minimum stresses in a plane perpendicular to the borehole axis, • Relatively simple tests in comparison with overcoring method.	• Only provides the information of principal stresses in a plane.
HTPF	• Pre-existing fracture reopening. • Used in petroleum engineering, • Suitable for the rock mass containing a large number of pre-existing fractures with varying dip and strike, • Essential to know precise locations and orientations of fractures prior to the test, • Measure the average normal stress perpendicular to the fracture plane, and then determine the 2D stresses in a plane perpendicular to the borehole axis.	• Limited to existing geological fractures.	• Currently provides the information of principal stresses in a plane, • Time-consuming.
Borehole slotting	• Local stress relief, • Used in mining and geotechnical engineering, • The rock mass is assumed to be homogeneous and isotropic and linear elastic theory is applied, • Determine the 2D stresses in the plane perpendicular to the borehole axis.	• No need of overcoring.	• Only provides the information of principal stresses in a plane, • Assess the stresses at measurement location.

Continued:

Method	Principles and Characteristics	Advantages	Disadvantages
Flat jack	• Partial stress relief, • Used in mining and geotechnical engineering, • Conducted at the surface of excavation, • The rock mass is uniform and isotropic, • The stress relief process is assumed to be completely reversible, • Measure the average excavation-induced stress perpendicular to the jack plane within the range of the cutting depth.	• Relatively simple measurement.	• Limited to stress measurement near the surface of an opening, • Evaluates the 2D stresses (not necessarily the in-situ stress) in the plane normal to the jack.
Back analysis	• Relieves partially the stress around a measurement device, • Used in mining, geotechnical and petroleum engineering, • The rock mass is assumed to be homogeneous and isotropic, • Used to determine the 2D in-situ stresses in the plane perpendicular to borehole axis.	• Can be used in small deep well, • No overcoring, • Relatively inexpensive, • Possible to determine the complete 3D stresses.	• Procedure to determine the complete 3D stresses is complex.
Geophysical methods	• Correlates mechanical parameters of rock formation and the in-situ stresses, • Normally used in petroleum industry, • Assumes the vertical stress component as a principal stress and then determine the magnitudes and orientations of the maximum and minimum horizontal stresses.	• Takes advantage of available data in well logging.	• The accuracy is affected by many factors, • Analysis is complex, • Difficult to determine stress magnitude in practice.
Borehole breakout	• Stress induced compressive failure, • Occurs mostly in high stress deep holes, • Estimates the orientation of the minimum stress in a plane perpendicular to the borehole axis.	• Relatively quick measurement.	• Only gives orientations of principal stresses in a plane, • Can not determine stress magnitude.
Geological observation	• Correlates principal stress direction and geological features, • Involves a very large rock volume on regional scale, • Assumes the vertical stress component as a principal stress and then determine the orientations of maximum and minimum horizontal principal stresses.	• Low cost, • Generally applied for the estimation of the orientations of historical horizontal principal stresses.	• The results of stress are historical and may not be the current state, • No stress magnitude given, • The results are on a regional scale.

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