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# A Review on Estimation of in Situ Rock Stress

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***Abstract: Successful estimation of in situ rock stress field (rock stress tensor) is of paramount importance for safe and economic design as well as execution of any project within the domains of Civil Engineering, Mining Engineering, Petroleum Engineering and Geological / Geophysical research. The regional rock stress field is primarily governed by the Earth's tectonic movements, whereas the project specific in situ stress field is controlled by overburden pressure, topography, geological structures etc. While using a geotechnical software for designing an engineering structure, in situ rock stress shares equal weightage beside rock strength parameters. Several authors have proposed different empirical relationships between overburden depth, rock density, deformation modulus to calculate the magnitude of vertical stress and ratio of average horizontal stress to vertical stress (k). Use of geological structures like fault, fold, intrusive dike, joint & fracture have also been proposed to decipher directions of principal stresses. Existence of high horizontal stress relative to vertical stress is indicated by phenomenon like core disking, borehole break out during exploratory drilling. However, in situ rock mechanical tests (Overcoring, Hydraulic Fracturing, Hydraulic Testing in Pre-existing Fractures or HTPF etc) must be performed to ascertain the magnitudes and directions of all three principal stresses, prevalent to a project site. Owing to the uncertainties associated with absolute quantification of rock stress magnitude, use of the term 'stress estimation' is preferred. Although the term 'stress measurement' is used when the stress tensor is estimated by applying aforesaid in situ rock mechanical tests.***
***Keywords: in situ rock stress, stress estimation, earth pressure co-efficient (k), Overcoring, Hydraulic Fracturing, HTPF***

## I. INTRODUCTION

Proper ground characterization forms the basement of any surface as well as subsurface engineering projects. This process has two basic components i.e. evaluation of (i) rock strength and (ii) rock stresses exerted on the rock mass. There are two basic types of rock stresses, i.e. (a) in situ stresses and (b) induced rock stresses. Various detrimental effect crops out if rock stress exceeds rock strength in form of ground settlement, slope failure, rock burst and squeezing in subsurface construction projects etc.

In situ rock stresses are the original stresses existent within a rock mass prior to the commencement of any project. It may be regarded as the sum total of all stresses that were subjected to the rock mass and locked-in by way of various geo-dynamic processes during geological past. Whereas the induced stresses are the new set of stresses generated in response to the activities of an engineering project.

In situ rock stresses at any ground is resolved into three mutually perpendicular components that are maximum, intermediate and minimum in magnitude to each other. These components are designated as σ1 (maximum principal stress), σ2 (intermediate principal stress) and σ3 (minimum principal stress) where $\sigma1 > \sigma2 > \sigma3$. As there is no shear stress parallel to the Earth's surface, any of the three principal stresses coincides with the vertical stress direction.

The vertical stress can be successfully calculated by multiplying overburden depth with average density of Earth's crust. From disposition of various geological structures (fault, fold, dike, joint etc), the orientation of maximum principal stress direction can be identified. It can also be identified from a world-wide database, called 'World Stress Map'. The ratio of average horizontal stress magnitude to vertical stress magnitude (Earth Pressure Co-efficient or k) can be estimated by various empirical relationships that use parameters like overburden depth, deformation modulus etc.

Maximum and minimum horizontal stress magnitudes are also possible to calculate using different formulas, proposed by various authors from time to time. However, horizontal in situ stresses are highly variable and nobody should rely on calculation only. There are many procedures to measure in situ rock stress tensor.

Some method disturbs the original stress field of rock mass whereas other depends on indirect measurements. Among all the methods for in situ rock stress measurement, available at market, Overcoring method, Hydraulic fracturing method and Hydraulic Testing in Pre-existing Fracture (HTPF) are widely utilized.

## II. DEFINITION AND TERMINOLOGY FOR DIFFERENT ROCK STRESSES

Reference [1] defined in situ rock stresses as "In situ stresses, also called natural, primitive or virgin stresses, are the stresses that exist in the rock prior to any disturbance." Generally, the existing in situ stresses in a rock mass are the cumulative product of all the geo-dynamic processes that were operative during long period of geological past. Several authors have proposed different classifications for in situ stresses and the terminology used to describe these stresses. Reference [2] classified in situ (virgin) stresses into two groups: gravitational and tectonic. The tectonic stresses were themselves divided into current and residual components. Reference [3] divided in situ stresses into external stresses composed of gravitational and tectonic stresses, and internal stresses composed of residual stresses. External stresses have also been called regional stresses [4]. The different terms to describe various types of rock stresses are depicted in Figure. 1. The classification of terminologies according to [5] and [6] are given in Table. 1.

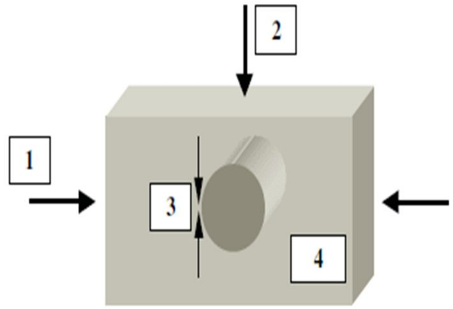


Figure. 1 Different descriptive terms for in situ and induced rock stresses

Table. 1 Classification of in situ rock stress terminology.

| Number of Stress State ** | Name of Stress State | Description of Stress State |
|---|---|---|
| 1 | Tectonic Stress | The stress state caused by tectonic plate movement. |
| 2 | Gravitational Stress | The stress state caused by the weight of the rock above. |
| 1 & 2 | Natural Stress | The in situ stress which exists prior to engineering. |
| 1 & 2 | Regional Stress | The stress state in a relatively large geological domain. |
| 1 & 2 | Far-field Stress | The stress state beyond the near-field. |
| 3 | Local Stress | The stress state in a small domain. |
| 3 | Near-field Stress | The stress state in the region of an engineering perturbation. |
| 3 | Induced Stress | The natural stress state as perturbed by engineering. |
| 4 | Residual Stress | A locked-in stress state caused by previous tectonic activity but currently acting. |
| 4 | Thermal Stress | The stress state caused by temperature change. |
| | Palaeo-stress | A previous natural stress that is no longer acting. |
| ** The number of stress state is assigned to denote relative disposition of various Stress State in above diagram i.e. Figure. 1 | | |

## III. DIFFERENT FACTORS CAUSING ROCK STRESSES

Among the major controlling factors behind generation of various kinds of rock stresses, the most significant are (i) weight of overlying rock strata, (ii) movement of tectonic plates and (iii) effect of human activities like drilling, blasting, excavation etc. According to [1], the different factors, responsible for giving rise to various kinds of in situ as well as induced rock stresses are displayed in Figure. 2.

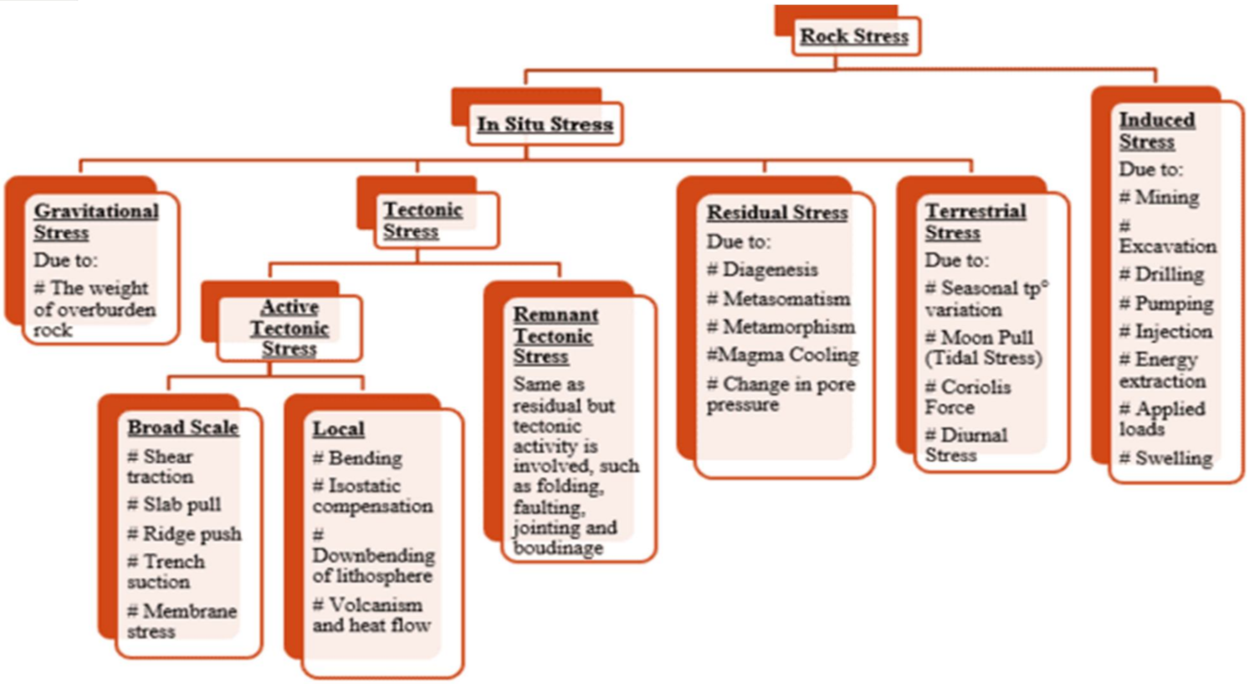


Figure. 2 Different factors responsible for causing rock stresses

## IV. ENGINEERING APPLICATIONS OF IN SITU ROCK STRESS ESTIMATION

Any surface or subsurface project related to Civil Engineering, Mining Engineering, Petroleum Engineering, Energy development as well as Geological / Geophysical research require knowledge of in situ rock stresses. Since 1930, Geologists, Geophysicists and Engineers have realised the need for proper quantification of rock stresses and have proposed many methods to do it from time to time. Reference [7] give a list of activities for which in situ stresses play a critical role, see Table. 2.

Table. 2 Applications of in situ rock stress knowledge in different engineering purposes

| Civil and Mining Engineering | Energy Development | Geology / Geophysics |
|---|---|---|
| 1) Stability of underground excavation (Tunnels, Mines, Caverns, Shafts, Stopes, Haulages)<br>2) Drilling and Blasting<br>3) Pillar design<br>4) Design of support systems<br>5) Prediction of rock burst<br>6) Fluid flow and contaminant transport<br>7) Dams<br>8) Slope stability | 1) Borehole stability and deviation<br>2) Borehole deformation and failure<br>3) Fracturing and fracture propagation<br>4) Fluid flow and geothermal problems<br>5) Reservoir production management<br>6) Energy extraction and storage | 1) Orogeny<br>2) Earthquake prediction<br>3) Plate tectonics<br>4) Neotectonics<br>5) Structural Geology<br>6) Volcanology<br>7) Glaciation |

## V. STRATEGY FOR IN SITU ROCK STRESS ESTIMATION

For any project, size, budget and ground complexity would dictate the accuracy level, required for in situ rock stress information. Based on the exact requirement, a strategy for in situ rock stress estimation has to be prepared, addressing the following questions [1]. What information is required and why? Are Principal stress directions required? Is the magnitude of one or more principal stress components required? Is the complete stress tensor required? How is the variation of the stress state across the site? Are general estimates required, or determination via actual measurements?

Are the values required with an interpretation of the site context? What accuracy is required? How are uncertainty and spatial variability to be assessed? Is a confirmatory procedure required? Is a multiple complementary approach required with a final quantitative harmonization? Do the results need to be supported by subsequent numerical modelling? How are the results to be presented? Is strict quality control required, or is an informal approach satisfactory?

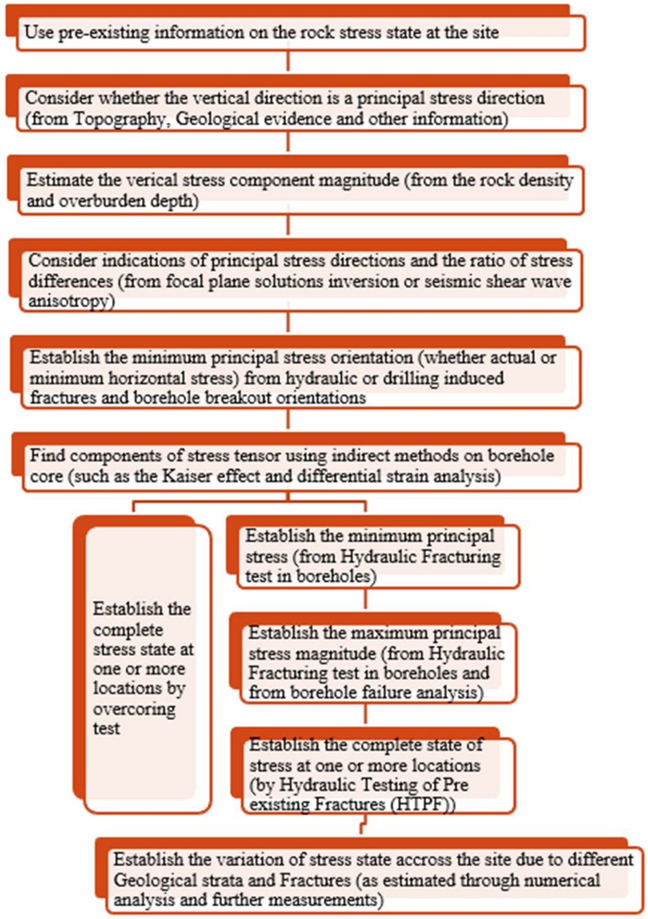


Figure. 3 Work-flow of in situ rock stress estimation programme (from Hudson et al, 2003)

## VI. ESTIMATION OF IN-SITU ROCK STRESS

During the preliminary investigation phase of any engineering construction project, gross information of in situ rock stress condition can be ascertained by using various empirical formulas. Analysis of Survey Contour Map, Geological & Geotechnical Map, Rock Mass Classification System, depth of overburden etc, can generate first hand 'in situ stress state database'. The process can navigate the future path of detail investigation to obtain more precise stress scenario for detail design purposes. In the aforesaid procedure, magnitude of vertical stress, ratio of average horizontal to vertical stresses (Earth Pressure Co-efficient or 'k'), magnitudes and directions of maximum & minimum horizontal stresses can be estimated.

### *A. Estimation of Vertical Stress*

Vertical stress at any point of the Earth is generated due to the weight of overlying earth material. It can be estimated by multiplying the height of overburden (Z) with average density of Earth's crust i.e. 2.7 g/cc. Therefore, Vertical Stress ($\sigma_v$) below an overburden depth (z) is estimated as below [8].

$$\sigma_v = \gamma z$$

$$\sigma_v = 0.027z \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

$\sigma_v$ = Vertical Stress in MPa

Z = Depth of overburden in Metre

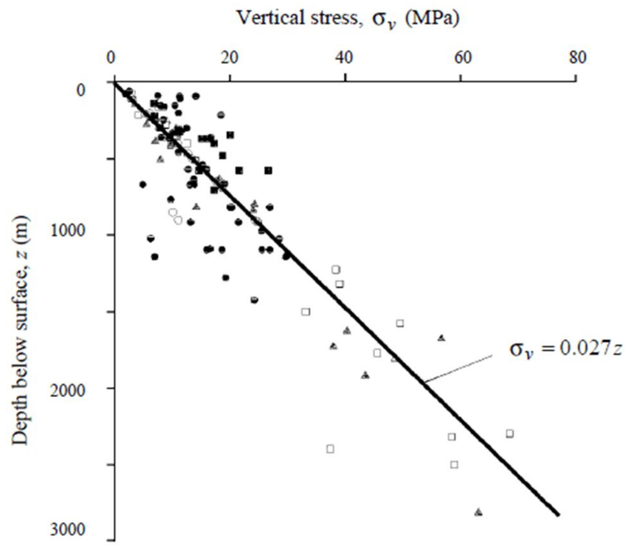


Figure. 4 Vertical stress measurements from around the world

"In fact, the vertical stress component is generally the lowest principal stress, independently of the local tectonics, for the first few hundred metres depth in hard rock" [9]. In general, stress-related stability problems increases with depth but can also be found in excavations at shallow depths (0-200 m) due to high horizontal in situ stresses such as in southern Ontario and upper New York State [10], and Australia [11]. High stresses can also be found when conducting underground excavation in mountainous regions near steep valley walls [12].

### *B. Estimation of 'Earth Pressure Co-efficient (k)'*

The 'Earth Pressure Co-efficient' that is denoted as 'k' is the ratio of average horizontal stress to vertical stress. Reference [8] proposed that the ratio of average horizontal stress to vertical stress, k, generally lies within the limits defined by following equation.

$$100/Z + 0.30 \leq k \leq 1500/Z + 0.50 \quad (2)$$

Reference [13] proposed the following equation for South African sites.

$$k = 248/z + 0.45 \quad (3)$$

Reference [14] proposed the following relation between k and z for USA.

$$k = 200/z + 0.80 \quad (4)$$

Reference [15] proposed the following equation for Australian sites.

$$k = 269/z + 0.80 \quad (5)$$

During the preliminary investigation and planning phase, [16] estimated the value of k with the help of an equation, developed in his elasto-static thermal stress model of the Earth. The equation is –

$$k = 0.25 + 7E_h\,(0.001+1/z) \quad (6)$$

Where z (m) is the height of overburden and $E_h$ (GPa) is the deformation modulus of the rock mass. The deformation modulus ($E_h$) can be estimated from RMR, Q and GSI values, obtained during geological field survey. Thus, the value of k and therefore the magnitude of average horizontal stress can be estimated.

### *C. Estimation of Horizontal Stress Magnitude*

Reference [8] estimated the range of average horizontal stress magnitude by substituting the value of $k = \sigma_{hav} / \sigma_v = \sigma_{hav} / 0.027z$ into equation 2, that yields the limits of $\sigma_{hav}$ as below equation.

$$2.7 + 0.008\,Z \leq \sigma_{h\,av} \leq 40.5 + 0.014\,Z \quad (7)$$

According to [17], the tectonic stress component (at ground level) depends upon the modulus of deformation of the rock mass as given below,

$$\sigma_{av} = 7\gamma E_d + \sigma_v\,(0.25 + 0.007E_d)\ \text{T/m2} \quad (8)$$

Where $E_d$ is modulus of deformation of rock mass in GPa and $\sigma_{av}$ is average horizontal stress.
Reference [18] has reported the following trend for in situ horizontal stresses at shallow depth (z < 1000 m) from hydro – fracturing tests.

$$\sigma_H = 2.8 + 1.48\ \sigma_v \text{ MPa} \quad \ldots\ldots (9)$$
$$\sigma_h = 2.2 + 0.89\ \sigma_v \text{ MPa} \quad \ldots\ldots (10)$$

Reference [19] inferred the following relations for z < 400m,
$\sigma_H = 1.5 + 1.2\ \sigma_v$ MPa ……………………………….………(11)
$\sigma_h = 1.0 + 0.5\ \sigma_v$ MPa ………………………………….……….(12)
It seems that Eq. 9 and 10 predict on a higher side, whereas Eq. 11 and 12 predicts on the lower side of the actual in situ stresses. Perhaps in steeply inclined mountainous terrain. Correlations according to [19] may be applicable in the stress region ($\sigma_H > \sigma_v > \sigma_h$) corresponding to Strike Slip Fault.

### *D. Stress Field Model for Horizontal Stress Estimation*

Many researchers have noticed that maximum horizontal stress orientation is sub-parallel with the movement direction of the tectonic plates [20]. Hence it can be concluded that stress field and tectonic plates movement have the same cause. Those horizontal forces induce the highest horizontal stress at the seismogenic depth. Many measurements at different locations confirmed that maximal horizontal stress has the same magnitude as the vertical stress at the depth of 3 km. Below this depth vertical stress magnitude is increasing faster than the magnitude of the horizontal stress.
For the average growth of the vertical stress of 27 MPa/km, at the depth of 3 kms,

$$\sigma_v = \sigma_H = 80 \text{ MPa} \quad \ldots\ldots (13)$$

At this depth, considering the stress wave velocity ($V_p$~ 6km/s), Poisson's ratio value ($\nu$ = 0.25) and average density of rock ($\rho$ ~ 2.7 gm/cm$^3$), the basic maximum horizontal stress ($\sigma_H'$) can be expressed as,

$$\sigma_H' \text{ [MPa]} = E_m \text{ [GPa]} \quad \ldots\ldots (14)$$

The deformation modulus can be calculated from GSI (Geological Strength Index) value obtained from Geological mapping. According to [21], the Equation 14 becomes:

$$\sigma_H' = E_m.(27.H)^{(1 - GSI/100)} \quad \ldots\ldots (15)$$

Where,
$\sigma_H'$ = basic maximum horizontal stress [MPa]
$E_m$ = modulus of deformation of the rock mass [GPa]
H = depth [km]
GSI = Geological Strength Index

Basic vertical (gravitational) stress component is:
$\sigma_v' = 27.H$ ……………………………..….… (16)

If $\sigma_v' = \sigma_H'$ then:
$\sigma_v = \sigma_v' = 27.H$ ……………………...……(17)
$\sigma_H = \sigma_H' + [(\sigma_v' - \sigma_H')\ \nu/(1 - \nu)]$ …………......(18)

If $\sigma_v' < \sigma_H'$ then:
$\sigma_v = \sigma_v' + [(\sigma_H' - \sigma_v')\ \nu/(1 - \nu)]$ ……….....….(19)
$\sigma_H = \sigma_H' = E_m.(27.H)^{(1 - GSI/100)}$ ……………..(20)

Minimum horizontal stress is expressed as:
$\sigma_h = (\sigma_H + \sigma_v)\ [\nu/(1 - \nu)]$ ………………….(21)
All the above mentioned equations and relationships should be used in feasibility or preliminary design studies of underground structures situated in regions where relationships between Z, k and $\sigma_v$ have been previously established. Where the regional relationships are not known or are highly variable, some form of sensitivity analysis using limits such as those given by equation (2) may be required in the preliminary stages of design.

Wide variations in the data even for sites in similar geological environments, emphasises the uncertainty inherent in attempts to predict in-situ horizontal stresses on the basis of simple theoretical concepts or empirical laws. It is essential that careful in-situ stress measurements be made as part of the site investigation programme for any important underground excavation project.

## VII. ESTIMATION OF PRINCIPAL STRESS DIRECTIONS

Reference [22] concluded that one of the three principal stress directions has to be vertical as there is no shear stress at the Earth's surface (shear stress can not occur in fluid). Reference [20] identified the direction of maximum horizontal stress as sub parallel to the regional direction of tectonic plate movement. Various Geological aspects may indicate the disposition of principal stress directions in the field and are discussed below.

### A. *The World Stress Map* [36]

During the preliminary investigation stage, the maximum horizontal stress direction can be identified from the World Stress Map (WSM), that is a global compilation of information on the crustal present-day stress field maintained since 2009 at the GFZ Helmholtz Centre for Geosciences within Section 2.6 Seismic Hazard and Risk Dynamics, (see Figure. 5.). All stress information is analysed and compiled in a standardized format and quality-ranked for reliability and comparability on a global scale. The latest WSM database release 2025 contains 100,842 data records located in the Earth's crust. The WSM is an open-access public database and is used by various academic and industrial institutions working in a wide range of Earth science disciplines such as geodynamics, hazard assessment, reservoir geomechanics, and geotechnical applications.

Web link: https://datapub.gfz.de/download/10.5880.WSM.2025.002-Kcenwui / World_Stress_Map_2025.pdf

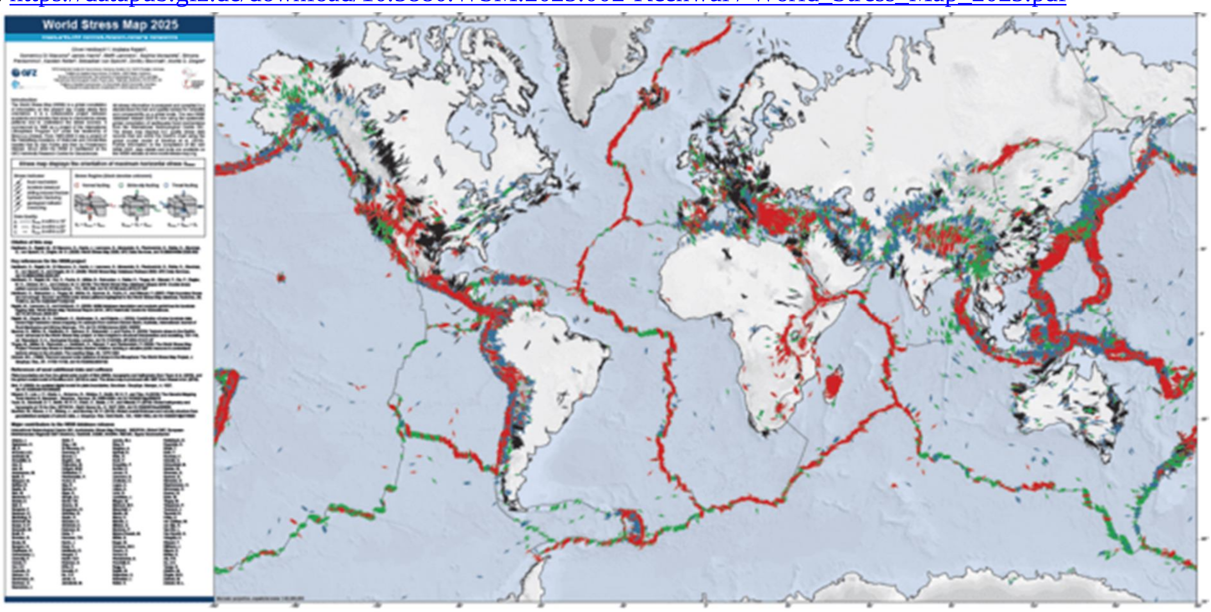


Figure. 5 World Stress Map 2025

### B. *Geologic Features (Fault, Fold, Joint, Volcanic Vent and Intrusive Sill & Dyke)*

Earth's geo-dynamic stress field give rise to various geological structures like fault, fold, dike intrusion, joint etc. Direction of such stresses control the spatial disposition of these geological structures. In the reciprocal way, orientation of geological structures can give a clue to the rock stress directions. However, caution must be exercised as most of the structures were formed long ago and past stress field might have altered.

#### 1) *Fault*

Depending on which of the three principal stresses is the vertical one, [22] defined three stress regimes. These are,

$\sigma_v = \sigma_1$; Normal-Fault Regime / Extensional Stress Regime

$\sigma_v = \sigma_2$; Strike-Slip Fault / Strike-Slip Stress Regime

$\sigma_v = \sigma_3$; Thrust-Fault Regime / Contraction or Compressive Stress Regime

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By identifying the regional as well as local fault pattern, one can ascertain the principal stress directions as shown in the below diagram.


Figure. 6 Classification of fault stress regime (from Anderson, 1951)

*2) Fold*

The axial plane of any compressional fold is oriented perpendicular to the maximum principal stress direction ($\sigma_1$). Under such situation, the stress regime becomes $S_{Hmax} > S_{hmin} > S_v$.

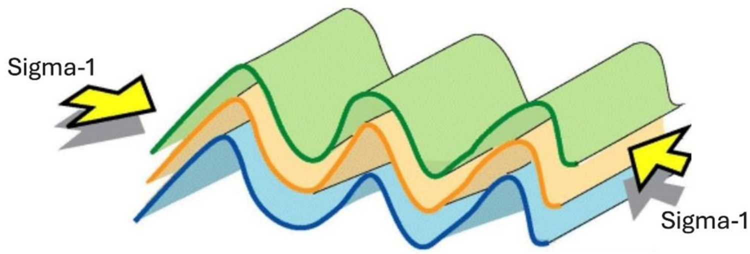



Figure. 7 Stress regime of a fold ($S_{Hmax} > S_{hmin} > S_v$)

*3) Joint*

Joints are formed in a plane perpendicular to the minimum principal stress direction ($\sigma_3$).

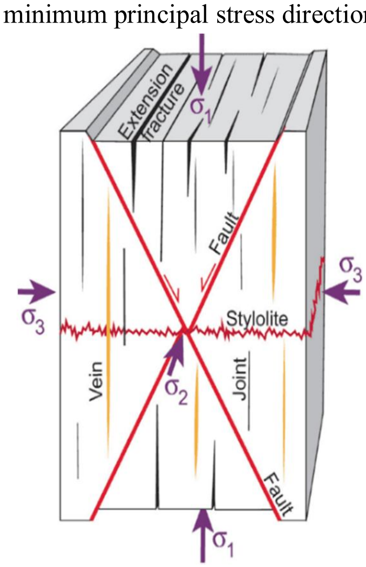



Figure. 8 Stress regime of this vertical joints ($S_v > S_{Hmax} > S_{hmin}$)

*4) Volcanic Vent*

In this Geological set up, the horizontal stress parallel to volcanic vent alignment represents the intermediate principal stress direction i.e. $S_{Hmax} = \sigma_2$ whereas the horizontal stress normal to the volcanic vent alignment represents minimum principal stress direction i.e. $S_{hmin} = \sigma_3$. [23].


Figure. 9 Stress regime of volcanic vent ($S_v > S_{Hmax} > S_{hmin}$)

*5) Intrusive Sill & Dyke*

The orientation of sheet intrusions such as dikes and sills has also been used to determine principal stress directions [24]. Reference [25] suggested that veins or dikes are commonly emplaced parallel to the maximum compressive stress as they follow the path of least resistance. He also suggested to use the orientation of flank volcanoes formed by radial dikes originating from the central conduit of a main volcano, to determine the orientation of in situ stresses. The rationales are (1) that the propagation of dikes is comparable to a large hydraulic fracturing test with magma instead of water, and (2) that the dikes are more likely to propagate in a direction normal to the minimum in situ principal stress.

Volcanic sills (filled, horizontal, tensile cracks) form in compressive stress regime ($S_{Hmax} > S_{hmin} > S_v$ where $S_v$ must be the least compressive stress) and will open perpendicular to the least principal stress [26]. However, strong horizontally compressive stresses should limit dike (filled, vertical, tensile cracks) propagation, effectively closing off pathways for magma to rise to the surface.

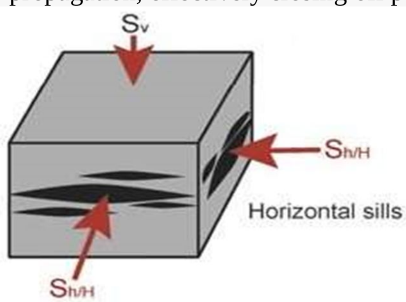



Figure. 10 Stress regime of Horizontal Sill ($S_{Hmax} > S_{hmin} > S_v$)

Vertical dykes should result from minimum horizontal compressive stresses such that two stress regimes are possible when dikes are observed: $S_v > S_{Hmax} > S_{hmin}$ or $S_{Hmax} > S_v > S_{hmin}$ [22]. If paired with a maximum vertical compressive stress ($S_v > S_{Hmax} > S_{hmin}$), minimum horizontal compressive stresses should also result in normal faulting or graben formation. Normal faults may also be used as pathways for magma to migrate upwards.

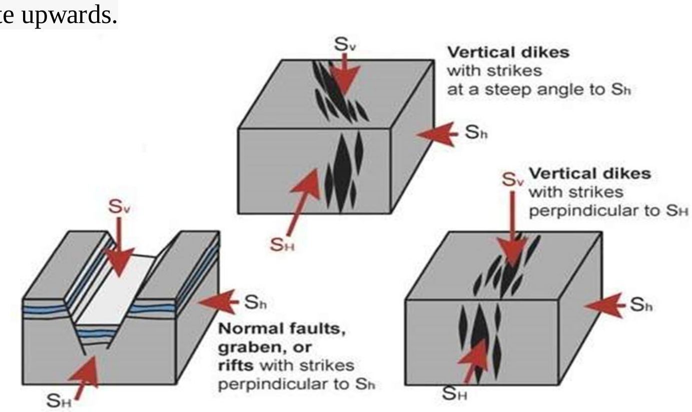
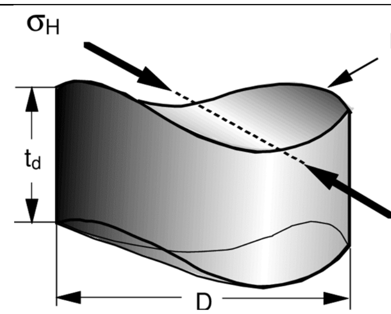



Figure. 11 Stress regime of Dykes ($S_v > S_{Hmax} > S_{hmin}$ or possibly $S_{Hmax} > S_v > S_{hmin}$)

### *C. Core Disking and Borehole Break-Out*

'Core disking' is a phenomenon by which core recovered from drilling into brittle rock is split up into many almost identical disks, sometimes looking more like a 'stack of potato chips'. Field and laboratory evidence suggest that core disking in vertical boreholes is the result of high horizontal stresses, and that the higher the stresses, the thinner the disks [27]. Disks are often saddle-shaped. A correlation between the trough axis of the saddle shaped disks and the direction of $\sigma_H$ has been observed, see Figure. 12(b). It is observed not only in the field [28], but also in laboratory simulations [29].




| Figure. 12 (a): Core disking in rock core sample | Figure. 12 (b): Correlation of saddle trough axis and $\sigma_H$ direction |
|---|---|

Borehole breakouts are borehole cross-sectional elongations resulting from preferential rock failure at and behind the borehole wall. This phenomenon is common in many other circular openings such as boreholes, tunnels, shafts and drifts in areas of high in situ stresses. Stress-induced vertical borehole breakouts are diametrically opposed brittle-failure zones concentrated around the borehole wall along the spring line of the least horizontal principal stress, $\sigma_{h.}$ Laboratory experiments have verified the alignment between breakout and $\sigma_h$ directions [30], see Figure. 13.

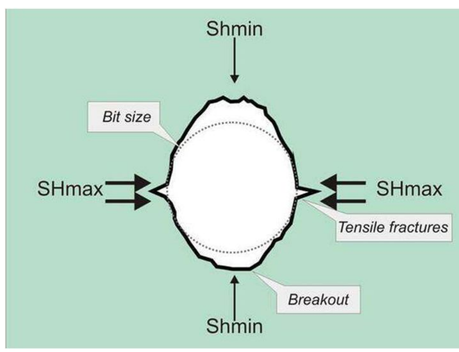



Figure. 13 Alignment of $S_{hmin}$ and borehole breakout directions

### *D. Locations of Over-Break in Tunnel*

Reference [23] corelated the position of over-break occurrences in a tunnel profile and the orientation of maximum principal stress direction ($\sigma_1$ or $\sigma_{max}$). The breaking of fragments in form of overbreak is assumed to occur parallel to the minimum horizontal stress ($\sigma_3$) and perpendicular to the maximum horizontal stress ($\sigma_1$).

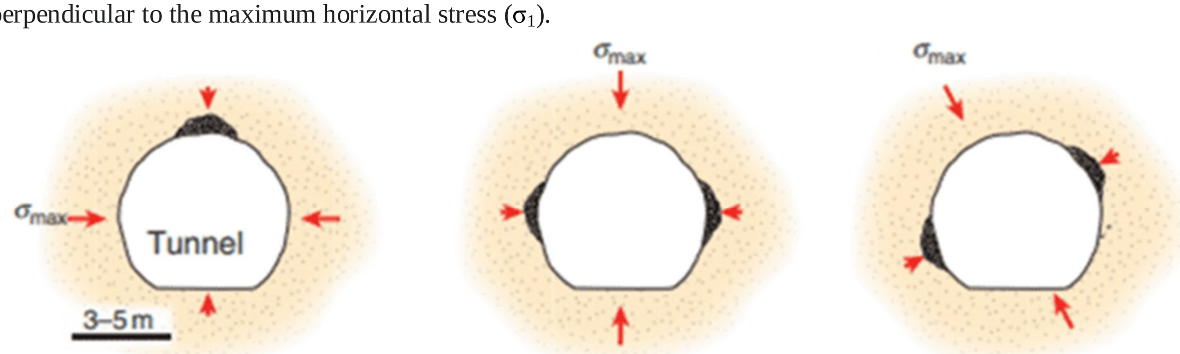



Figure. 14 Locations of tunnel over-break w.r.t. the orientation of $\sigma_{max}$

## VIII. CLASSIFICATION OF METHODS FOR IN SITU ROCK STRESS MEASUREMENT

Methods for the determination of in situ rock stress can be classified into two main categories. The first consists of methods that disturb the in situ rock conditions, i.e. by inducing strains, deformations or crack opening. The following methods may be included in this category.

1) Hydraulic methods, including hydraulic fracturing (HF) and hydraulic tests on pre-existing fractures (HTPF),
2) Borehole relief methods
3) Surface relief methods.

The second category consists of methods based on the observation of rock behaviour without any major influence from the measuring method. The following methods belong to this category:

- Statistics of measured data (database),
- Core-disking,
- Borehole breakouts,
- Relief of large rock volumes (back analysis)
- Acoustic methods (kaiser effect),
- Strain recovery methods,
- Geological observational methods and
- Earthquake focal mechanisms.

References [31] and [32] summarised the different methods for in situ rock stress determination, presented in below Figure. 15.

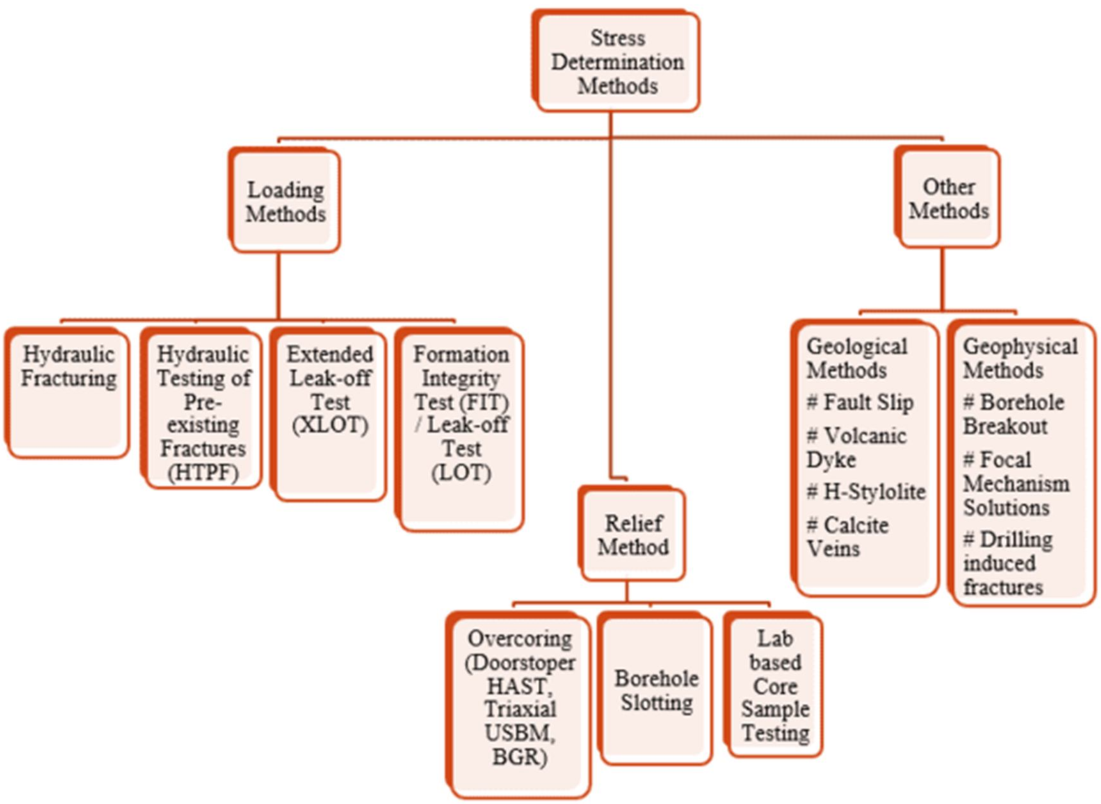



Figure. 15 Different methods for in situ rock stress measurement

The methods can also be classified by their operational type and an indication of the rock volume (Representative Elementary Volume or REV) involved in their use [33]. The main factors limiting the rock volume for which the stress field may be judged to be representative are the vertical depth variation, the geological boundaries, and the presence of major faults. The classification is presented in Table. 3.

Table. 3 Operational type and rock volume for different rock measurement methods

| Category | Method | Rock Volume ($m^3$) |
|---|---|---|
| Methods performed in boreholes | Hydraulic fracturing | 0.5 – 50 |
| | Overcoring | $10^{-3} – 10^{-2}$ |
| | Hydraulic tests on pre-existing fractures (HTPF) | 1 – 10 |
| | Borehole breakouts | $10^{-2}$ – 100 |
| Methods performed using drill cores | Strain recovery methods | $10^{-3}$ |
| | Core-disking | $10^{-3}$ |
| | Acoustic methods (Kaiser effect) | $10^{-3}$ |
| Methods performed on rock surfaces | Jacking methods | 0.5 – 2 |
| | Surface relief methods | 1 – 2 |
| Analysis of large scale Geological structures | Earthquake focal mechanism | $10^{9}$ |
| | Fault slip analysis | $10^{8}$ |
| Other | Relief of large rock volumes (back analysis) | $10^{2} – 10^{3}$ |

## IX. APPLICABILITY OF DIFFERENT STRESS MEASUREMNET METHODS

Reference [33] summarises various applicability of different stress measurement methods as listed in Table. 4.

Table. 4 Applications of different in situ rock stress measurement methods.

| Method | 2D/3D | Advantages | Limitations | Suitable for |
|---|---|---|---|---|
| Overcoring | 2D/3D | Most developed technique in both theory and practice. | Scattering due to small rock volume. Requires drill rig. | Measurement depth down to 1000m. |
| Doorstopper | 2D | Works in jointed and highly stressed rocks. | Only two-dimensional. Requires drill rig. | For weak or highly stressed rocks. |
| Hydraulic Fracturing | 2D | Measurement in existing hole. Low scattering in the result. Involves a fairly large rock volume. Quick. | Only two dimensional. There are theoretical limitations in the evaluation of $\sigma_H$. disturbs water chemistry. | Shallow to deep measurements to obtain stress profiles. |
| HTPF | 2D/3D | Measurements in existing hole. Can be applied when high stresses exist and overcoring & hydraulic fracturing fail. | Time consuming. Requires existing fractures in the hole with varying strikes and dips. | Of interest in situations where other methods fail. |
| Core disking | 2D | Existing information, which is obtained already at the drilling stage. | Only qualitative estimation. | Estimation of stress at early stage. |
| Borehole breakout | 2D | Existing information obtained at an early stage. Relatively quick. | Restricted to information on orientation. Theory needs to be further developed to infer the stress magnitude. | Occurs mostly in deep holes. |
| Focal mechanisms | 2D | For great depths. | Information only from great depths. | |
| Kaiser effect | 2D/3D | Simple measurements | Relatively low reliability. | Rough estimations |
| ASR/DSCA/ RACOS | 2D/3D | Usable for great depths. | Complicated measurements on the microscale, sensitive to several factors. | Estimation at great depth. |
| Back calculation | 2D | Quick and simple. High certainty due to large rock volume. | Theoretically not unique solution. | Can only be used during construction. |
| Analysis of Geological data | 2D/3D | Low cost | Very rough estimation, low reliability. | At early stage of project. |

## X. MASUREMENT OF IN-SITU ROCK STRESS

Any surface or subsurface project involving considerable size, budget and or complex geological condition need precise estimation of rock stress magnitudes and directions. The methods described in preceding chapters does not prove to be sufficient and calls for minute in situ rock stress measurement. Such rock stress measurement can only be attained by undertaking in situ rock mechanical test within boreholes, drilled within the rock mass. Among the various categories of methods for in situ rock stress measurement, most acceptable and commercially available methods are Overcoring, Hydraulic Fracturing (HF) and Hydraulic Test in Pre-existing Fractures (HTPF). The reliability of rock stress measurements/ estimations is partially dependent on the measuring technique and equipment, and partially dependent on the nature of rock masses. [33]

The 'International Society for Rock Mechanics and Rock Engineering (ISRM)' suggested methods for rock stress estimation, published in a Rock Stress Estimation Special Issue of the International Journal of Rock Mechanics and Mining Sciences, 2003, Volume 40, Issue 7–8. According to the commercial application of stress measurement, two methods dominate the others: hydraulic methods and borehole relief methods. [33]

The ISRM Suggested Methods (SMs) for rock stress measurement methods are as follow.

### *A. Overcoring Method*

Overcoring method measures in situ rock stress from a borehole. The principle of rock stress measurement is based on measuring strain when a sample of rock is released from the rock mass and the stresses act upon it. From a borehole, complete three-dimensional stress tensor can be calculated from measured strain and elastic properties of the rock. Overcoring method requires homogeneous rock close to bottom portion of the pilot hole (36 mm dia hole). Also, the rock mass should be free from any open fractures. If such condition does not prevail, the 76mm borehole is extended for another 1–3 m.

According to [34], all the steps of Overcoring method is presented in Figure. 16. The strain difference is measured before, during, and after overcoring and can be related to the in situ stress state assuming continuous, homogeneous, isotropic, and linear-elastic rock behaviour. The test results comprise the complete stress tensor, expressed as three principal stresses (magnitudes and orientations) which can be transformed to any preferable coordinate system. Normally, several sets of measurements are taken with 0.5 – 1.0 m spacing, and the results averaged using the stress tensor components of a common coordinate system.

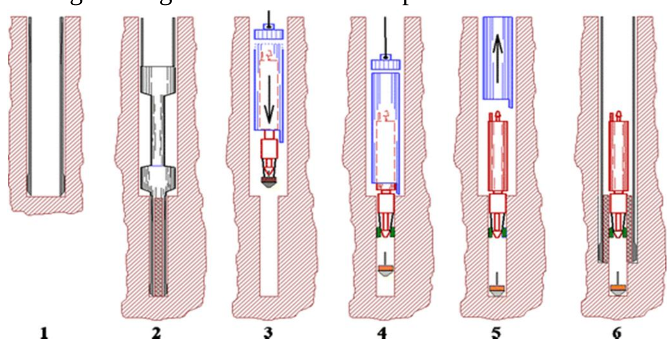



Figure. 16 Installation and measurement procedure for overcoring with the Borre probe. (1) Advance 76mm diameter main borehole to measurement depth. Grind the hole bottom using the planing tool. (2) Drill 36mm diameter pilot hole and recover core for appraisal. Flush the borehole to remove drill cuttings. (3) Prepare the probe for measurement and apply glue to strain gauges. Insert the probe in installation tool into hole. (4) Tip of probe with strain gauges enters the pilot hole. Probe releases from installation tool through a latch, which also fixes the compass, thus recording the installed probe orientation. Gauges bonded to pilot hole wall under pressure from the nose cone. (5) Pull out installation tool and retrieve to surface. The probe is bonded in place. (6) Allow glue to harden overnight. Overcore the probe and record strain data using the built-in data logger. Break the core after completed overcoring and recover in core barrel to surface. [34]

### *B. Stress calculation for Overcoring method*

In this method, solving for the in situ stress involves expressing global coordinate stress components in the local borehole system and then accounting for the stress redistribution around the hole. From these secondary stresses, the strains at the borehole wall for each of the gauge orientations are determined, using Hooke's law and is expressed as.

$$\sigma_{local} = [B]\sigma_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

$$\varepsilon_k = [F]\,\sigma_{local} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(23)$$

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Where $\sigma_{local}$ is the local (in situ) stress state tensor, $\sigma_{ij}$ is the global (in situ) stress tensor ($\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{yz}$, $\tau_{zx}$), [B] is a transformation matrix, [F] is a matrix accounting for stress redistribution around the borehole as well as Hooke's law (both E and ν included), and $\varepsilon_k$ are the strains for each of the strain gauges of the probe (k = 1,2,….9).

As these strains are measured (the strain differences due to overcoring), the in situ stresses can be calculated by combining Equations (22) and (23) and inverting the obtained matrix equation. The details of the formulation can be found in [1]. Measurements from at least six independent directions are required to determine the stress tensor. [34]

### *C. Hydraulic Fracturing (HF) and/or Hydraulic Testing of Pre-existing Fractures (HTPF)*

Hydraulic Fracturing (HF) and Hydraulic Testing in Pre-existing Fractures (HTPF) methods use hydraulics to stimulate the rock surrounding a borehole to determine the stress field. Both methods use the same type of equipment, including straddle packers, impression packers and high-pressure pumps to generate high-pressure water during either the formation of new fractures or reopening of pre-existing fractures.

To be successful, Hydraulic Fracturing (HF) test requires borehole section free from any fractures. Such section should be a few metres long. This method can not be successfully applied to any region with very high in situ stress, such as core disking is encountered during drilling. Also, various geological weak planes like foliations can reduce success rate of this method.

While conducting HTPF tests, a sufficiently large number of fractures with different strike and dips are required with planar fractures geometry. If a complete stress tensor determination is required, a minimum of eight tests are necessary. The fracture size should be suitable enough wherein normal stress can be assumed to be uniform. The HTPF method relies only on four field parameters; test depth, shut-in pressure, dip and strike of the tested fracture. The method is valid for all borehole orientations. It is independent of pore pressure effects and does not require any material property determination.

For both HF and HTPF methods, a section of a borehole is sealed off by use of two inflatable rubber packers sufficiently pressurized so that they adhere to the borehole wall. Hydraulic fluid (typically water) is pumped under constant flow rate into the section, gradually raising the pressure on the borehole wall until a fracture is initiated in the rock, or a pre-existing fracture is mechanically opened. Pumping is stopped, allowing the interval pressure to decay. Several minutes into the shut-off phase, the pressure is released and allowed to return to ambient conditions. The pressure cycle is repeated several times maintaining the same flow rate. Key pressure values used in the computation of the in situ stresses are picked from the pressure–time record. The repeated cycles provide redundant readings of the key pressures. The attitude of the induced HF, or of the pre-existing fracture, is obtained using an oriented impression packer or one of several geophysical logging methods. HF orientation is related to the directions of the principal stresses. With HF, data from the pressurization and fracture orientation phases of the test are used to obtain the in situ principal stresses in the plane perpendicular to the borehole axis. With HTPF, tests yield an evaluation of the normal stress supported by fracture planes with different known orientations, and the complete stress evaluation results from an inversion of these results. [35]

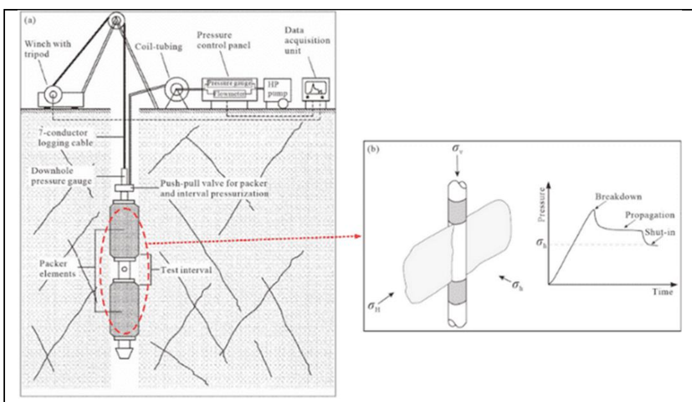


Figure. 17(a) Schematic view of a hydraulic fracturing system (from Rummel et al. 2002).

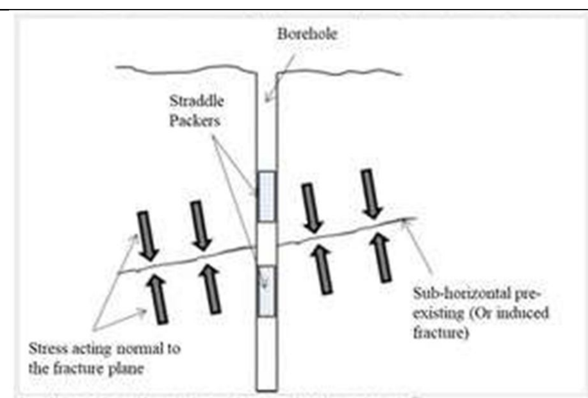


Figure. 17(a) Schematic view of a hydraulic fracturing of pre-existing fractures (HTPF) system (from Gaines, et al. 2012).

*D. Stress Calculations for HF and HTPF*

*1) Hydraulic Fracturing (HF)*

The calculations of in situ principal stresses given hereafter are for vertical boreholes (commonly used for HF), and for tests yielding vertical fractures (both within ±15° or so). This corresponds to the case in which the vertical stress component acts along a principal direction.

- Least horizontal principal stress magnitude and direction ($\sigma_h$):

Vertical HFs are oriented perpendicular to the direction of the minimum horizontal principal stress. The shut-in pressure (Ps) is the pressure needed to equilibrate the fracture-normal stress, which in this case is $\sigma_h$.

$$\sigma_h = Ps \quad \text{......................(24)}$$

The direction of $\sigma_h$ is obtained directly from the azimuth of the HF:

$$\sigma_h \text{ direction} = \text{direction of normal to vertical hydraulic fracture} \quad \text{................ (25)}$$

- Largest horizontal principal stress direction and magnitude ($\sigma_H$):

This principal stress is calculated based on the assumption of linear elasticity and insignificant effect of fracturing fluid rock infiltration: In the absence of pore fluid in the rock mass, the maximum horizontal principal stress magnitude is given by Eq. 26.

$$\sigma_H = T + 3\,\sigma_h - P_b \quad \text{....................(26)}$$

where T is the tensile strength of the tested rock, and $P_b$ is the breakdown pressure.

In saturated rocks with low permeability, so that there is no percolation of the fracturing fluid in the formation before fracture opening, it is often assumed that pore pressure is unaffected by the state of stress and that Terzaghi's effective stress concept applies to tensile ruptures. In this case Eq. 27 is employed:

$$\sigma_H - P_o = T + 3(\sigma_h - P_o) - (P_b - P_o) \quad \text{...........(27)}$$

More elaborate pore pressure corrections have been proposed by Detournay et al, (1989) and Schmitt and Zoback, (1989)

The maximum horizontal principal stress is perpendicular to the $\sigma_h$ direction:

$$\sigma_H \text{ direction} = \text{direction of vertical hydraulic fracture strike} \quad \text{................(28)}$$

When extracted core is not available, or laboratory tests are not feasible, or when tension tests appear to yield an unreasonable value for use in Eqs. 26 or 27, an alternative relation has been used, invoking the fracture reopening pressure ($P_r$). This pressure is assumed to be that at which the induced fracture, which has closed completely after initial pressure cycle, reopens. This time, however, fracture reopening does not have to overcome the tensile strength T; and thus Eq. 27 becomes,

$$\sigma_H - P_o = 3(\sigma_h - P_o) - (P_r - P_o) \quad \text{......... (29)}$$

*2) Hydraulic Testing of Pre-existing Fractures (HTPF)*

With the HTPF method, the stress tensor is evaluated so as to best fit the normal stress measurements obtained for all the tested fractures. This requires a parameterization of the stress field and the definition of a misfit function.

- Parameterization of the stress field

It takes six parameters to characterize the complete stress tensor at any given point. Hence a complete stress determination requires theoretically a minimum of six different tests on fractures with different dip and azimuth in order to solve the linear system provided by the following equation.

$$\sigma^m{}_n = \sigma(X_m) n_m n_m \quad \text{.................. (30)}$$

Where $X_m$ is the location of the *m*th test, $\sigma^m{}_n$ is the measured normal stress supported by the fracture plane with normal $n_m$ and $\sigma(X_m)$ is the stress tensor at $X_m$. m varies from 1–N; for a total of N complete HTPF measurements (normal stress and fracture plane orientation determination).

However, because measurements are never exact and always encompass some uncertainty, it is always desirable to conduct more tests than there are unknowns. If a complete stress tensor determination is required, a minimum of eight tests are necessary. When less than eight tests are available, efforts are undertaken to decrease the number of unknown for the stress tensor. For example, in some instances, it may be assumed that the vertical direction is principal (this leaves only four unknowns) and that the vertical component is equal to the weight of overburden (this leaves only three unknowns). In the latter case, only five HTPF measurements will be necessary for the stress determination, but the vertical component will not be determined directly from the HTPF results.

It may also happen that the distances between the various tests are so large that stress gradients must be considered. Then, the number of unknowns increase and so does the minimum number of tests required for a satisfactory determination. It has found to be convenient to parameterize the stress field by assuming a linear variation along the borehole axis in which measurements are conducted:

$$\sigma(X_m) = \sigma(X_0) + (X_m - X_0)\alpha \quad \dots\dots\dots\dots\dots\dots (31)$$

Where the stress at point Xm may be expressed as a linear function of the stress at point X0 and α is the stress gradient along the borehole axis.

- Definition of the misfit function

The misfit function defines the discrepancy between observed and computed values as determined with a possible stress model. The solution is defined as the stress model which minimizes the misfit function, i.e. the model which is the closest to all the measurements. The misfit must include both errors in normal stress determination and in fracture orientation determination. Various misfit functions have been proposed in the literature. A more complete discussion is offered at Cornet, (1993).

### *C. Integration of HTPF with Hydraulic Fracturing (HF):*

While the HTPF method may be used completely independent of the HF method, it has been found convenient to combine both methods when the borehole is parallel to a principal stress direction (generally, the vertical direction). Indeed, in such cases, the HF method yields accurate determination of the minimum principal stress direction and magnitude, while the HTPF results help constrain the magnitudes of the maximum horizontal principal stress and the vertical stress components, without any consideration of either pore pressure or tensile strength. In such instances, only two unknowns exist in Eq. 30, so that only three or four tests on pre-existing fractures are needed to complement the HF tests (a minimum of three is required for redundancy considerations). [35]

## XI. CONCLUSIONS

The foregoing sections have given a brief review of origin, mode of occurrences and significance of in situ rock stresses within the Earth’s crust. Also, the available methods to estimate / measure in situ rock stress magnitude and direction have been covered. Following conclusions can be drawn out of the preceding discussions.

1) Estimation of the in situ rock stress field is the most unpredictable and complex phenomenon related to any rock engineering project.
2) Various factors control the generation and distribution of rock stresses in regional as well as local scale. The dominant factors include Earth’s tectonic movement, weight of overburden rock, effect of topography, disposition of geological structures etc.
3) During preliminary investigation phases, magnitudes of vertical and horizontal stresses can be calculated from overburden depth, Rock density and deformation modulus of rock. The directions of horizontal stresses can be obtained from orientation of various geological structures in the field.
4) For final stage of design and construction of any rock engineering project, measurement of in situ rock stress tensor in form of magnitudes and directions of three principal stresses (i.e. σ1, σ2 and σ3) is required. This becomes obvious when the project is large sized and or situated in complex geological region.
5) There exist many methods for in situ rock stress measurement, but the widely used methods are Overcoring method, Hydraulic Fracturing method and Hydraulic testing in pre-existing fractures (HTPF) method
6) All three methods have limitations. But application of Hydraulic Fracturing (HF) in conjunction with Hydraulic testing in pre-existing fractures (HTPF) can reveal the complete three-dimensional scenario of in situ rock stresses, prevalent in any ground.

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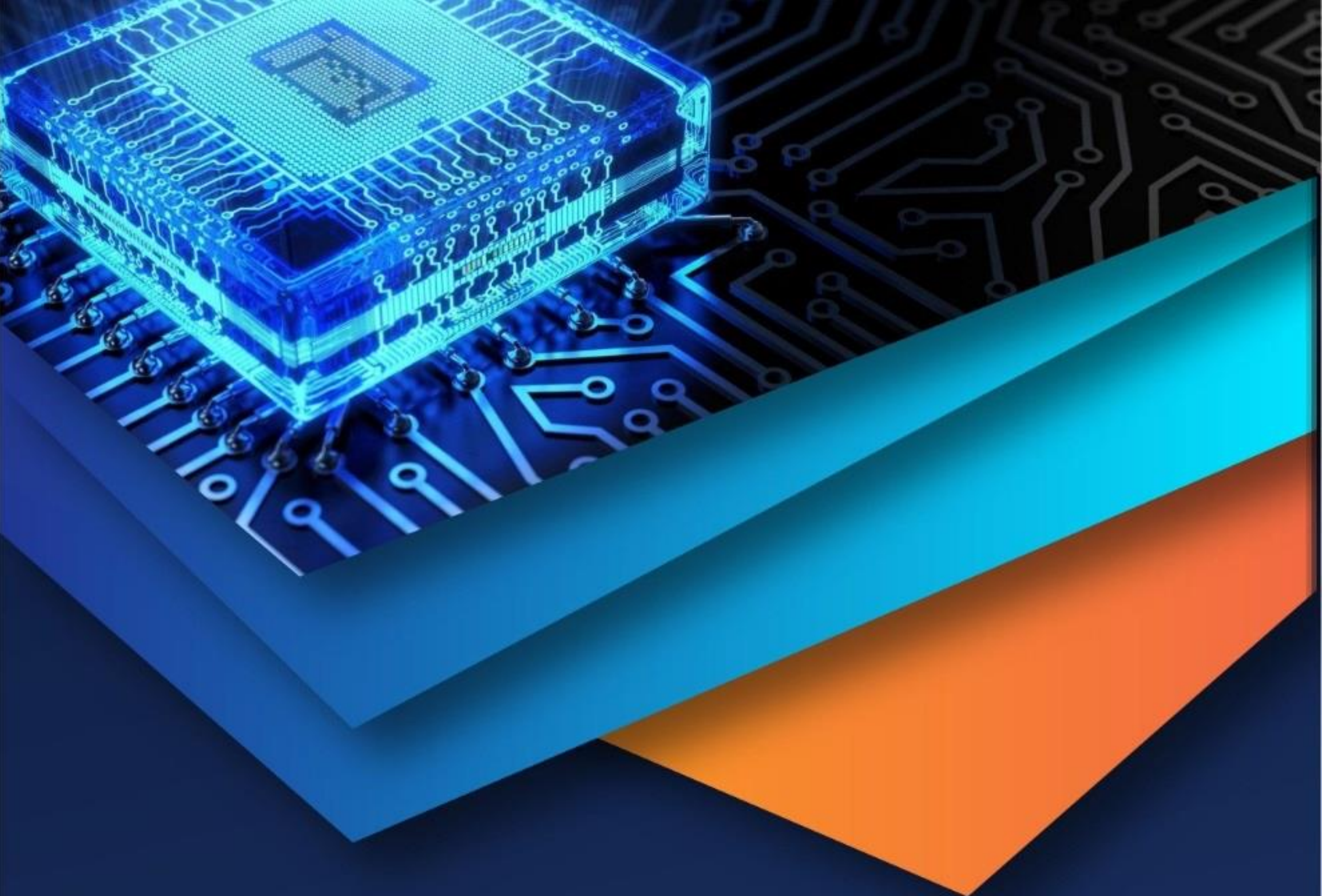


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