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Rock Stress Measurement Methods in Rock Mechanics—A Brief Overview

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Abstract

The current brief review paper on rock stress measurement methods is very crucial factors in mining, civil infrastructure, geothermal energy, nuclear underground disposal, large underground oil storage caverns, etc as well as in geology and geophysical area. Measurement of *in situ* rock stress is a very challenging and difficult quantity and not possible to measure directly. Measure the deformation or displacements or hydraulic factors by perturbing the rock and converting the measured quantity into rock stress. There are two main categories for measuring methods: direct and indirect methods. The most common methods of direct *in situ* stress techniques are briefly described including advantages, disadvantages and limitations. Moreover, authors included the application of Artificial Intelligence (AI) for rock stress measurement methods.

Keywords

Rock Stress, *In Situ* Stress, Hydraulic Fracturing, Flat Jack and Artificial Intelligence

1. Introduction

Understanding of the rock stress is of great importance and central concern in rock mechanics. Rock stress has a strong connection to a variety of issues in civil, mining, petroleum engineering, and geology and geophysics. Table 1 listed of activities where rock stresses play a critical role [1] [2]. The stability of underground openings such as mines, shafts, tunnels, or caverns in civil and mining engineering projects is largely determined by the distribution and magnitude of rock stresses [2] [3]. Excessive magnitude of rock stress around underground openings (stress concentrations) can result in the failure of the rock mass locally or on a larger scale, causing roof collapse, sidewall movement and/or ground subsidence [4] [5] [6]. There are a number of publications published since long time regarding the rock stress problems in civil and mining projects and a large amount of literature exists on the subject of rock stresses and these factors [2] [6]-[17].

Rock stress is enigmatic and fictitious quantities and can be classified into *in situ* stresses and induce stresses (**Figure 1**). The other terms used for *in situ* stress are natural, primitive or virgin, which exist in rock mass before any disturbances of human activities. Alternatively the induce stresses are generated due to human activities in or on the rock for build of engineering structures, *i.e.*, tunnel, surface or underground mining, caverns, highway slopes etc [18]. Overall, *in situ* stresses are product of geological events which have several cycle of thermal, mechanical and physicochemical geological processes and majorly contributed for *in situ* stresses. Different classifications of *in situ* stresses have been proposed by several authors. According to Voight (1966), *in situ* stresses can be divided into two main categories: gravitational and tectonic [19]. This tectonic stress can be further broken down into two subgroups: current and residual, whereas Obert (1968) composed *in situ* stresses into internal and external stresses [20].

Table 1. Activities requiring knowledge of rock stress [1] [21].

Civil and Mining Engineering
Stability of underground excavations (tunnels, mines, caverns, shafts, stopes, haulages)
Drilling and blasting
Pillar design
Design of support systems
Prediction of rock bursts
Fluid flow and contaminant transport
Dams
Slope stability
Energy development
Borehole stability and deviation
Borehole deformation and failure
Fracturing and fracture propagation
Fluid flow and geothermal problems
Reservoir production management
Energy extraction and storage
Geology/Geophysics
Orogeny
Earthquake prediction
Plate tectonics
Neotectonics
Structural geology
Volcanology
Glaciation

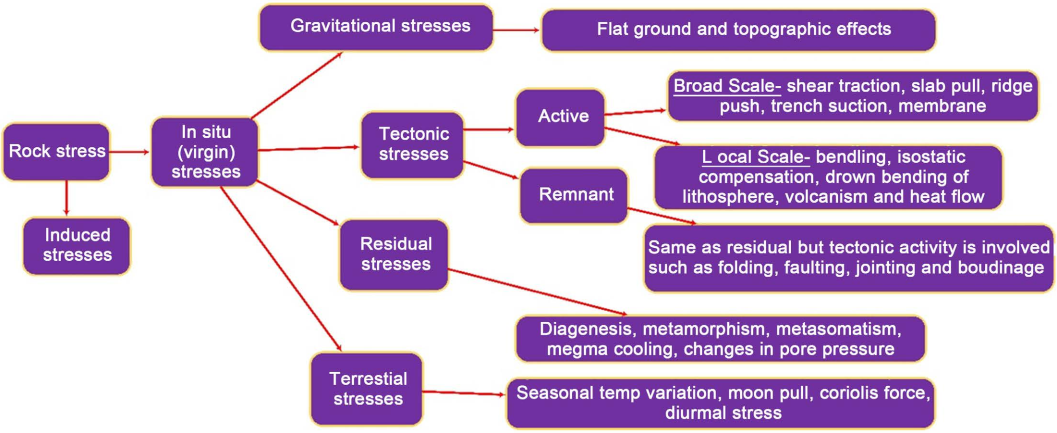

Figure 1. Rock stress types and sources of *in situ* stress.

External stresses contained gravitational and tectonic stresses (regional stresses), whereas internal stresses contained of residual stresses. Various other author classified the *in situ* stresses almost in same categories [17] [22] [23] [24]. This paper included the general agreement of all authors and followed the Fairhurst, (2003) classifications.

The details of each types of *in situ* stress can be obtained through the reference book of Amadei and Stephansson (1997) [1]. One of the sources of *in situ* stress is tectonic forces. Tectonic stress can be felt like earthquake (*i.e.*, active tectonic stress), however, it can occur silently in most cases (*i.e.*, passive tectonic stress) either at plate-scale or broad regional scale as shown in **Figure 2** [25]. Passive tectonic stress may create greater vertical and horizontal stress thus it is the safety key for underground constructions, *i.e.*, mining drift, caverns and tunnels etc. [26].

Residual stresses (lock-in stresses) are the stresses that persist in a material even when no external loads or temperature gradients are present. These stresses are not caused by any external stimuli, but rather are inherent in the material itself. Residual stresses and strains can build up strain energy internally, which can have a major impact on the stability of rock structures, such as underground openings and surface excavations [25]. The stress brought by gravity's force on a rock mass is known as gravitational stress. This stress is mainly caused by the weight of the overlying rocks and the self-weight of the rock mass. Gravitational stress can cause a significant amount of stress to be present in the rock mass, which can lead to instability and potential failure of the rock mass [27]. Terrestrial stress is the sum of all the stresses acting on a rock mass, including gravitational, tectonic, residual, and atmospheric stresses. These stresses can cause deformation in the rock mass, resulting in instability and potential failure [21] [28].

Heidbach *et al.* (2018) presented the present-day *in situ* stress field on world map [29]. This project initiated in 1986 and continuous working in different phases. The latest phase end in 2016 and provided the World Stress Map (WSM)

[29]. Authors outlined the 2016 WSM database release in detail and analyze the patterns of global and regional stress (**Figure 3**). For example, the WSM contained data on the present-day stress field of Saudi Arabia, primarily from petroleum wells in the country. According to the map, the majority of Saudi Arabia is in a region of normal to high tectonic stress, with some areas of very high stress in the northeast and southwest. Additionally, the WSM indicates that the region has seen a lot of activity in recent years, with many earthquakes recorded in the region over the past decade. This paper classifies methods under two main categories direct *in situ* measurement methods and indirect methods as shown in **Figure 4**. This paper will discuss methods of both categories with an emphasis on review of direct methods.

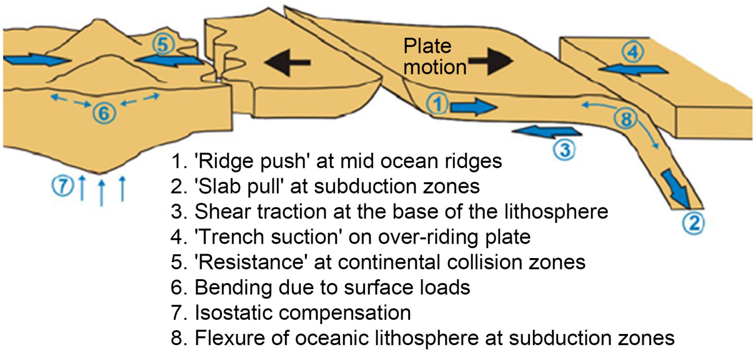

Figure 2. Forces controlling the present-day tectonic stress field at the plate-scale (large arrows) and broad regional scales (small arrows).

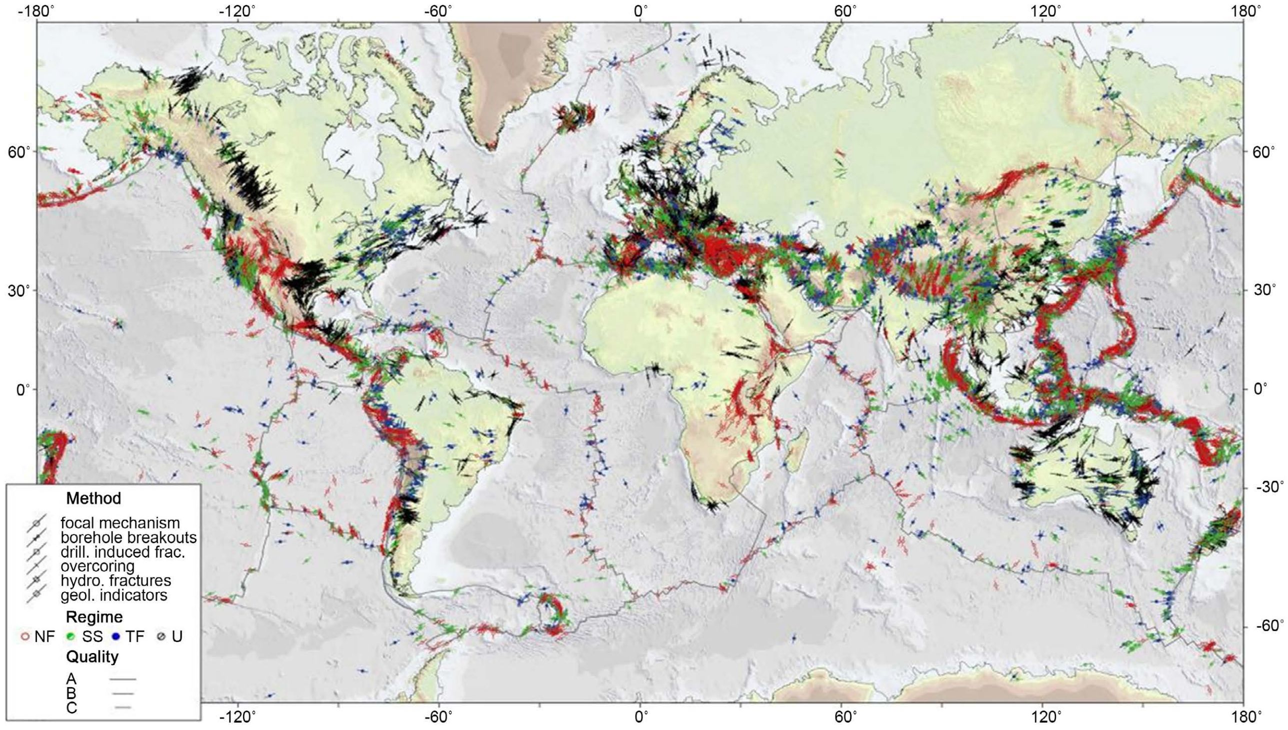

Figure 3. The World Stress Map (WSM) 2016 [29].

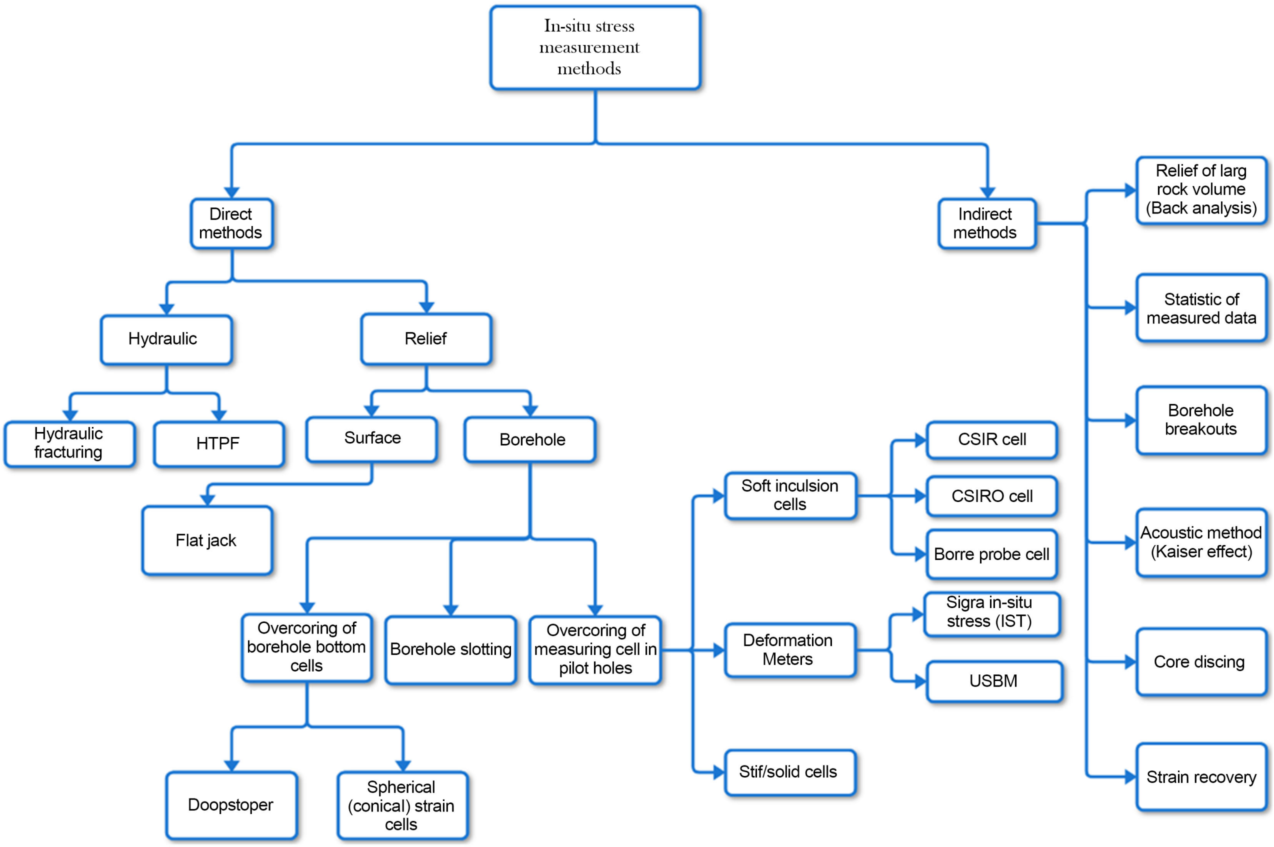

Figure 4. Classification of *in situ* stress measurement methods [33].

2. *In Situ* Measuremnt Methoeds

There are two main categories for *in situ* stress measurement methods which are indirect and direct methods. The indirect methods based on the observation of rock behavior without any major disturbance of rock, *i.e.*, core discing, statistics data, borehole breakout etc. Whereas disturb the rock by develop crack or crack opening, and induced strain. The examples are Hydraulic fracturing and relief methods (**Figure 4**).

In this paper, brief review description is presented for indirect methods and direct methods, but more emphasized on direct methods. Indirect methods of measuring *in-situ* stress include the use of statistics from collected data (database), back analysis of large rock volumes, core discing, the acoustic method (Kaiser effect), strain recovery methods and borehole breakouts. Each of these methods has its own advantages and limitations, and they can be used in combination to achieve a more comprehensive understanding of the subsurface conditions (**Table 2**). For example, statistic of measured data (database) can be employed in hydraulic fracturing field data to improve the accuracy of determining the shut-in pressure or estimating the *in situ* tensile strength of hydraulic fractures [30] [31]. While core discing can provide detailed information about the stress state of a specific rock formation [32] as shown in **Figure 5**. The conditions for core discing are high *in situ* stresses and the brittle rock. The thickness of the chips depends on stress intensity. As stresses increases, the size of disc decreases and in extreme cases, the discs can become so thin. Borehole breakout is a phenomenon that occurs when the rock is unable to sustain the compressive stress concentrations around a borehole (**Figure 6**). Borehole breakouts can be used to identify the direction of maximum horizontal stress. This results in breakage of the wall on two diametrically opposed zones, called 'breakout'. In relief method the large rock volumes (back analysis) can be used to estimate the magnitude of the *in-situ* stress [33] [34]. The main issue with relief methods is that they only involve a small volume of rock, making the measured stresses vulnerable to shifts due to tiny changes in the mineral composition and rock grain size. To obtain more accurate results, it is possible to measure the local or average stresses over a larger volume of rock by overcoring multiple strain gages in a large-diameter bored raise at various heights [35] [36]. Over the years, the Acoustic method (Kaiser Effects) approach has been researched as a viable technique for identifying *in situ* stressors. The approach is based on an observation Kaiser made in 1950 and strain recovery methods are used to determine the anisotropy of the rock formation and the orientation of the principal stress axes.

Table 2. Advantages and limitations of indirect *in situ* stress measurement methods.

Method	Advantages	Limitations
Statistic of Measured Data (Database)	Can be used to analyze a large amount of data quickly and efficiently.	Results can be affected by outliers or incorrect data.
Core Discing	Can be used to determine rock properties such as strength and stiffness. Operated at 10^{-3} m^3 rock volume.	Sample size is limited and may not be representative of the entire formation.
Borehole Breakouts	Can be used to determine the orientation of stress in the rock surrounding the borehole. Operated at 10^{-2} - 10^2 m^3 rock volume.	Results can be affected by borehole deviation and the presence of drilling-induced fractures.
Relief of Large Rock Volumes (Back Analysis)	Can be used to determine the location and size of large rock volumes. Operated at 10^2 - 10^3 m^3 rock volume.	Results can be affected by the accuracy of the data and the assumptions made during the analysis.
Acoustic Method (Kaiser Effect)	Can be used to determine the mechanical properties of rock. Operated at 10^{-3} m^3 rock volume.	Results can be affected by the presence of fluid in the pores of the rock.
Strain Recovery Methods	Can be used to determine the deformation of rock. Operated at 10^{-3} m^3 rock volume.	Results can be affected by the accuracy of the data and the assumptions made during the analysis.

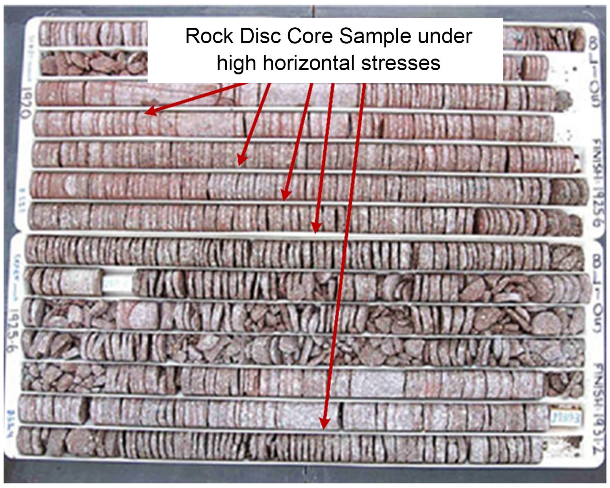

Figure 5. Core discing rock sample from core drilling.

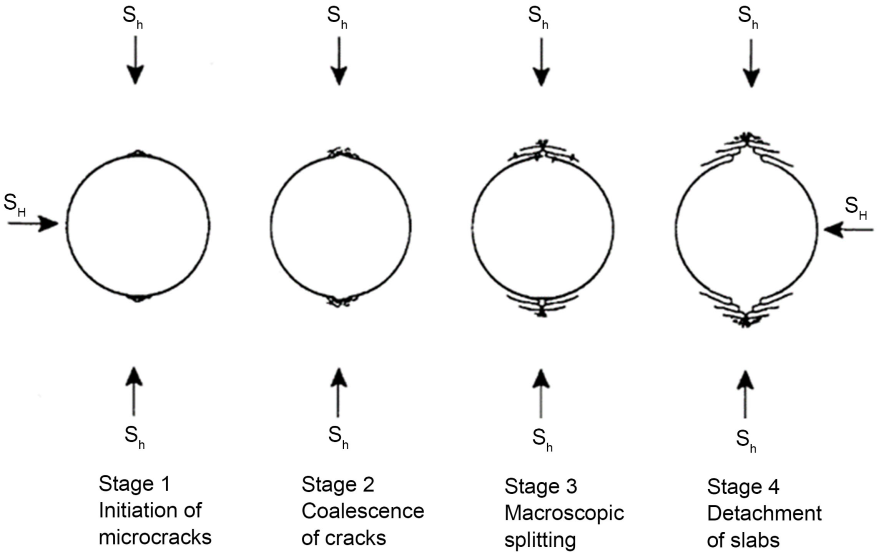

Figure 6. Expansion of borehole breakouts.

3. Hydraulic Methods

Hydraulic methods are one of the most widely used techniques for measuring *in-situ* stress levels. This method involves injecting pressurized liquids into an existing fracture in a rock formation, causing it to widen and create new fractures. By measuring the pressure response of these fractures, the stress levels of the material can be determined. Conventional or classical hydraulic fracturing and hydraulic tests on pre-existing fractures (HTPF) are two of the most used methods for measuring stress levels using hydraulic methods.

3.1. Conventional (Classical) Hydraulic Fracturing (HF)

Hydraulic fracturing (HF) was used in the 1940s, originally to stimulate production from low permeable oil-bearing formations. In 1957, Hubbert and Willis developed the classical concept of hydraulic fracturing to be useful for *in-situ* stress measuring. HF is the best-known method to evaluate *in-situ* stress at deeper levels [33]. A straddle packer is used to seal off a section of a borehole, which is usually no longer than 1 meter in length. This sealed off section is then pressurized with a fluid, usually water, at a slow rate. This causes tensile stresses to build up at the borehole wall until it ruptures, initiating a hydro fracture.

HF is used to measure the *in-situ* stress of subsurface rock by propagating a fracture in the rock. Two fractures begin on opposing sides of the borehole's perimeter, with the fracture plane typically parallel to the borehole axis. The direction of the fracture is identified by looking at the traces on the borehole wall, and it spreads in the direction of least resistance. The components recorded in a vertical borehole are two of the primary stresses, and this orientation is related to the direction of the highest horizontal stress in vertical or sub-vertical boreholes [33]. This technique is two-dimensional and only measures the greatest and least normal stresses in the plane perpendicular to the borehole axis as presented in **Figure 7**. The setup of HF is provided under the next method which is hydraulic tests of pre-existing fractures (HTPF) since both share same setup as presented in **Figure 8**.

HF is an effective and cost-efficient *in-situ* stress measurement method, allowing for direct and accurate measurements at depths not accessible by other methods. It can measure stress in multiple orientations, providing a more comprehensive analysis of the stress field and its impact. Additionally, it is fast and non-destructive, making it a great option for stress measurements [37]. HF method can provide high confidence measurement of *in-situ* stress at several kilo meters depths [33]. "Rummel has successfully determined *in situ* stresses by hydraulic fracturing at a depth of approximately 6 km, using aluminum packers". So far, hydraulic fracturing has been successfully used to measure *in-situ* stress at a depth of up to 9 km. **Figure 8** shows the technique of HF [38].

On the other hand, the main drawback of using hydraulic fracturing as an *in-situ* stress measurement method is that it has the potential to cause damage to the surrounding rock. Additionally, the measurements obtained may be affected by factors such as temperature, pore pressure, and the presence of fractures in the rock [37].

3.2. Hydraulic Tests on Pre-Existing Fractures (HTPF)

Hydraulic Tests on Pre-existing Fractures (HTPF) is a method of measuring the horizontal stress in the rock mass by using hydraulic pressure to reopen existing fractures in the rock [39] [40]. It is used to determine the depth and orientation of existing fractures, and to measure the *in-situ* stress in the surrounding rock. The HTPF method can be used to measure the stress in the horizontal, vertical, and diagonal directions, and can provide information about the magnitude of the stresses in the rock [39]. Valette and Cornet presented both the theoretical foundations and practical implementation of HTPF, eliminating the need to create new fractures in the rock mass by instead re-opening existing fractures [33].

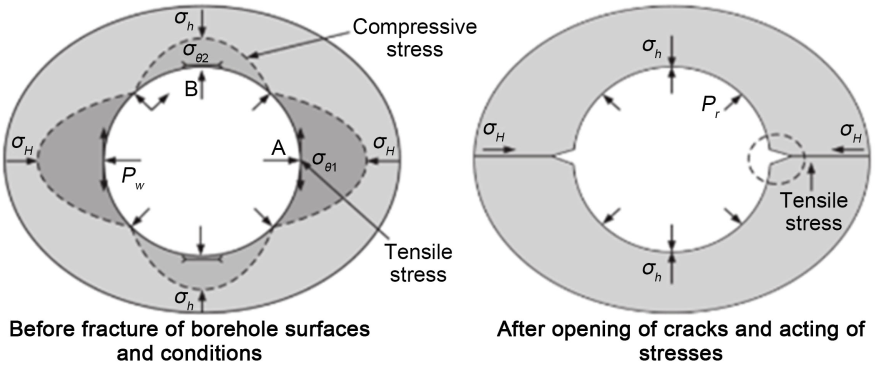

Figure 7. Stress distribution and HF around a borehole.

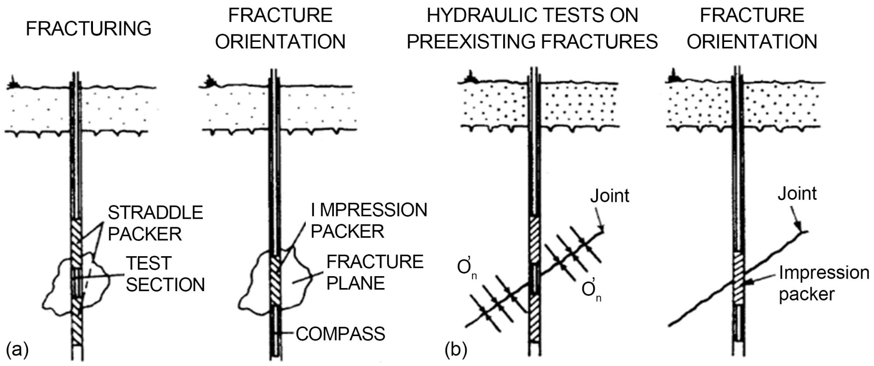

Figure 8. Vertical down hole *in situ* stress measurement by (a) HF (b) HTPF.

Combining the HF and HTPF methods is often beneficial when the borehole is parallel to one of the principal stresses (typically the vertical direction). The HF method can be used to accurately determine the direction and magnitude of the minimum principal stress, while the HTPF results can be used to estimate the magnitude of the maximum horizontal principal stress and the vertical stress components, without taking into account either pore pressure or tensile strength [40]. When cost and time are the most important considerations, the HTPF method should replace hydro-fracturing only when the borehole axis is not expected to be parallel to the principal stresses, or when there are significant weak points in the rock mass [41].

4. Relief Methods

The core purpose of relief methods is to detach a piece of rock from the stress environment in the surrounding rock mass and observe its response [1]. Relief methods can be categorized into two main groups: surface relief methods and borehole relief methods.

4.1. Surface Relief Methods

The rock's response to stress reduction is measured by surface relief techniques like the flat jack method and the curved jack methods, which measure the distance between gauges (pins) on the rock surface before and after the relief. This technique is most appropriate for measuring tunnel surfaces, and for more information, readers should refer to Amadei and Stephansson [33]. Surface relief methods have a few drawbacks. Humidity and dust can affect the accuracy of the gages or pins used. Additionally, the strain or displacement measurements are taken from a rock surface that could have been altered due to the effects of weathering or the excavation process. To connect localized stresses in the sides of the excavation to the more distant stress components, estimates of stress concentration factors must be utilized [1].

4.2. Flat Jack Method

Flat jack is one of the earliest techniques used in rock mechanics to measure *in-situ* stress within the rock mass [17]. During the 1950s and 1960s, it was suggested to assess the deformability of rock masses and it soon became widely used for calculating stresses [1]. One of the earliest methods of stress measurement in rock mechanics was the flat jack method [1]. Flat jacking is a method used to determine the *in situ* stress and also used in finding engineering properties of existing structures for structural evaluation. It is also used to determine compressive strength of masonry structures.

A flat jack is a thin, hydraulic load cell that is inserted into a typical mortar joint, in which a slot has been formed (**Figure 9**). When pressurized, the flat jack exerts stress on the surrounding masonry and by measuring surface deformations, information on the existing state of stress as well as the stiffness and strength of the masonry can be obtained. This method directly measures the actual state of compressive stress present within the masonry and is useful for determining stress gradients present within a masonry wall or column [42]. Mechanically, the route taken by the rock during a flat jack test can be represented as illustrated in **Figure 10**. The rock is thought to be elastic and to be compressed perpendicular to the jack surface [1]. The original spacing between two reference pins is marked as d_o, and the unidentified normal stress is marked as σ (at point A), When the slot is cut, the normal stress across the slot is reduced from σ to zero (at the free surface), and the distance between the pins is reduced by a magnitude of 2d (at point B). The pins restore to their initial position once the jack is pressured to the cancellation pressure pc. (**Figure 11**). The main benefit of the flat jacking technique was that it could be used with a basic extensometer (*i.e.*, located between points A and B) without having to create unique tools or sensors that could fit into a narrow hole [17].

Other advantages of flat jacking method are relatively straight forward, cost-effective, and can be implemented without needing to calculate the elastic modulus. On the other hand, flat jacking can only be used at the surface of the excavation, where rock is likely to be overly stressed, leading to an unreliable estimate [43]. A refined version of flat jacking method was done by Jaeger and Cook to make it suitable for measuring *in-situ* stress at deeper levels. The maximum depth they measure stress at was 7 m [17]. The advantages, disadvantages and limitation of flat jack methods are tabulated in **Table 3**.

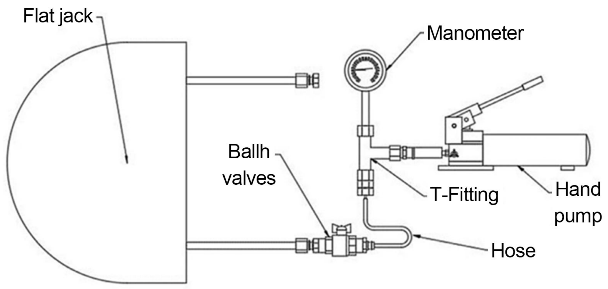

Figure 9. Flat jack and its components.

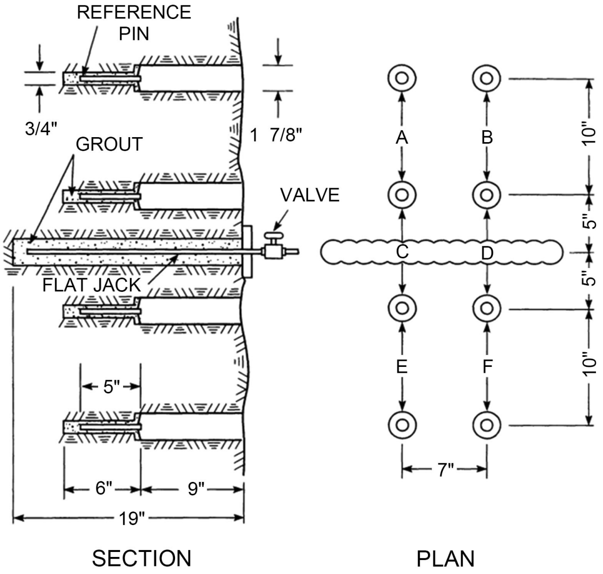

Figure 10. Flat Jack method.

Table 3. The advantages and disadvantages of flat jacking method.

Advantages
- Direct measurement of the compressive stress present within the masonry.
- Useful for determining stress gradients within a masonry wall or column.
- Can be used to determine the *in-situ* stress and compressive strength of masonry structures.
- Provides information on the existing state of stress as well as the stiffness and strength of masonry.
Limitations
- Requires the cutting of a slot in the masonry, which may cause damage to the structure.
- Can be time-consuming and labor-intensive.
- Requires specialized equipment and trained personnel to **perform** the test.
Suitable for:
- Evaluation of existing masonry structures such as walls and columns.
- Determining the *in-situ* stress and compressive strength of **masonry** structures.
- Structural evaluation of existing structures.

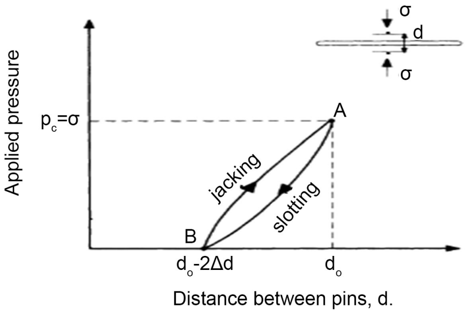

Figure 11. Path followed by a rock during a flat jack test. The rock is assumed to be elastic (linear or non-linear) and under compression in a direction perpendicular to the jack surface.

4.3. Borehole Relief Methods

Borehole relief methods (also known as overcoring methods) are used to measure *in situ* stress based on the stress relief around the borehole. This method involves drilling a borehole into the ground, then measuring the amount of relief in the external forces around the borehole. The relief of external forces can then be used to estimate the magnitude of the *in-situ* stress as well as the lateral pressure coefficient [44]. Borehole relief methods involve three types: overcoring of measuring cells in pilot holes, borehole slotting and overcoring of boreholes bottom cells.

Overcoring of Measuring Cells in Pilot Holes

Based on overcoring principle, overcoring of measuring cells in pilot holes can be broken down into three further categories: soft inclusion cells, deformation meters to measure wall displacements during overcoring, and stiff/solid cells [33].

- Soft Inclusion Cells

Soft inclusion cells are a technique used to measure *in-situ* stresses in rocks and soils by inserting a soft, pliable material into a borehole and measuring the deformation of the material to calculate the stress in the surrounding rocks [45] as shown in **Figure 12** and **Figure 13**.

The core concept of a soft cell is based on the linear elasticity theory for continuous, homogeneous, and isotropic rocks. By measuring at least six strain components on the borehole wall in different orientations, it is possible to determine the total stress tensor at the test location. Moreover, there are recognized theories for detecting stress in anisotropic rocks [33].

Based on the aforementioned concept, the most often used instruments are the CSIR cell, CSIRO cell, and Borre Probe cell [33]. In good rock conditions, these devices have a range of between 10 and 50 meters from existing free surfaces. Unbroken cores at least 150 to 300 millimeters in length are required to provide accurate results. In vertical water-filled boreholes up to depths of 500 to 1000 meters, many adaptations of the CSIR triaxial strain cell have been proposed and tested as presented in **Table 4** [1] [33].

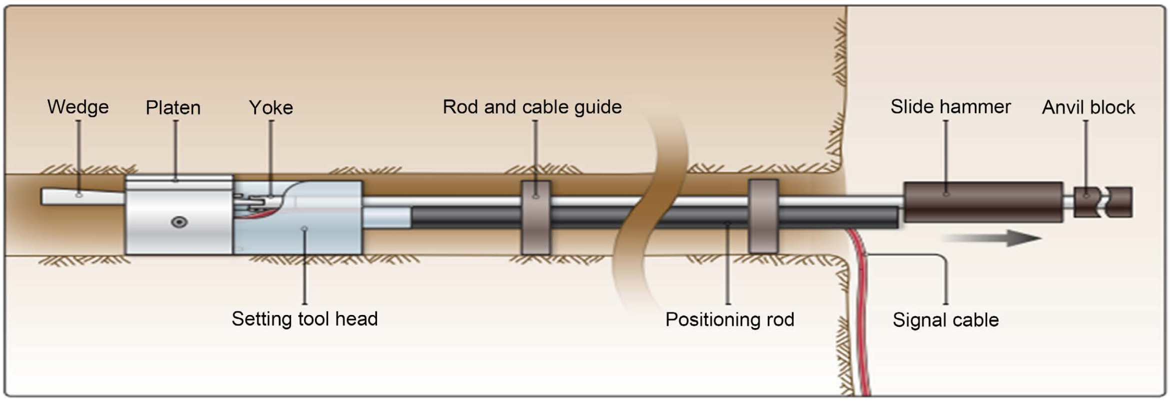

Figure 12. Soft Inclusion Stress Cell shown with mechanical installation tools.

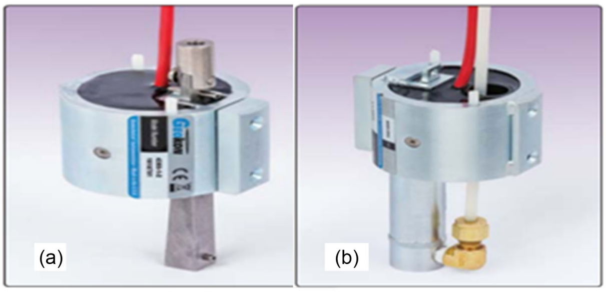

Figure 13. Soft inclusion stress cell (a) Mechanically activated (b) hydraulically activated.

Table 4. Characteristics of the most common soft overcoring cells.

Instrument	No of active gauges	Measuring depths	Continuous logging
CSIR cell	12	10 - 50 m	No
CSIRO cell	9/12	Up to 1000 m	Yes, by cable
Borre probe cell	9	Up to 30 m	Yes, built in data logger.

The Borre Probe is a soft stress cell, which is used to measure the stress field within a single borehole measurement. It works by measuring the strains induced by overcoring in the rock and then calculating the stress from the measured strains. The Borre Probe is different from other stress cells in that it does not measure displacement but rather strains. This means that the Borre Probe is more accurate than other stress cells in determining the stress field in a single borehole [39] [43]. All three of these instruments have the advantage of being able to measure the 3D state of stress from a single measurement point as shown in **Figure 14** and **Figure 15**. This is a major benefit that they all share [33].

- Deformation Meters

The theory behind deformation meters is the same as it is for soft inclusion cells for measuring displacements. After being over cored, the instrument is inserted into a pilot hole. Instead of measuring strain during overcoring, these sensors measure one or more variations in pilot hole diameter. The Sigra *in situ* stress tool and the USBM gage are two commercial deformation-type gages (IST) [33].

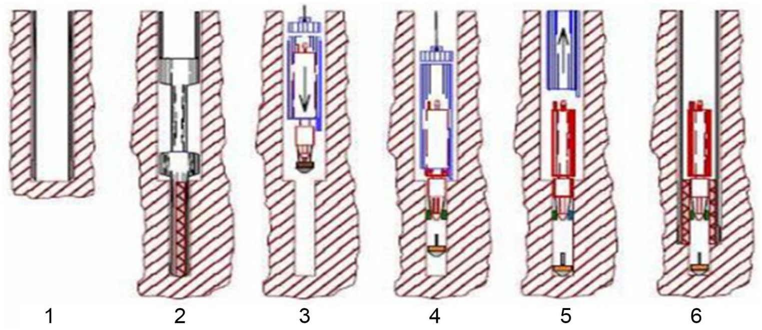

Figure 14. Principle of soft, 3D pilot hole overcoring measurement.

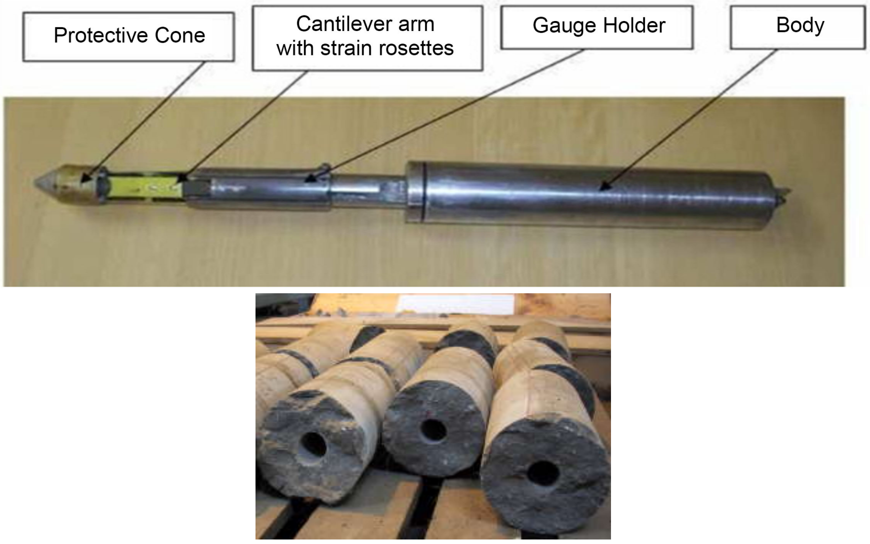

Figure 15. The Bore probe used for overcoring in pilot hole

- STIFF/SOLID CELLS

The disparity in material qualities between the rock and inclusion material causes stiff/solid cells, which are less common than the other two categories, to generally have problems [33]. Overcoring techniques performed in a borehole are among the most popular ways to relieve stress. The US Bureau of Mines stress gauge is one stress-measurement tool that makes use of the idea of overcoring. The USBM gauge is simply a cylindrical instrument with three pairs of pistons that are diametrically opposed and evenly distributed around the circumference. These pistons are coupled to cantilevers within the tool, which deflection is gauged by strain gauges. A tiny borehole, about the same diameter as the gauge (38 mm), is driven into the rock to be used with the USBM gauge. The pistons are initially tensioned to create adequate contact with the borehole walls before the gauge is placed into the hole (**Figure 16(a)**). Then, a drill bit with a bigger diameter (usually 150 mm) is used to overcore this small hole to a depth that extends at least one overcore diameter past the gauge (**Figure 16(b)**). A nearly stress-free circular rock zone will be produced by the overcoring process. The three sets of cantilevers monitor the radial deformation of the (inner) borehole as the stresses acting on this annular region are released [46].

Table 5 denoted all direct methods of in situ stress measurement techniques advantages and limitations.

5. Use the Artificial Intelligence *In-Situ* Stress Measurement

One way in which Artificial intelligence (AI) can be used in *in-situ* stress measurement is through the application of machine learning algorithms to data collected from boreholes [47] [48]. Boreholes are drilled into the subsurface and instruments are used to measure various parameters, such as rock strength, pore pressure, and temperature [47]. These data can be used to train machine learning models, which can then be used to make predictions about the stress state at other locations in the subsurface (**Figure 17**). Overall, AI can greatly enhance

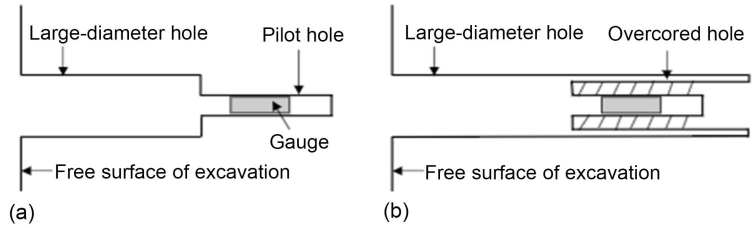

Figure 16. Stress measurement by overcoring, using a device such as the USBM gauge: (a) gauge is inserted into the pilot hole, (b) which is then overcored, creating an annular region (shaded) that is relieved of stress.

Table 5. Advantages and limitations of direct *in-situ* stress measurement Methods.

Method	Advantages	Limitations
Relief (Overcoring)	Most developed technique in both theory and practice. Operated at 10^{-3} - 10^{-2} m^3 rock volume.	Scattering due to small rock volume. Requires drill rig. Only 2D.
Doorstopper	Works in jointed and high stressed rocks.	Only 2D. Requires drill rig.
Flat jacking	Direct measurement of the compressive stress present. Both 2D/3D within the masonry. Useful for determining stress gradients within a masonry wall or column. Operated at 0.5 - 2 m^3 rock volume.	Requires the cutting of a slot in the masonry, which may cause damage to the structure. Can be time-consuming and labor-intensive. Requires specialized equipment and trained personnel to perform the test.
Hydraulic fracturing (HF)	Measurements in existing hole. Low scattering in the results. Involves a fairly large rock volume. Quick. Operated at 0.5 - 50 m^3 rock volume.	Only 2D. The theoretical limitations in the evaluation of σ_h. Disturbs water chemistry. Only 2D.
HTPF	Measurements in existing hole. Can be applied when high stresses exist and overcoring and hydraulic fracturing fail. Both 2D/3D. Operated at 1 - 10 m^3 rock volume.	Time-consuming. Requires existing fractures in the hole with varying strikes and dips.

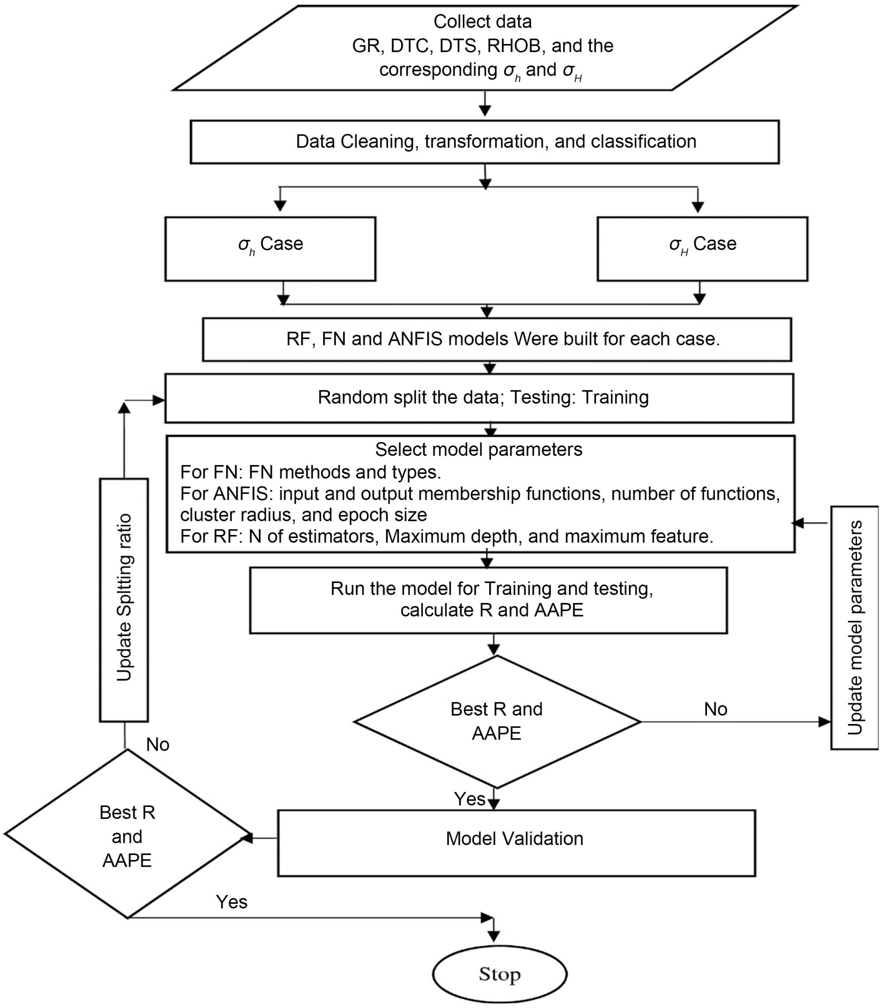

Figure 17. Flowchart for building the different RF, FN, and ANFIS models you can find the Acronym and the Description in [47].

the efficiency, accuracy and robustness of *in-situ* stress measurement, by providing a fast and efficient way to analyze data and make predictions about the subsurface stress state.

There is a case study in this field, a geometric equation for borehole deformation under stress was developed using the basic principles of elasticity. The relationship between *in situ* stress and borehole deformation was then established, and a prediction model for *in situ* stress was proposed. Numerical simulations were used to analyze the deformation effect in different types of rock. The study also used an artificial neural network to predict the shear wave time difference using logging parameters such as density and natural gamma radiation. The results showed that the borehole geometry under stress was quasi-elliptic and that the predicted geometry was consistent with the actual geometry. The overall error of the *in situ* stress predicted using this method was less than 9.2%, with the highest accuracy in coal seams. This suggests that the proposed method is feasible [49]. Also, there are another paper aims to compare and improve the minimum horizontal stress estimation through various machine learning regression techniques, including parametric and non-parametric models. The study was based on 79 laboratory data and validated against 23 field data. The results showed that the artificial neural network was able to predict the minimum horizontal stress with an average error rate of 10.16% and a root mean square error of 3.87 MPa, which is a meaningful improvement compared to conventional *in-situ* measurement techniques [50]. On the other hand, an AI-based methodology is proposed to identify geomechanical parameters from borehole injection pressure curves obtained during hydraulic fracturing tests. A genetic algorithm minimizes the difference between observed and predicted pressure curves while an artificial neural network substitutes hydraulic fracture simulations to reduce computational time. A recursive strategy predicts pressure curves and a hyperparameter tuning technique selects appropriate neural network parameters. The framework was applied to a KGD problem and confirmed its ability to identify geomechanical parameters from fracturing tests [51].

Another study that used machine learning to predict *in-situ* stresses from logging data was conducted by Ibrahim *et al.* 2021 [52]. In this study, the researchers collected logging data from boreholes drilled in the subsurface. They then used machine learning algorithms, such as Random Forest or Support Vector Machine, to train models on this data.

These models were able to predict the *in-situ* stresses at different locations in the subsurface with high accuracy. The results of this study showed that machine learning can be a powerful tool for *in-situ* stress prediction and can improve the efficiency and accuracy of subsurface stress measurements. However, the practical use of these AI models is still a concern as many require some level of expertise to be used, as they are not in a form of simple mathematical equations. There is still a need to explore advanced AI methods and the limited availability of data for AI simulations is also a major challenge [53].

6. Conclusion

Knowledge of *in situ* stress have major impact to any infrastructure project related mining, civil engineering, geothermal, large underground opening etc. Therefore, this paper given a brief review of the *in situ* stress measurement methods and more emphasized on most common methods. Each method has their limitation for applicability. In direct methods are commonly used by experts without disturbing the rock mass. Some area where no access of underground opening for direct measurement of *in situ* stress, hydraulic fracturing tends to be appropriate choice at greater depth up to several kilometers. Applicable of HTPF technique if large amount of intersection of fracturing existing, which remove the ambiguity associate with conventional hydraulic fracturing. Relief methods used for *in situ* stress measurement where underground accessibility possible. Some methods can be carried out directly on rock core sample in laboratories without visiting the project site. At last authors tried to link Artificial Intelligence (AI) for measure the *in situ* stress which will be remain a major and interesting topic in rock mechanics.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Amadei, B. and Stephansson, O. (1997) Rock Stress and Its Measurement. Springer, Berlin. https://doi.org/10.1007/978-94-011-5346-1

[2] Singh, P.K., Wasnik, A.B., Kainthola, A., Sazid, M. and Singh, T.N. (2013) The Stability of Road Cut Cliff Face along SH-121: A Case Study. *Natural Hazards*, **68**, 497-507. https://doi.org/10.1007/s11069-013-0627-9

[3] Hoek, E. and Brown, E.T. (2019) The Hoek–Brown Failure Criterion and GSI—2018 Edition. *Journal of Rock Mechanics and Geotechnical Engineering*, **11**, 445-463. https://doi.org/10.1016/j.jrmge.2018.08.001

[4] Ansari, T., Kainthola, A., Singh, K.H., Singh, T.N. and Sazid, M. (2021) Geotechnical and Micro-Structural Characteristics of Phyllite Derived Soil; Implications for Slope Stability, Lesser Himalaya, Uttarakhand, India. *Catena*, **196**, Article ID: 104906. https://doi.org/10.1016/j.catena.2020.104906

[5] Sazid, M., Wasnik, A., Singh, P., Kainthola, A. and Singh, T.N. (2012) A Numerical Simulation of Influence of Rock Class on Blast Performance. *International Journal of Earth Sciences and Engineering*, **5**, 1189-1195.

[6] Sazid, M. and Singh, T.N. (2015) Numerical Assessment of Spacing–Burden Ratio to Effective Utilization of Explosive Energy. *International Journal of Mining Science and Technology*, **25**, 291-297. https://doi.org/10.1016/j.ijmst.2015.02.019

[7] Adams, J. and Bell, J.S. (1991) Crustal Stresses in Canada. In: Slemmons, D.B., Engdahl, E.R., Zoback, M.D. and Blackwell, D.D., Eds., *Neotectonics of North America*, Geological Society of America, Inc., Boulder.

[8] Franklin, J.A. and Hungr, O. (1978) Rock Stresses in Canada Their Relevance to Engineering Projects. In: Franklin, J.A. and Hungr, O., Eds., *Geomechanik gebirgsbildender Vorgänge und deren Auswirkungen auf Felsbauten ober und unter Tage* [*Geomechanics of Orogenetic Events and Their Effects on the Construction of Rock Structures on Subsurface and Underground*], Springer, Vienna, 25-46. https://doi.org/10.1007/978-3-7091-4160-1_3

[9] Lee, C.F. (1981) *In-situ* Stress Measurements in Southern Ontario. 22*nd U.S. Symposium on Rock Mechanics,* Cambridge, 29 June-2 July 1981, 465-472.

[10] Lee, C.F. and Lo, K.Y. (1976) Rock Squeeze Study of Two Deep Excavations at Niagara Falls. *Rock Engineering for Foundation and Slopes,* 116-140 https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0265474

[11] Lo, K.Y. and Morton, J.D. (1976) Tunnels in Bedded Rock with High Horizontal Stresses. *Canadian Geotechnical Journal*, **13**, 216-230.

[12] Carlsson, A. and Olsson, T. (1982) Rock Bursting Phenomena in a Superficial Rock

Mass in Southern Central Sweden. *Rock Mechanics*, **15**, 99-110.

[13] Hast, N. (1958) The Measurement of Rock Pressure in Mines. Norstedts Förlag, Stockholm.

[14] Myrvang, A.M. (1993) Rock Stress and Rock Stress Problems in Norway. *Rock Testing and Site Characterization*, **3**, 461-471. https://doi.org/10.1016/B978-0-08-042066-0.50025-2

[15] Stephansson, O. (1993) Rock Stress in the Fennoscandian Shield. *Rock Testing and Site Characterization*, **3**, 445-459. https://doi.org/10.1016/B978-0-08-042066-0.50024-0

[16] Stephansson, O., Särkkä, P. and Myrvang, A.M. (1986) State of Stress In Fennoscandia. *Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements*, Stockholm, 1-3 September 1986, 21-32. https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Altu%3Adiva-40174

[17] Fairhurst, C. (2003) Stress Estimation in Rock: A Brief History and Review. *International Journal of Rock Mechanics and Mining Sciences*, **40**, 957-973.

[18] Kainthola, A., Singh, P.K., Wasnik, A. and Singh, T.N. (2012) Finite Element Analysis of Road Cut Slopes Using Hoek & Brown Failure Criterion. *International Journal of Earth Sciences and Engineering*, **5**, 1100-1109.

[19] Voight, B. (1966) Interpretation of *In-Situ* Stress Measurements. 1*st Congo International Society for Rock Mechanics* (*ISRM*), September 1966, Lisbon, 48-332.

[20] Obert, L. (1968) Determination of Stress in Rock. A State of the Art Report. ASTM Special Technical Publication NO. 429, 1966, 1-56. https://doi.org/10.1520/STP44677S

[21] Sazid, M. (2017) Effect of Underground Blasting on Surface Slope Stability: A Numerical Approach. *American Journal of Mining and Metallurgy*, **4**, 32-36.

[22] Bielenstein, H.U. and Barron, K. (1971) *In-Situ* Stresses. A Summary of Presentations and Discussions Given in Theme I at the Conference of Structural Geology to Rock Mechanics Problems. Department of Energy, Mines Branch, Ottawa.

[23] Hyett, A.J., Dyke, C.G. and Hudson, J.A. (1986) A Critical Examination of Basic Concepts Associated with the Existence and Measurement of *in Situ* Stress. *ISRM International Symposium,* Stockholm, 31 August-3 September 1986, 387-391.

[24] Price, N.J. and Cosgrove, J.W. (1990) Analysis of Geological Structures. Cambridge University Press, Cambridge.

[25] Deb, D. and Verma, A.K. (2016) Fundamentals and Applications of Rock Mechanics. PHI Learning Pvt. Ltd., New Delhi.

[26] Sperner, B., Müller, B., Heidbach, O., Delvaux, D., Reinecker, J. and Fuchs, K. (2003) Tectonic Stress in the Earth's Crust: Advances in the World Stress Map Project. *Geological Society London Special Publications*, **212**, 101-116. https://doi.org/10.1144/GSL.SP.2003.212.01.07

[27] Sazid, M. (2019) Analysis of Rockfall Hazards along NH-15: A Case Study of Al-Hada Road. *International Journal of Geo-Engineering*, **10**, Article No. 1. https://doi.org/10.1186/s40703-019-0097-3

[28] Figueiredo, B., Lamas, L. and Muralha, J. (2016) Stress Field Assessment for Determining the Long-Term Rheology of a Granite Rock Mass. *ISRM International Symposium on In-Situ Rock Stress*, Tampere, 10-12 May 2016, 1-12.

[29] Heidbach, O., *et al.* (2018) The World Stress Map Database Release 2016: Crustal Stress Pattern Across Scales. *Tectonophysics*, **744**. 484-498. https://doi.org/10.1016/j.tecto.2018.07.007

[30] (1982) Lawrence Berkeley National Laboratory, Determination of the State of Stress at the Stripa Mine, Sweden. https://escholarship.org/uc/item/4298625n

[31] Ratigan, J.L. (1982) An Examination of the Tensile Strength of Brittle Rock. *The* 23*rd U.S. Symposium on Rock Mechanics*, Berkeley, 25-27August 1982, 423-440. https://doi.org/10.1016/0148-9062(83)91356-6

[32] Perreau, P.J., Heugas, O. and Santarelli, F.J. (1989) Tests of ASR, DSCA, and Core Discing Analyses to Evaluate *In-Situ* Stresses. *Middle East Oil Show*, Manama, 11-14 March 1989, 325-336. https://doi.org/10.2118/17960-MS

[33] Ljunggren, C., Chang, Y., Janson, T. and Christiansson, R. (2003) An Overview of Rock Stress Measurement Methods. *International Journal of Rock Mechanics and Mining Sciences*, **40**, 975-989. https://doi.org/10.1016/j.ijrmms.2003.07.003

[34] Dong, Q., Li, X., Jia, Y. and Sun, J. (2021) A Numerical Simulation of Blasting Stress Wave Propagation in a Jointed Rock Mass under Initial Stresses. *Applied Sciences* (*Switzerland*), **11**, Article 7873. https://doi.org/10.3390/app11177873

[35] Brady, B.H.B., Friday, R.G. and Alexander, L.G. (1976) Stress Measurement in a Bored Raise at the Mount Isa Mine. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, **13**, 123. https://doi.org/10.1016/0148-9062(76)90639-2

[36] Chandler, N.A. (1993) Bored Raise Overcoring for *in Situ* Stress Determination at the Underground Research Laboratory. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, **30**, 989-992. https://doi.org/10.1016/0148-9062(93)90058-L

[37] Gaone, F. M., Doherty, J. and Gourvenec, S. (2016) Self-Boring Pressuremeter Tests at the National Field Testing Facility, Ballina NSW. In Lehane, B.M., Acosta-Martínez, H.E. and Kelly, R., Eds., *Geotechnical and Geophysical Site Characterisation, ISC*5, Vol. 1, Australian Geomechanics Society, 761-765.

[38] Brudy, M., Zoback, M.D., Fuchs, K., Rummel, F. and Baumgartner, J. (1997) Estimation of the Complete Stress Tensor to 8 km Depth in the KTB Scientific Drill Holes Implications for Crustal Strength. *Journal of Geophysical Research*, **102**, 18453-18475. https://doi.org/10.1029/96JB02942

[39] Lindfors, U. and Ab, S. (2007) Svensk Kärnbränslehantering AB Oskarshamn Site Investigation Hydraulic Fracturing and HTPF Rock Stress Measurements in Borehole KSH01A. https://skb.se/

[40] Haimson, B.C. and Cornet, F.H. (2003) ISRM Suggested Methods for Rock Stress Estimation-Part 3: Hydraulic Fracturing (HF) and/or Hydraulic Testing of Pre-Existing Fractures (HTPF). *International Journal of Rock Mechanics and Mining Sciences*, **40**, 1011-1020. https://doi.org/10.1016/j.ijrmms.2003.08.002

[41] Hustrulid, W.A. and Johnson, G.A. (1990) Rock Mechanics Contributions and Challenges. CRC Press, London, 1082. https://doi.org/10.1201/9781003078944

[42] Merrill, R.H., *et al.* (1964) Stress Determination by Flat Jack and Borehole Deformation Methods. U.S. Department of Interior, Bureau of Mines, RI 6400, 39.

[43] Lin, H., Oh, J., Masoumi, H., Zhang, C., Canbulat, I. and Dou, L. (2018) A Review of *in Situ* Stress Measurement Techniques. *Proceedings of the* 18*th Coal Operators' Conference*, *Mining Engineering*, University of Wollongong, 95-102.

[44] Mukai, A., Yamauchi, T., Ishii, H. and Matsumoto, S. (2007) *In Situ* Stress Measurement by the Stress Relief Technique Using a Multi-Component Borehole Instrument. *Earth*, *Planets and Space*, **59**, 133-139. https://doi.org/10.1186/BF03352686

[45] Liu, Q., Jiang, J., Zhang, C. and Zhu, Y. (2016) Analytical Investigation for *in Situ*

Stress Measurement with Rheological Stress Recovery Method and Its Application. *Mathematical Problems in Engineering*, **2016**, Article ID: 7059151. https://doi.org/10.1155/2016/7059151

[46] Jaeger, N.G.W.C.J.C. and Zimmerman, R.W. (2007) Fundamentals of Rock Mechanics. 4th Edition, Wiley-Blackwell, Hoboken.

[47] Gowida, A., Elkatatny, S. and Gamal, H. (2021) Unconfined Compressive Strength (UCS) Prediction in Real-Time While Drilling Using Artificial Intelligence Tools. *Neural Computing and Applications*, **33**, 8043-8054. https://doi.org/10.1007/s00521-020-05546-7

[48] Al Dhaif, R., Ibrahim, A.F. and Elkatatny, S. (2022) Prediction of Surface Oil Rates for Volatile Oil and Gas Condensate Reservoirs Using Artificial Intelligence Techniques. *Journal of Energy Resources Technology*, *Transactions of the ASME*, **144**, Article 033001. https://doi.org/10.1115/1.4051298

[49] Fang, X., Feng, H., Wang, Y. and Fan, T. (2022) Prediction Method and Distribution Characteristics of *in Situ* Stress Based on Borehole Deformation—A Case Study of Coal Measure Stratum in Shizhuang Block, Qinshui Basin. *Frontiers in Earth Science* (*Lausanne*), **10**, 1-36. https://doi.org/10.3389/feart.2022.961311

[50] Lin, H., *et al.* (2022) An Investigation of Machine Learning Techniques to Estimate Minimum Horizontal Stress Magnitude from Borehole Breakout. *International Journal of Mining Science and Technology*, **32**, 1021-1029. https://doi.org/10.1016/j.ijmst.2022.06.005

[51] Abreu, R., Mejia, C. and Roehl, D. (2022) Inverse Analysis of Hydraulic Fracturing Tests Based on Artificial Intelligence Techniques. *International Journal for Numerical and Analytical Methods in Geomechanics*, **46**, 2582-2602. https://doi.org/10.1002/nag.3419

[52] Ibrahim, A.F., Gowida, A., Ali, A. and Elkatatny, S. (2021) Machine Learning Application to Predict *In-Situ* Stresses from Logging Data. *Scientific Reports,* **11**, Article No. 23445. https://doi.org/10.1038/s41598-021-02959-9

[53] Lawal, A.I. and Kwon, S. (2021) Application of Artificial Intelligence to Rock Mechanics: An Overview. *Journal of Rock Mechanics and Geotechnical Engineering*, **13**, 248-266. https://doi.org/10.1016/j.jrmge.2020.05.010