CHAPTER 1

INTRODUCTION

1.1 Background of Research

In geology, anisotropy is a rock whose engineering properties vary with direction. For example, limestone that show a great amount of anisotropy has a compressive strength that varies depending upon the orientation of the foliation to the applied load. Based on mechanical properties of anisotropic rocks that made their behaviour is unpredictable.

In this research, mechanical properties of anisotropic rock are studied. Basically anisotropic is one of the factors that effect behaviour of the rock. Generally rocks have some degrees of anisotropy and isotropic rocks are rarely found in nature (Kwasniewski 1993). Metamorphic rocks are mostly anisotropic whereas igneous rocks are more isotropic in nature than sedimentary and metamorphic. Rocks such as slates, shalles, phyllites and gneisses have anisotropic behaviour. The main objectives of the investigation are to study anisotropic uniaxial behaviour.

Laboratory rock testing is performed to determine the strength and elastic properties of intact specimens and the potential for degradation and disintegration of the rock material. The derived parameters are used in part for the design of rock fills, cut slopes, angle of bedding layer when the load is exerted, shallow and deep foundations, tunnels, and the assessment of shore protection materials (rip-rap). In evaluating the larger-scale rock mass that is significantly controlled by bedding layer, joints, fissures, discontinuity features (spacing, roughness, orientation, infilling), water pressures, and ambient geostatic stress state is aid the information of deformation and strength properties of intact specimens.

Type of rocks that used in this study is limestone. Limestone is a sedimentary rock consisting mainly of the mineral calcite (CaCO3) and dolomite (MgCa(CO3)2) the other minor occurrence of Siderite (FeCO3) and magnesite (MgCO3). A Metamorposed limestone, marble is a metamorphic rock consisting predominantly of fine to coarse grained recrystallized calcite and dolomite. Most limestone formations in Malaysia actually have been metamorphosed into marble. For example, the limestone formations in the Klang Valley (K.L. area) and the Kinta Valley (Ipoh area) are strictly all marble (Tan 2002) then no wonder marble also shows the same behaviour as limestone.

No limestone hills occur in the southern regions of Peninsular Malaysia (Johor, Melaka), and at one time it was thought that limestone does not occur at all in the southern region of Peninsular Malaysia.

The direction of minerals such as chlorite and mica under the influence of tectonic stresses is one of the main reasons for presence of foliation and schistocity in the such rocks (Nasseri and Ramamurthy, 2003).

1.2. Purpose of Study

The purpose of this study is to

1. To study mechanical behaviours anisotropic rock properties.
2. To study failure of anisotropic rock.
3. To analyse the fracture pattern.

Anisotropic behaviour plays an important role in the mechanical properties of anisotropic rock. A rock or rock mass can be anisotropic as a result of its inhomogeneity. For example, the strata in a sedimentary sequence will have different properties in the different directions parallel and perpendicular to the strata sequence. Alternatively, the intact rock may contain an inherent anisotropy due to its mode of formation, such as slate, or the gneiss shown in figure 1.1

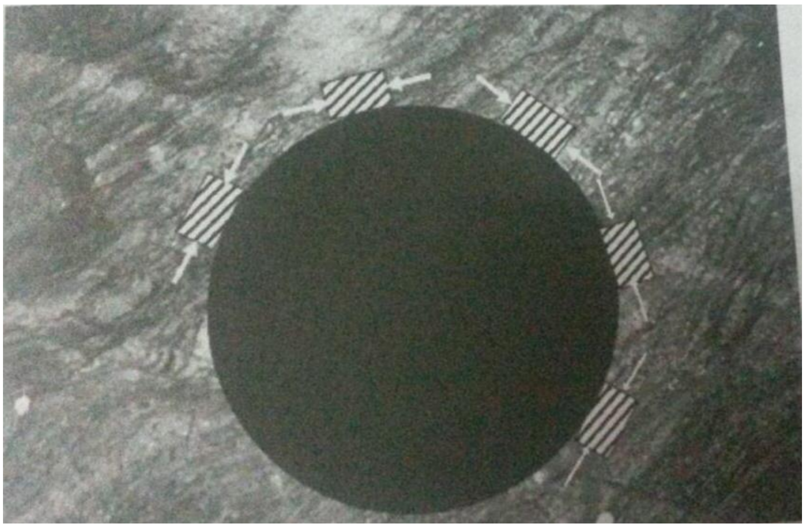


Figure 1.1 Influence of anisotropy on the potential location for failure around an excavation in gneissic rock

There are three main types or classes of rock are sedimentary, metamorphic and igneous and the differences among them related with how they are formed. Out of the three generic categories of rocks, metamorphic rocks exhibit highest degree of anisotropy. Segregation of constituent minerals, in response to high pressure and temperature gradients, is related to tectonic evolution and layers of contrasting mineralogical assemblages development. Rock flows and recrystallize under new tectonic stresses to form weak foliation planes. Such planes of weakness (eg schistosity) affect the strength and deformational behaviours of rocks with orientation to the applied stresses.(Nasseri, Rao, & Ramamurthy, 2003)

1.3. Strategy for Approaching the Problem

The project was carrying out at the lab of the School of Material and Mineral Resources Engineering. The samples are taken at LafargeHolcim and Hume Cement which located at Perak. Both quarry sites are chosen because it has the stratified limestones which match with the parameter to be tested in the Brazilian test.

There are many ways to study anisotropic rock properties such as point load index, unconfined compression, triaxial compression, Brazilian test, and direct shear test. Geomechanics study of anisotropy rock is important for project such as wellbore instability and optimization of hydraulic fracture. Understanding the mechanical behaviors of anisotropic rocks has important impacts on anisotropic rock energy exploration, wellbore stability, interpretation of microseismic monitoring, etc. This project studied the mechanical behaviors of anisotropic rocks using Uniaxial compressive strength test. Unique characteristics of anisotropic behaviour, which has important impacts on the fracture pattern. Anisotropic compression and tensile strengths of anisotropic rocks were measured by uniaxial compression tests (Gao, Tao, Hu, & Yu, 2015) . The problem related to anisotropic rock is solving anisotropy problem is more difficult to isotropy because number of variables in an anisotropy problems is several times more than isotropy problem.

As intimated in Figure 1.1 , the anisotropy has apronounced effect on the strength of the rock as a function of the direction of the applied stress and hence on the location where failure might initially occur around a tunnel periphery. To consider the potential for rock failure around the opening, the stress (i.e. the pre existing stress concentrated by the circular opening) is compared to the local rock strength. This can be envisaged by the loading of each of the rectangles placed around the opening in Figure 1.1 with the shading representing the direction of the foliation. Each of these cases must be studied separately due to the different local rock strengths, the different local rock stress, and the different local effect of the angle of the foliation with respect to the tangential stress around the opening.

There are many papers that studied anisotropic behaviours of rocks such as slates, shales, sadstones, geneisses, phyllites, etc. They are mainly Donath, 1964, Chenvert and Gatline, 1965, Mclamore and Garry, 1967, Ramurthy, 1993, Ramurthy et al., 1998. The review of these studies show that the minimum strength value is at an orientation angle of $\beta = 30°$ and the maximum failure strength is either at $\beta = 0°$ or $\beta = 90°$.

1.4. Study Area

The sampling location are Ipoh for limestone from Lafarge and Hume. LafargeHolchim is a manufacturer of building materials (primarily cement, aggregates and concrete) which claims to be the largest in the world. It is a merge of two leading world's company of cement that is Lafarge which based in French and Holchim which is a Swiss-global company.

In the cement business, LafargeHolchim currently employs 115,000 employees and operated in more than 90 centuries and network of facilities, which incudes 3 integrated cement plants in Pulau Langkawi, Kanthan Perak and Rawang Selangor, a grinding plant in Pasir Gudang, Johor.

Gunung Kanthan in LafargeHolchim Kanthan Plant in Chemor, Perak is the limestone quarry where the studybeen carry out besides of Hume Perak.

For the Hume Cement, it is located in Gopeng. It is the same company as LafargeHolcim which produce building material such as cements. It is a new company which operate for almost 4 years. The quarry is the ex-pond of tin mining. The pinnacle of the quarry is actually at the ground level since the limestone is excavated after the water of the pond is pump out. Therefore, it has a bit different of Figure 1.2 map for showing state boundaries and the position of Perak and Gunung Kanthan. 4 physical appearance of limestone compared to LafargeHolcim. The rock sample at the Hume Cement is quite massive compare to the LafargeHolcim. It is a bit difficult to determine the stratified rock that parallel with the parameter required.

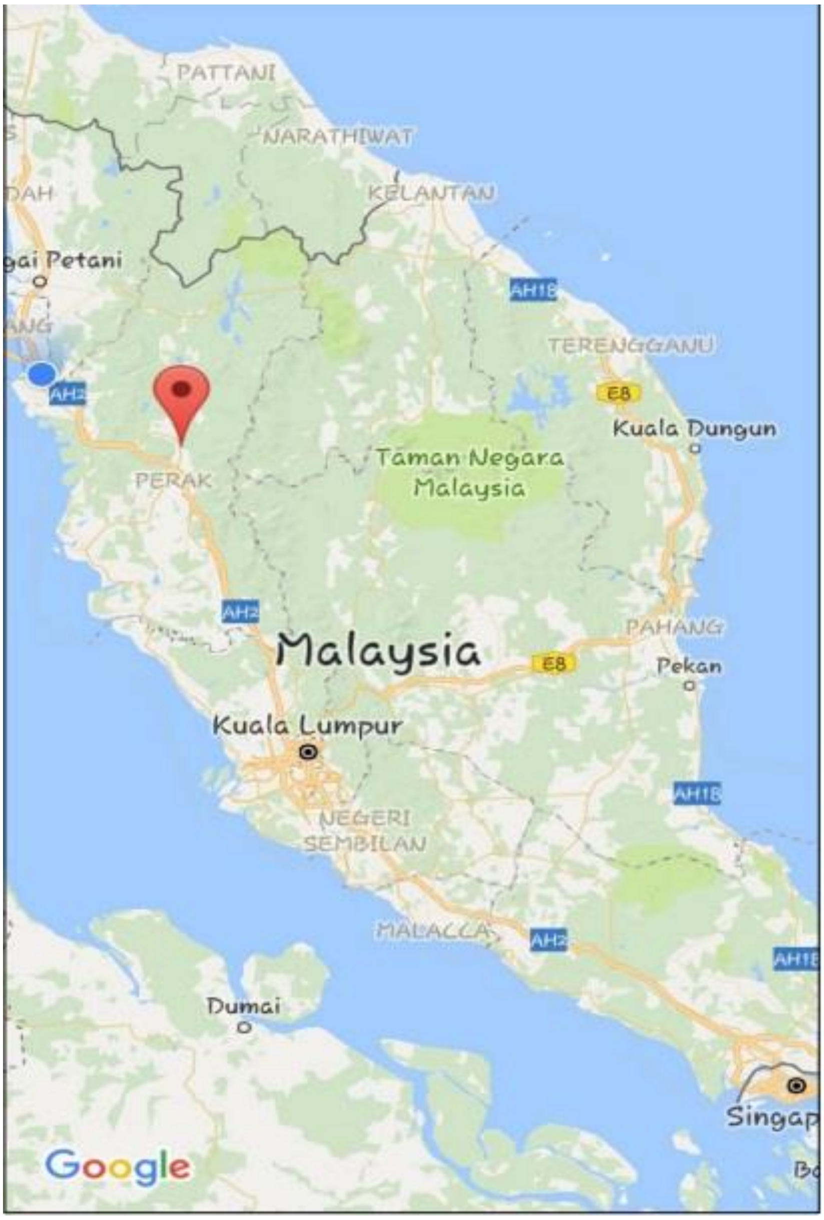


Figure 1.2: Map of Peninsular Malaysia showing state boundaries and the position of Perak and Gunung Kanthan.

Figure 1.3: Map of Peninsular Malaysia showing state boundaries and the position of Perak and Hume Cement

1.5 Outline of Thesis

This thesis is divided into seven chapters. The first chapter is briefly discussed about the general idea of this project and its purpose. The second chapter is the literature review which is the information is extracted from the journals and books. The chapter three is methodology which will be discussing about the way to conduct the research. Besides, it also discussed the apparatus and the material used for the research.

In the chapter four, this thesis discuss about the result and discussion of the 20 UCS test based on the fracture pattern and the tensile strength of the anisotropic rocks. In chapter five, it is respectively state the conclusion and the recommendations for future works

CHAPTER 2

LITERATURE REVIEW

2.1 Basic Rock Anisotropy

In this study, it focused for the mechanical behaviour of the anisotropic rock such as tensile strength and fracture pattern. Anisotropy is a well known feature of rock because it have different properties in different directions and is one of interest in the field of engineering and rock mechanics. Based on elasticity theory, the number of mechanical properties needed to characterise a rock as follows:isotropic (2-Young's modulus and Poisson's ratio); transversely isotropic (5-two Young's moduli, two Poisson's ratios and a shear modulus); orthotropic (9-three Young's moduli, three Poisson's ratios and three shear moduli); and general anisotropy (twenty one constants).

As mentioned above, rocks which have properties different with directions are said as anisotropy. A mineral can be considered as anisotropic if it can allow some light to pass through it. It can affect the polarization of light and the velocity also different and there is also double refraction where the light will split into two ways. In anisotropic mineral, double refraction can lead to uniaxial or biaxial.

Most elastic analyses assume that the rock is isotropic. In some cases, transverse anisotropy can be accommodated, as for example when using hollow inclusion over coring devices for stress measurement. Rarely considered rock is orthotropy and based on former studies no one has ever attempted to measure all 21 elastic constants for a generally anisotropic rock.

Typical types of rock, such as sedimentary rocks and metamorphic rocks consisting of a fabric with preferentially parallel arrangements of flat or long minerals may be considered to be transversely isotropic having different properties parallel and perpendicular to the dominant fabric. Schist, shale, clay-stone and siltstone show strong inherent anisotropy, manifesting itself in a directional dependence of the deformational characteristics. Also, isotropic rock material which is cut by regularly orientated discontinuities (joints and faults) may be considered to have transversely isotropic mass properties, e.g., granite and basalt. The expectation is the overall anisotropic mechanical behaviour to be partly a reflection of the anisotropic micro-structure. The study of the mechanical behaviour of sedimentary rocks, especially shale and mudstone, is of particular interest to the oil exploration industry, as well as to civil and mining engineering. In the foundations of a broad range of civil structures such as in tunnelling and other underground excavations these materials are usually unavoidable.

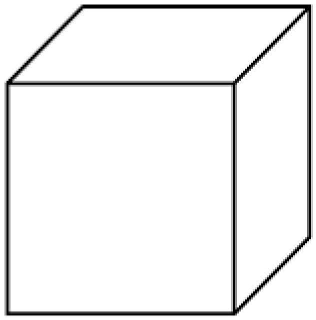
A main difficulty in characterising and modelling the failure mechanisms for roc subjected to different loads is the fact that rock, a natural material, is Discontinous, Inhomogenous, Anisotropic and Not Elastic. This is in contrast to the absolute material for analytical solutions which is Continous, Homogenous, Isotropic and Linearly Elastic. The discontinuos nature of rock and rock masses is caused by the many fractures existing on all scales, from the minute cracks within crystal grains to faults which can extend over many kilometres.

The intact rock and rock mass in homogeneity are caused by many factors, depending on whether the rock is of igneous, sedimentary or metamorphic origin. An igneous rock mass can have different properties at different locations because of the processes occurring in the fluid magma motions during the formation of the rock. A sedimentary rock mass, such as sandstone, limestone, mudstone sequence, is composed of strata having varies properties. A metamorphic rock can be inhomogenous because the metamorphic process were different at different locations or because the original rock was inhomogeneous.

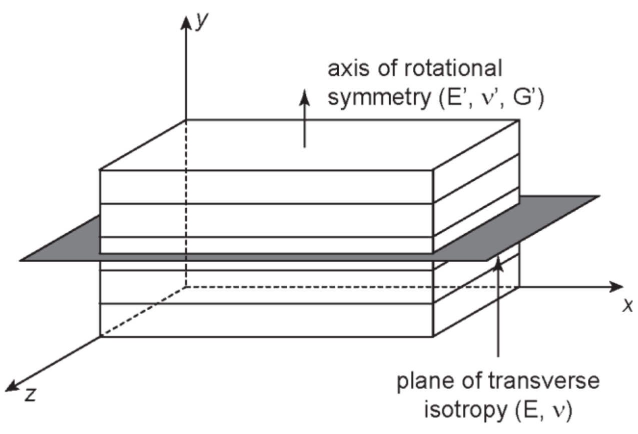
From other experimental studies on transversely isotropic rocks show that the maximum axial compressive strength is correlated with specimens in which the bedding planes are either parallel or perpendicular to the loading directions. The minimum strength is typically related with failure along the weakness planes, which connects to specimen orientations within the range 30° - 60 °. Failure criteria have been developed for transversely isotropic in order to characterise the variation of rock mechanics properties with the orientation angles and when subject to various confining pressures. In 1960 Jaeger introduced the basic analysis for rocks containing a well-defined discontinuity (a single plane of weakness) and there have been many modifications to the basic idea.

Since, regarding definition, the mechanical properties of anisotropic rocks must be established by testing in different directions, the number of specimens required for a full characterisation is much greater than that required for isotropic rocks. Moreover, for laboratory testing it is often difficult to obtain a sufficient number of specimens with uniform properties and at different angles to the main anisotropy direction because of the effects of heterogeneity, weathering, mineral composition, texture, fracture or joint characteristics, and core drilling directions. For this reason, many experimental studies have focused on the preparation and mechanical properties of artificial transversely isotropic rocks. Different studies have obtained different results with different components introduced into isotropic rock like materials. Unlike natural anisotropic rocks, the artificial transversely isotropic rock like specimens are more uniform and easy to produce to meet the requirements of the researchers.

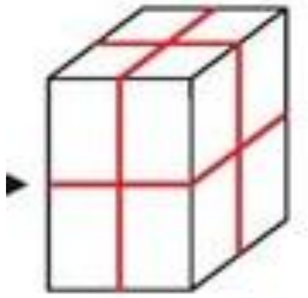
a) Isotropic



b) Transversely isotropic



c) Orthotropic



d) General anisotropy

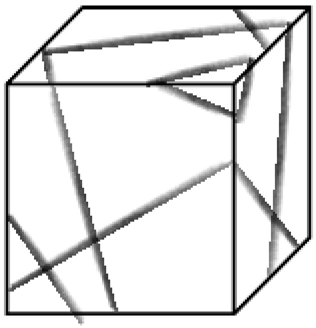


Figure 2.1: Types of elastic anisotropy

2.1.1 Constitutive Model of Anisotropic Rocks.

As shown in Figure 2.2, it is the global (x',y',z') and local (x,y,z) coordinate system. A local coordinate system is attached to the plane of anisotropic of the rock media. The y-axis is the axis of rotation symmetry that is normal to the isotropic planes and the x and z axes are contained within the isotropic plane. The z'-axis coincides with the z-axis. For a anisotropic rocks in a local and global coordinate, generalized Hooke's law can be given in the following tensor equation:

$\varepsilon = S\ \boldsymbol{\sigma}$ (1)

Where,

ε = strain S = elastic compliance σ = stress

Equation (1) can be also expressed in matrix form as

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1+\nu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1+\nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1+\nu \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}$$

In the compliance matrix, there are five independent elastic constants exist. E is the elastic moduli in the plane of isotropic and E’ are the elastic moduli in the direction normal to it. While v is the Poisson’s ratios that characterize the lateral strain response in the plane of anisotropic to a stress acting parallel and v’ is the Poisson’s ratios that characterize the lateral strain response in the plane of anisotropic to a stress acting normal to it.

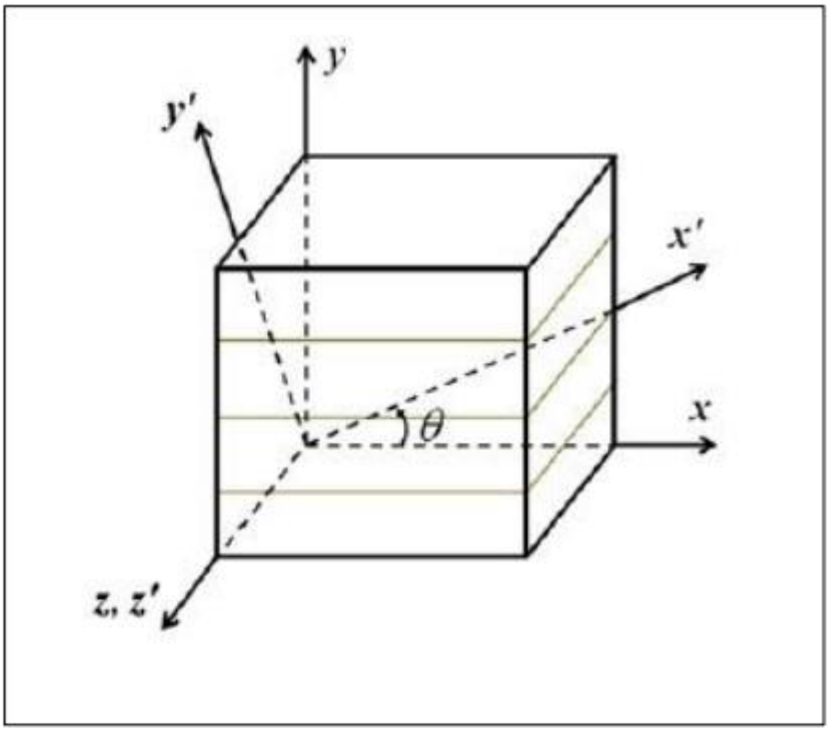


Figure 2.2: Definition of global and local coordinates in anisotropic rocks

The generalized Hooke's law in global coordinates is expressed as follows:

$$\varepsilon' = S'\sigma' \qquad (3)$$

Equation (3) can be expressed in matrix form as

$$\begin{bmatrix} \varepsilon_{x'} \\ \varepsilon_{y'} \\ \varepsilon_{z'} \\ \gamma_{y'z'} \\ \gamma_{z'x'} \\ \gamma_{x'y'} \end{bmatrix} = \begin{bmatrix} S'_{11} & S'_{12} & S'_{13} & S'_{14} & S'_{15} & S'_{16} \\ S'_{21} & S'_{22} & S'_{23} & S'_{24} & S'_{25} & S'_{26} \\ S'_{31} & S'_{32} & S'_{33} & S'_{34} & S'_{35} & S'_{36} \\ S'_{41} & S'_{42} & S'_{43} & S'_{44} & S'_{45} & S'_{46} \\ S'_{51} & S'_{52} & S'_{53} & S'_{54} & S'_{55} & S'_{56} \\ S'_{61} & S'_{62} & S'_{63} & S'_{64} & S'_{65} & S'_{66} \end{bmatrix} \begin{bmatrix} \sigma_{x'} \\ \sigma_{y'} \\ \sigma_{z'} \\ \tau_{y'z'} \\ \tau_{z'x'} \\ \tau_{x'y'} \end{bmatrix} \qquad (4)$$

The compliance matrix in equation (4) can be obtained through the tensorial transformation, which involves direction cosine with θ signifying counter clockwise rotation.

2.1.2 Effects of Geometric Anisotropy on Permeability Anisotropy

The distinct element method is used to carry out the numerical modelling of fluid flow through fractured rock. In the flow model, fractures are assumed to have a fixed, uniform aperture and the flow rate through the fracture, qj, is calculated by the cubic law:

$$qj = kja^3 \frac{dH}{dL} \qquad (4)$$

Where:

kj = the permeability factorof a fracture, kj = 1/(12μ), μ is the dynamic viscosity

a = the fracture aperture.

dH/dL = the pressure gradient along the contact length, L.

2.2 Failure of anisotropic rock

As an introduction to this research, we need to become familiar with the way in which rock fails in a variety of engineering circumstances-in laboratory tests, on or near the surface in foundations and slopes, and underground in tunnels, caverns and mines. In contrast to other engineering disciplines where materials are manufactured to certain specifications, rock masses are pre-existing natural substances and so we recognise the contribution that structural geology brings to the understanding of pre-existing rock mass features.

In 2003, Mark Eberhardt, professor of chemistry and geochemistry at the Colorado School of Mines in the USA, published a book with the title “Why things break”(Eberhardt, 2003). In this book and with reference to the history of tool making, the author notes the antiquity of using shaped of rock pieces as tools and that only certain types of rock , i.e. flint, obsidian and pertified wood, fractured to produce a sharp cutting edge. He also explains that the distinction between bending (when planes of atoms slide across one another) and breaking (when the planes of atoms are pulled apart). He explains that the tendency to break or bend in polycrystalline materials is dependent on a dislocation’s ability to move across grain boundaries: when this movement is suppressed, the material fractures. As with metals, rock fracture begins at the tip of a pre-existing crack although, as we shall sea, the initiation of such crack growth does not necessarily lead to total structural collapse of the rock volume in question.

Professor Eberhardt notes that, through our understanding of the fracturing of materials in general, in less than a century we have moved from society where breakage was considered the norm to the current time when we can make tough containers, strong sheets of glass and polymers that absorb the energy of bullets. However, these advances have been achieved by varying the manufacturing processes of the materials.

In rock mechanics, we do not have the same advantage with the pre-existing rock. Nevertheless, despite the fact that the study of rock failure does not have such a long history as for other materials, we do now understand rock failure and we are able to simulate such failure using numerical computer modelling. With the latest technology, we can illustrate both real rock failure and simulated rock failure.

In the development of a failure criterion, the failure modes of rock specimens are test under the different orientation angle and under different confining pressure. It is an ideal failure criterion if it is able to predict the state of stress at failure and the failure mode. The failure mode of anisotropic rock under the triaxial test is influenced by the orientation of the stresses and the confining pressure. Therefore, it is more complicated rather than isotropic rocks. Many researchers described in detail the failure modes of anisotropic rock into two modes as follow: a) Sliding along the discontinuities. b) Fracture through the rock material. Jaeger's criterion is mainly based on the simplified assumption of failure modes described above.

During the history of the Earth, there have been many turbulent events involving the deformation and fracture of rock formations. Thus, there is considerable forensic chance to study the nature of earlier rock failure and to take advantage of structural geology knowledge. Because brittle rock failure occurs through the application of stress, in particular tensile stress and shear stress, a chief feature of the structural geology analysis of natural rock failure considers extensional and shear failure.

Also, because the rock fractures are initiated by stress within the rock mass and stress has three orthogonal principal components, the fractures generally form in sets, as is clearly evident in the Carboniferous stratum in Figure 2.3 This orthogonality of the three principal stress components, also brings to the Anderson (1942) classification of fault types as thrust, transcurrent and reverse. Even though rock fractures can be caused by a different of natural and anthropogenic means, e.g. meteorite impacts and underground blasting (Backstorm, 2008), it is the application of stress to the rock that causes the fractures. For this reason, the existence and measurement of rock stress has received considerable attention (Zhang and Stepahnson,2010).

Figure 2.3: Sets of rock fractures in a Carboniferous stratum, S. Wales, UK.

Besides, during geological history, there has been a series of stress changes, resulting in a succession of superimposed rock failure events. Thus rock masses, as viewed today represent the cumulative effect of many such episodes, the geologist or engineer need to interpret the current geometry to understand the succession of failure events and hence to understand the discontinuous nature of rock mass. In certain situations, the geometry of fractures is crystal clear, while in other situations, it can be much more complex. However, because the subject of structural geology is now so well evolved, there is a considerable body of knowledge to reinforce understanding of the discontinuous nature of rock masses (Bahat et al., 2005).

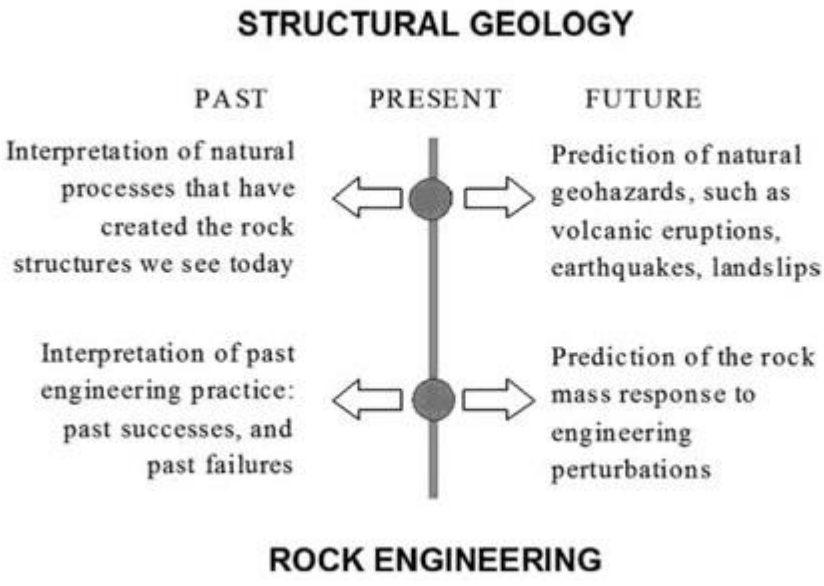


Figure 2.4: The distintion between structural geology and rock engineering in the context of interpreting past processes and predicting the future.

As showed in Figure 2.4, the geologist illuminates the past geological processes through study of rock structures observed today and is able to make predictions regarding natural events such as volcanic eruptions and landslides. Similarly , civil, mining and petroleum engineers are capable to study past engineering construction located on and in rock masses in order to understand how rock failure has affected the engineering whether the intention was to avoid rock failure or to cause it. So with this knowledge, the engineer can then predicted the consequences of a particular design. This predictive capability is really important in rock engineering because if engineers cannot predict the consequences of a particular rock engineering approach, there is no basis for coherent design and for this reason the understanding of rock failure is vital.

This experiment focused on the fundamental mechanism of the observed anisotropic behaviours and the implications for the engineering practice need to be further studied. Geomechanics study of anisotropic rocks important for engineering application such as wellbore instability, optimization of hydraulic fracture and slope stability. However, it is often poorly understood.

Most researchers assumed the rock mass failure criteria that joint orientation does not have a dominant effect on failure. This assumption may not lead to serious errors if the number of joint sets is large or if the joints are close and randomly orientated. Situations in excavations design sometimes arise when the orientation of a single plane or set of planes of weakness planes in relation to the direction of the principal stresses induced.

It is well known that rock strength is different depending on whether the applied major stress is perpendicular or parallel to the weakness plane. Between these two extreme values, strength varies with the angle between the weakness plane and the major stress.

2.2.1 Effect of Strength Anisotropy on the Stability of Slopes

The effect of strength anisotropy of geomaterials is normally due to the presence of the weak planes in the material which on the stability of the slope. To incorporate with the effects of weak planes in finite element simulation, two different approaches were invented. Where the approaches as below: I. The weak planes were introduced to the model by inserting a joint network in the finite element model. II. One of the constitutive models of the material included the planes of weakness. Based on from the approached made, it was shown that the stability of slopes is dependent on the presence and configuration of the weak planes in the material. The shape of the possible slip surface is likewise impacted by the introduction of the weak planes. The got numerical comes about utilizing the two methodologies were in a decent concurrence with each other in assessment of the factor of safety of slopes.

2.2.2 Effect of Anisotropy on the Analysis of Overcoring Measurements

Overcoring technique is the borehole relief method where it is a method and procedure to separate rock sample from the stress field in the surrounding rock by coring. Strain or displacement measurements on the specimen thus separated are recorded in the vicinity of the point at which the state of stress has to be determined. This requires the stress field to be homogeneous all through the zone of enthusiasm before the estimations are performed which is a sensible presumption in the absence of heterogeneities or major geological in the rock mass. Figure 2.5 shown the step that commonly involved when measuring in situ stress by overcoring with instrumented devices. Firstly, a large diameter of hole is drilled to the required depth in the volume of rock in which stresses have to be determined. Secondly, a small pilot hole is drilled at the end of the previous hole before an instrumented device is inserted into the pilot hole. Lastly, the large diameter hole is continuing which will result changes in strain or displacement within the instrumented devices are recorded.

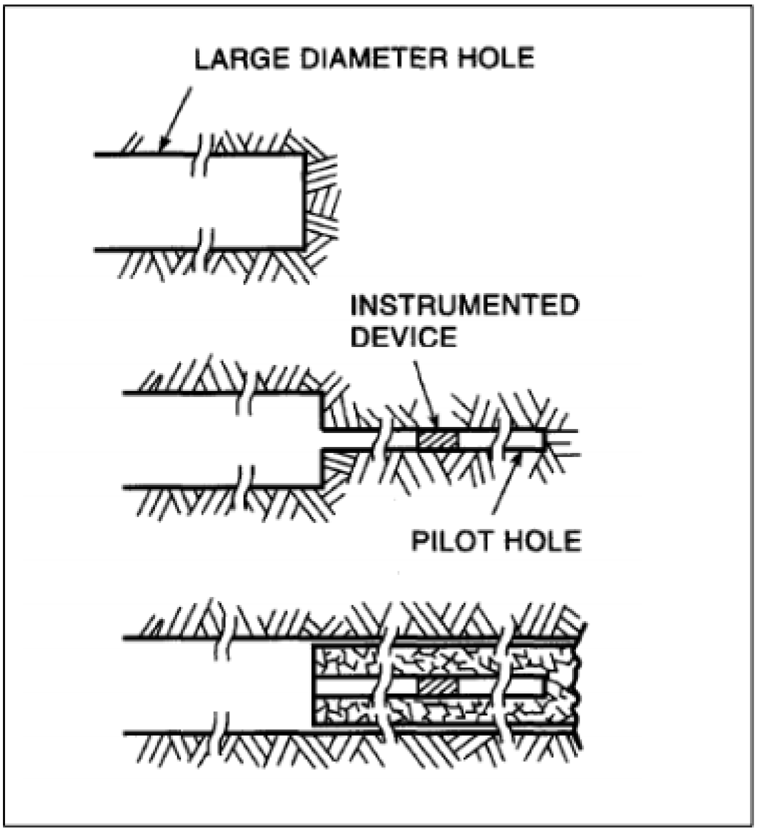


Figure 2.5: Overcoring technique with instrumented devices

The successful interpretation of this test depends to a great extent on the ability:

I. To establish a stress-strain relationship for the

II. II. To be able to determine rock mass properties from tests on core samples.

2.2.3 Effects of Anisotropic on Underground Oil Storage Caverns

Oda's method for determining the anisotropic permeability is used for an underground oil storage cavern. In this method, anisotropic permeability of the site is determined from fracture orientation distribution and in situ stress obtained from field