SAND PRODUCTION PREDICTION ANALYSIS IN UNCONSOLIDATED RESERVOIR

By

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DISSERTATION

Submitted to the Petroleum Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons.)
(Petroleum Engineering)

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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UNIVERSITI TEKNOLOGI PETRONAS

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD AMIR HAIZAT BIN HASHIM

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CHAPTER 1

1.0 ABSTRACT

The objective of project is to design an analytical model to predict the possibilities of sand production during the drilling and production operation. By having this information, it can helps in providing the save operation condition by the plotting a graph of flowing bottom hole pressure, critical reservoir pressure, and critical drawdown pressure prediction which will indicate the operation area without possibilities of producing strength.

The major indication of possibilities of producing strength is the formation strength. Thus, in this project the author will study and design an experiment on testing the strength of formation by two main experiment which are thick-walled cylinder and unconfined compressive strength method.

This report consists of 6 chapters that will cover more on the theory behind the prediction of sand. In chapter 1, the author list down all figure and table that used in this prediction.

In chapter 2, the author discussed on the background study of this project, the problem statement, objective and scope of this study, relevancy of this project and finally discussed on the feasibility of this project.

In chapter 3, the author discussed on the literature review that related to this project. The main contents of this literature review are the field observation of sand production, laboratory sand production experiments, calculation of sand production prediction, the theory of Poisson ratio, compressive strength and Mohr coulomb.

In chapter 4, the author discussed on the methodology used for this project, the project activities, key milestones and equipment required to complete this project. The last two chapters, the author discussed on the expected result and discussion for this project that will complete by next part of this project.

In chapter 5, the author conducts the experimental work on the Unconfined Compressive Strength test. Not all the experiment studied in the literature review can be conducted because of the equipment in the university have its limitation. Thus, after discussing from experienced people, the author finally comes to the solution that changed the soil properties by using clay instead of sand. Only the UCS test can be conducted in the university while the TWC test cannot be conducted because the equipment in the university is malfunction.

1.1 LIST OF FIGURE AND TABLE

CHAPTER 2

2.1 BACKGROUND STUDY

Approximately 70% of the world oil and gas reserve are found in poor/week unconsolidated reservoir. Sand production has been a major concern to the industry for decades and become more critical today as more aggressive production schedules are implemented and production are increased in offshore environment where tolerance to sand production is very low.

Sand influx into the wellbore may lead to various problems such as erosion of the valves and pipelines, plugging of production liner and sand deposits in the separators. In addition the economic loss due to production limitations, sudden deposition of produced sands on the production equipment in high pressure gas wells presents a major safety risk.

Sand production prediction is not an exact science. Although theoretical analytical and numerical models exist, it is necessary to approach the problem with a good engineering based understanding of the limitations of the rock, well and reservoir data. Numerical model is one of the effective modeling to predict the sand formation.

Sand production is natural consequences of fluid flow into the wellbore from reservoir and the process may be divided into three stages which are:

- **The loss of mechanical integrity and the rock surrounding an open hole or perforation**
- **Separation of solid particles from the rock due to hydrodynamics force**
- **Transformation of the particles to the surface by reservoir fluid.**

Being able to predict whether a well will produce fluids without producing sand or predicting that some type of sand control will be required has been the goal of many completion engineers and research projects. In spite of the fact that there have been a number of analytical techniques and guidelines developed to assist in determining if sand control is necessary, no technique has yet proven to be universally acceptable or completely accurate.

Therefore for the studies of project research, the author will study on developing the numerical modeling that can predict the sand production. Basically there are 4 type of modeling that related to predict the sand productions which are:

- **Geopressure and geomechanic analysis**
- **Finite element method**
- **Elastic and poromechanical modeling**
- **Goemechanical modeling**

Geopressure and geomechanic analysis evaluate the reservoir pressure, in situ stress and rock strength. The finite element method is the method to optimize borehole perforation and reduce sand rick. The elastic and poromechanical modeling is the study to develop critical flowing bottom hole pressure and reservoir drawdown that can indicate the operation area without the tendency of sand to produce. The last modeling which is geomechanical modeling is the study to predict sand and the effect to casing, tubing, and facilities equipment.

Thus for the whole of this project, the author will focusing on developing the analysis on critical flowing bottom hole pressure and critical reservoir drawdown pressure as it is the final result in predicting the sand production and evaluate the operation so that they can prevent at early stage from sand problem.

2.2 PROBLEM STATEMENT

Sand production is a major problem in almost all fields that produce from unconsolidated or weekly sandstone reservoir. The industry has long been aware of both sand production and its associated problems which are; erosion to the equipment, high maintenance cost for installation a surface equipment to separate oil and sand, adoption of expensive frac pack, gravel pack and sand screen completion. It also will cause casing collapse and the major effects are on the amount of produces oil and gas.

A number of prediction models have been developed to identify completions that may be expected to produce sand. Earlier attempts to develop prediction techniques included statistical model, numerical models, mechanical properties logs, sand strength logs, and core studies. Often the individual's attempts to develop a predictive model were specify to the type and locale of the reservoir being studies such as water production, pore pressure depletion, formation geometry, pressure drawdown causes by skin effects, and a variety of other critical parameters were not always considered.

Thus, the author will be focusing on the most cost effective method to determine the sand production and need of sand control is by analogy from data collected from wells. Complex 3D numerical modeling in concert with the extensive laboratory analysis of the core and log data is not always economically practical but is the most technically correct method with an acceptable degree of accuracy when properly performed.

2.3 OBJECTIVE AND SCOPE OF PROJECT

2.3.1 OBJECTIVE

The objectives of this "Sand Production Prediction Analysis" are:

1) To provide a manual guideline on predicting the sand production from the formation.
2) To modeling the potential sandstone that has a high possibility to produce sand.
3) As an early stage to implement any sand control management as is can reduced the operation and maintenance cost.
4) To provide the save operation condition by the plotting of flowing bottom hole pressure, critical reservoir pressure, critical drawdown pressure prediction and calculation.

2.3.2 SCOPE OF PROJECT (FYP I and II)

The scopes of this "Sand Production Prediction Analysis" project are as below:

1) Study on the various technique that most accurate to predict the sand formation
2) Study on field observation of sand production :
   - One parameters
   - Two parameters
   - Multi parameters
3) Study on the theoretical of sand production experiments :
   - Thick wall cylindrical approach (TWC)
   - Unconfined compressive strength analysis (USC)
4) Study on theoretical of :
   - Stress – strain analysis
   - Mohr Coulomb circle
   - Young Modulus
   - Poisson Ration
5) Study on methodologies of
   - Production rate
   - Well logs data
   - Laboratory testing

2.4 RELEVANCY OF THE PROJECT

2.4.1 EVALUATE THE NECESSITY OF SAND CONTROL

This research on sand production prediction analysis will help in evaluating the necessity of sand control to the formation either required or not. Besides that it helps in selecting the type sand control technique by choosing between selective perforating and gravel packing

2.4.2 ASSIST IN SELECTING THE EFFECTIVE AND ECONOMICALLY SAND PREDICTION TECHNIQUE

As we aware, there are lots of prediction models that have been developed to identify the potential of formation to produce sand such as statistical models, munerical models, mechanical properties logs, sand strength logs, core studies and many more. All these models have their own advantages and the disadvantages. Thus, by having this research on sand production prediction analysis, it is an approach to the best models and methods to predict the sand production.

2.4.3 REDUCE THE TENDENCY OF FORMATION TO PRODUCE SAND

By evaluating the possibility of sand production, we can reduce the tendency of formation to produce sand at early stages. With all method and analysis use within this project it is very useful as an identification on predicting the sand produce.

2.4.4 ASSIST IN EVALUATE THE PARAMETERS INFLUENCE SAND PRODUCTION

This research helps and assists to evaluate the parameters that influence the sand production. There are several parameters that need into consideration which are the formation rock criteria, reservoir criteria, completion design criteria and production analysis. All these parameters will be study in detail through this research and it influences to sand production can be analyze easily.

2.4.5 DEVELOPING THE CDP AND CRP ANALYSIS GRAPH

By plotting the reservoir pressure, flowing bottom hole pressure, critical draw down pressure and critical reservoir pressure, the graph can be analyze the zone with and without sand production criterion. Thus, it helps to maintain the operation without producing the sand.

2.5 FEASIBILITY OF PROJECT WITHIN SCOPE AND TIME FRAME

2.5.1 LITERATURE REVIEW

This project is feasible within scope and the time frame as majority of the project is more towards the literature review and research on the production of sand. Besides that, the author will focusing more on the theory applied in predicting sand such as; Mohr coulomb circle theory, stress-strain theory, compressive strength theory, young modulus theory and Poisson ratio theory. Thus, studying and research on those theories will take a long time and all the information is feasible and can be accessed.

2.5.2 LABORATORY TEST

The second part of this project is the laboratory testing where the author will test the core sample for the compressive strength, stress-strain analysis and this will be the most challenges task as the author needs to find the core sample and the equipment to test the core. Thus, the solution is that there are existing core samples at UTP laboratory and this core sample can be used as an identification to find the character and parameters required to predict the sand formation.

CHAPTER 3

3.0 LITERATURE REVIEW

3.1 SAND PRODUCTION PREDICTION REVIEW: DEVELOPING AN INTEGRATED APPROACH

3.1.1 Introduction

A reliable but non conservative, field validated prediction and sand production is essential to decide whether sand control measures need to be installed during well completion. In this SPE paper, field measurements of sand production are classified and quantified to obtain a better perspective of the down hole situation. Existing sand prediction techniques are presented, critically evaluated and their limitation discussed.

3.1.2 Sand Prediction Technique

The existing sand production techniques are based on either field observation of sand production, laboratory sand production experiments or theoretical modeling of sand production. The various approaches to sand prediction are presented and evaluated, divided in three corresponding categories. The theoretical analysis is complemented by description of it fields applications where possible. The three categories are;

I. *Field observation of sand production*
II. *Laboratory sand production experiments*
III. *Calculation of sand production prediction*

I. Field Observation of Sand Production

Sand prediction techniques based on field experience rely on establishing a correlation between sand production well data and field and operational parameters. Table 1 presented an inventory of the parameters that may influences sand production. Normally, only a small selection of these parameters is used due to the practical difficulties of monitoring and recording several years' worth of data for all the wells involved in a study.

FORMATION	COMPLETION	PRODUCTION
<u>Rock</u> • Strength • Vertical and horizontal in situ stress • Depth <u>Reservoir</u> • Far field pore pressure • Permeability • Fluid composition • Drainage radius • Reservoir thickness • Heterogeneity	• Wellbore orientation • Wellbore diameter • Completion type • Perforating policy • Sand control • Completion fluid • Size of tubular	• Flow rate • Drawdown pressure • Flow velocity • Damage • *Shut in policy* • Artificial lift policy • Depletion • Water/gas coning • Cumulative sand volume

Table 1: Parameters influencing sand production

In field observation of sand production, there are three main scopes of parameters analyzed which are 1) one parameters, 2) two parameters, and 3) multi parameters. These different parameters give different implication in predicting sand production in the simplest identification to the tough identification analysis.

1) <u>One Parameters</u>

In its simplest form, the field data based sand prediction tool uses only one parameter. For example, a **cut-off depth criterion** for the installation of sand control measures is used in

several deltaic environments: sand control is not installed below a certain depth. The critical depth is regionally dependent around 12,000 and 7,000 ft respectively. Another cut-off criterion frequently applied specifies a compression sonic wave transit time (Δtc) below which sand control is not required. The limit Δtc is again field or regionally dependent and may vary from 90 to120 μs/ft.

A limit value for the sonic and density log was established which derived parameter G/Cb (G is the dynamic shear modulus, Cb the bulk compressibility): no sanding problem is expected when G/Cb exceeds 0.8*10 psi 2. This limit value has been applied successfully but appears to depend on the regional environment. The criteria specifying critical depth, Δtc and G/cb are related. For example, Δtc decreases as depth increases; thus, the Δtc criterion can be translated into a depth criterion and vice versa.

Also, G/Cb =0.8*10 psi typically corresponds to Δtc =115-120 μ/ft. The one-parameter approach is practical, though conservative, and frequently used due to its ease of use.

2) Two Parameters

The above one parameter models do not explicitly include the depletion of the **reservoir pressure** (ΔPde) and the **drawdown pressure** (ΔPdd). These parameters are considered in the two parameter petrophysical tool illustrated in Fig. 1. In Fig. 1 the total drawdown pressure (ΔPtd = ΔPde + ΔPdd) is plotted versus the sonic transit time for sand and no sand producing wells located in the same oil field. A risk region with a slope of -0.74 . MPa/(μs/ft) (-108 psi/(μ/ft)) and a width of 10.8 MPa (1560 psi), see Fig. 1, has been established on the basis of data from several fields.

Sand-free production can be realistically expected to the left of the risk region, while it is essentially impossible to produce wells to the right of the risk region. Fig. 1 indicates that increasing the total drawdown may trigger sand production. The position of the risk region is field dependent; sand production tests or routine monitoring can be used to determine its position.

3) Multi Parameters

The *width of the risk region in* Fig. *1 can be attributed to the influence of* other parameters. Multi-parameter correlations can improve the resolution between sand and no-sand producers. Fig. 2 illustrates the use of the multiple discriminate analysis technique for the data set of Fig. 1. Sand production is correlated with a wide range of parameters including **depth, sonic transit time, production rate, drawdown pressure, productivity index, shaliness, water cut and gas cut**. The sand and no-sand producing wells are well separated. The parameter influencing sand production most in case of Fig. 2 is water cut: sand and no sand producers are characterized by an average water cut of 19% and 2% respectively. The discriminate function describing the influence of the various factors is regionally dependent. The multi-parameter techniques are not commonly used because of the extensive data requirements.

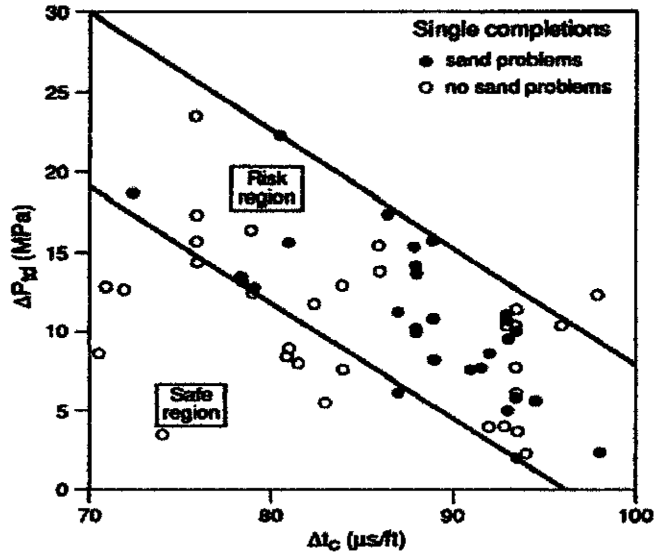


Figure 1 : Total drawdown versus transit time for interval with and without sand problems

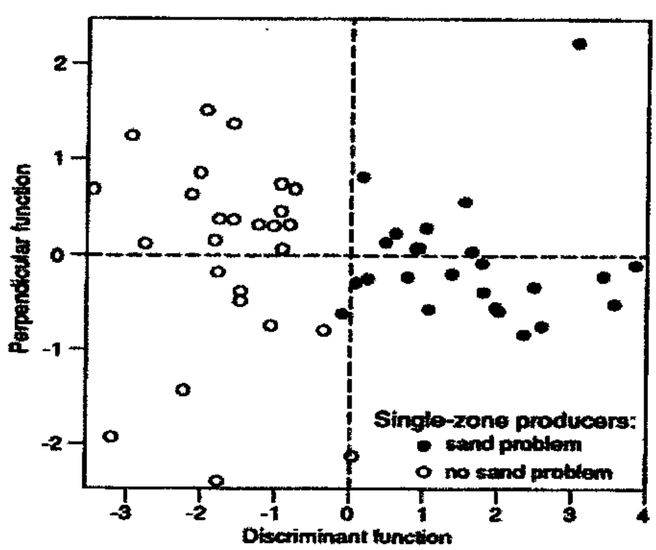


Figure 2 : Plot showing result of multiple discriminate analysis

II. Laboratory Sand Production Experiments

Laboratory sand production experiments are carried out to observe and simulate sand production in a controlled environment. It helps develop insights into the sand production mechanisms and in the influence of the various field and operational parameters on sand production. Theoretical sand prediction models can be validated against the laboratory observations. Moreover, the laboratory sand production experiments can be used as a field sand prediction tool after translation of the test results to the field situation.

In the tests on unconsolidated material, sand production is dominated by the flow rate and capillary forces. Sand production creates a cavity which gradually enlarges with increasing flow rate until at a critical flow rate it collapses. There are 2 type of test that can be modeled which is using a **thick-walled cylinder sample** and **unconfined compressive strength sample** for field application based on sand production test carried out on hollow cylinder sample.

1) Thick-Walled Cylinder Approach

The initial failure of a perforation can be related to the initial failure of a hollow cylinder core sample. The maximum near-wellbore vertical effective stress ($\sigma v,w$) sustained by a horizontal perforation is equal to the initial failure pressure of a representative thick-walled cylinder ($\sigma twc,i$).

$$\sigma v,w = \sigma twc,i \qquad (1a)$$

Where initial failure corresponds to visual damage of the inner wall. The standard dimensions of the TWC (thick-walled cylinder) sample are 25 and 8.5 mm inner and outer diameter and 50 mm length; the test configuration is shown in Fig. 3. The near-wellbore vertical effective stress is rather arbitrary defined as :

$$\sigma v,w = \sigma v + \Delta Pdd \qquad (2)$$

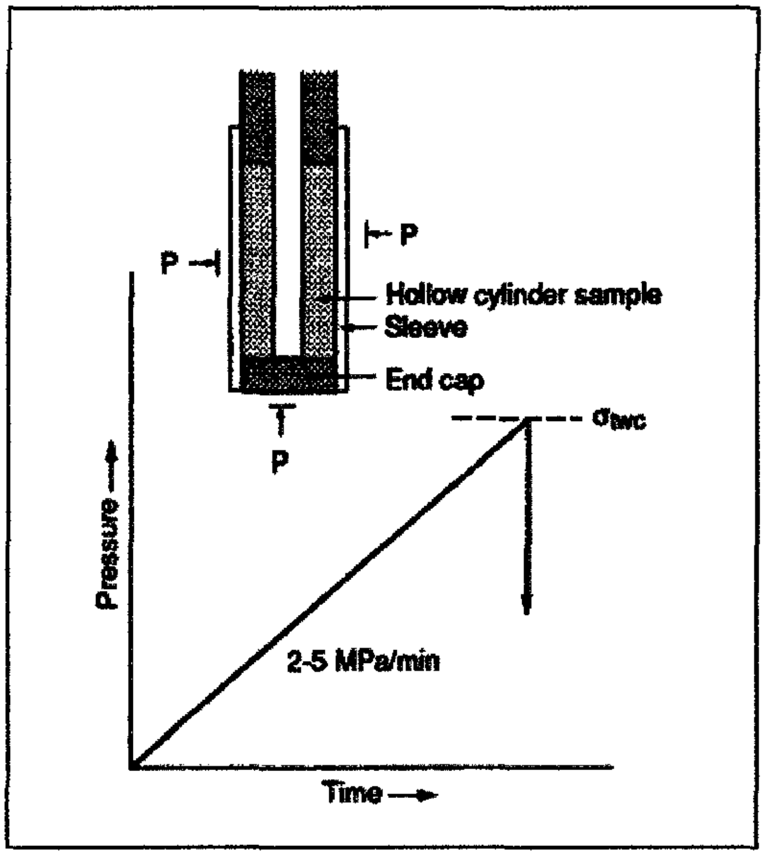


Figure 3: Thick walled cylinder collapse

Where σv is the far-field vertical effective stress. A great many TWC collapse tests carried out on friable-consolidated sandstone have established that the collapse pressure of the TWC (σtwc) is 0-30% higher than the initial failure pressure: on average σtwc,i = 0.86* σtwc · Eq. (la) may now be expressed in terms of the more readily observable TWC collapse pressure (see Fig. 3).

$$\sigma v, w = 0.86^* \sigma twc \qquad (1b)$$

The representativeness of the TWC collapse test for initial perforation failure has been investigated both experimentally and numerically. For example, the effect of the different stress regime (isotropic in the lab, anisotropic in-situ) and of the limited ratio between outer and inner diameter of the TWC sample have been investigated over a realistic range of conditions. The influence of these parameters lies within the uncertainty range quoted above
(±15%).

Eq. (1) describes initial perforation failure; but not the subsequent enlargement and (post failure) stabilization. Also, it should be noted that eq. (1) is based on intact rock testing.

Perforating introduces a zone of damaged, weakened rock around the perforation which volume can easily exceed 10 L per perforated meter (27). The prediction based on eq. (lb) is compared to field observations of sand production events (transient, continuous and catastrophic) in Fig. 4. As can be seen from Fig. 4, eq. (lb) has been found to be conservative and may be used with confidence.

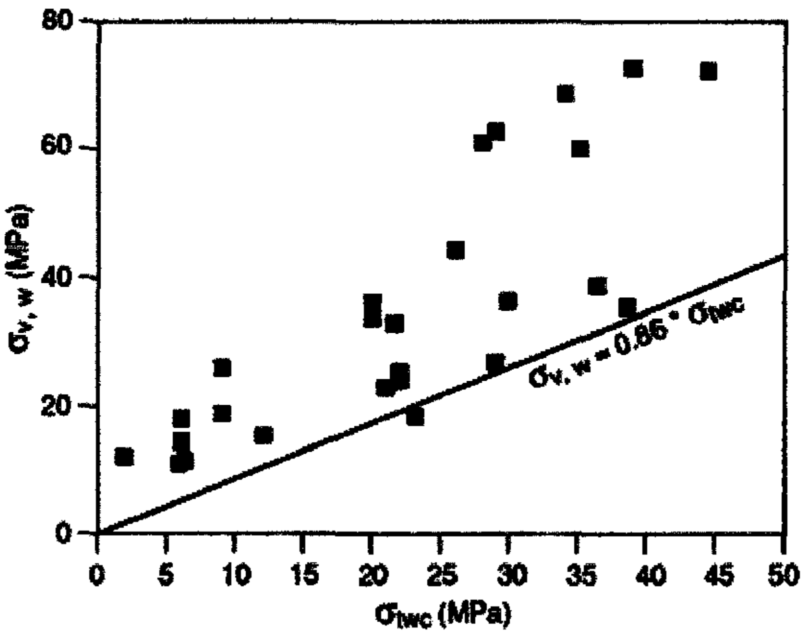


Figure 4: Near Wellbore vertical effective stress versus TWC collapse pressure

2) Thick-Walled Cylinder With Internal Pressure

The objective of thick walled cylinder approach is to obtain the radial strain, tangential and the radial stresses in a thick walled cylinder subjected to internal pressure. The sketch shows a thick walled cylinder subjected to internal pressure.

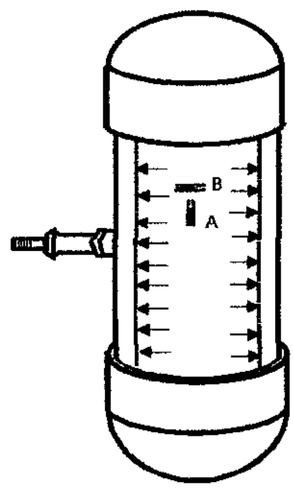


Figure 5: Thick-Walled cylinder

At any section, the stresses and strains in radial, transverse and longitudinal direction exist. The stress at any section 'A 'varies across the thickness of the cylinder. The stresses at any point at a radius of 'r' and can be calculated from the following relationship:

$$\sigma_{rr} = \frac{Pa^2}{b^2 - a^2}\left[1 - \frac{b^2}{r^2}\right] \qquad (1)$$

$$\sigma_{\theta\theta} = \frac{Pa^2}{b^2 - a^2}\left[1 + \frac{b^2}{r^2}\right] \qquad (2)$$

$$s_{rq} = t_{xy} = 0 \qquad (3)$$

where :

s = stress, psi (N/m^2)

a = internal radius = 0.94 in

b = external radius = 1.19 in

$a < r < b$

The maximum radial stress occurs at the outer edge and the maximum tangential stress occurs at the inner edge. The above stresses, longitudinal and transverse strains from the strain gage readings, can be substituted in the following relationships to compute the radial strain and longitudinal stress.

$$\varepsilon_\theta = \frac{1}{E}\left[\sigma_\theta - \nu(\sigma_r + \sigma_z)\right] \qquad (4)$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_r + \sigma_\theta)\right] \qquad (5)$$

$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \nu(\sigma_\theta + \sigma_z)\right] \qquad (6)$$

Since this is an axisymmetric problem, there are no longitudinal stresses. Hence $s_z = 0$

Equipment and supplies

- A thick walled PVC cylinder, fitted with caps, of the following dimensions

  Outer diameter = 2.38 inches

  Thickness = 0.25 inches

  Length = 11.25 inches
- Micro-Measurements temperature-compensated strain gages (4)
- IMTL Mobile Cart
- Vernier Calipers
- Accurate 12-inch scale
- Miscellaneous construction items

General Procedure

In this experiment, the cylinder will be pressurized to a required value. A strain gage at section A is bonded in the longitudinal direction and one at B is bonded in the transverse direction at section B, where the measurements can be made more conveniently and accurately.

The longitudinal and the transverse strains are measured at A and B. The radial and transverse stresses are calculated using the equations (1) and (2). Substitute r = b because we are interested in surface stresses and strains. The radial strains can be computed from the equation (6).

The longitudinal strain at section A can be corrected for transverse sensitivity by multiplying e_z by 1.025. If there is axial loading in the above problem, the longitudinal stresses are not zero and can be calculated from equations (4) or (5).

3) Unconfined Compressive Strength Approach

The primary purpose of this test is to determine the unconfined compressive strength, which is then used to calculate the unconsolidated undrained shear strength of the clay under unconfined conditions. According to the ASTM D 2166 - Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, the unconfined compressive strength (qu) is defined as the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. In addition, in this test method, the unconfined compressive strength is taken as the maximum load attained per unit area, or the load per unit area at 15% axial strain, whichever occurs first during the performance of a test.

Significance

- A quick test to obtain the shear strength parameters of cohesive (fine grained) soils either in undisturbed or remolded state
- The test is not applicable to cohesionless or coarse grained soils

Consistency	q_u (lb/ft^2
Very soft	0–500
Soft	500–1000
Medium	1000–2000
Stiff	2000–4000
Very stiff	4000–8000

Table 2 : Relative consistency as a function of unconfined compressive strength

$$S_t = \frac{q_{u(\text{undisturbed})}}{q_{u(\text{remolded})}}$$

Sensitivity calculation, St

Sensitivity, S_t	Description
1–2	Slightly sensitive
2–4	Medium sensitivity
4–8	Very sensitive
8–16	Slightly quick
16–32	Medium quick
32–64	Very quick
> 64	Extra quick

Table 3 : Sensitivity range

Test Procedure

- Remolded specimens are prepared in the laboratory depending on the proctors data at the required molding water content
- If testing undisturbed specimens retrieved from the ground by various sampling techniques, trim the samples into regular triaxial specimen dimensions (2.8" x 5.6")
- There will be a significant variation in strength of undisturbed and remolded samples
- Measure the diameter and length of the specimen to be tested
- If curing the sample (treated soils), wrap the samples in a geotextile and then a zip bag. Place the sample in a humidity room maintained at a relative humidity of 90%
- Prior to testing, avoid any moisture loss in the sample, place on a triaxial base (acrylic). The ends of the sample are assumed to be frictionless
- The triaxial cell is placed above the sample and no confinement is applied
- The rate of strain is maintained at 1.2700 mm/min as per ASTM specifications
- The data acquisition system collects real time data and the test is stopped when there is a drop observed in the strain versus load plot

III. Calculation of Sand Production Prediction (method of UCS)

There is several work flow that need to be completed in order to calculate the sand production prediction. The work flow for calculating the sand production use the method of unconfined compressive strength is:

i. Gather all sonic log data
ii. Find the dynamics rock properties
iii. Convert to static rock properties
iv. Transforming into derived rock properties
v. Calibrated of measure and calculated data
vi. Find the critical drawdown pressure and critical reservoir pressure
vii. Plotted the graph of CDP and CRP to find the area of no sand production

The data from sonic log helps in interpreting the depth of reservoir layer and give all the parameters that required in calculating the compressive strength such as the value of compressive wave velocity, sonic transit time, formation bulk density and others.

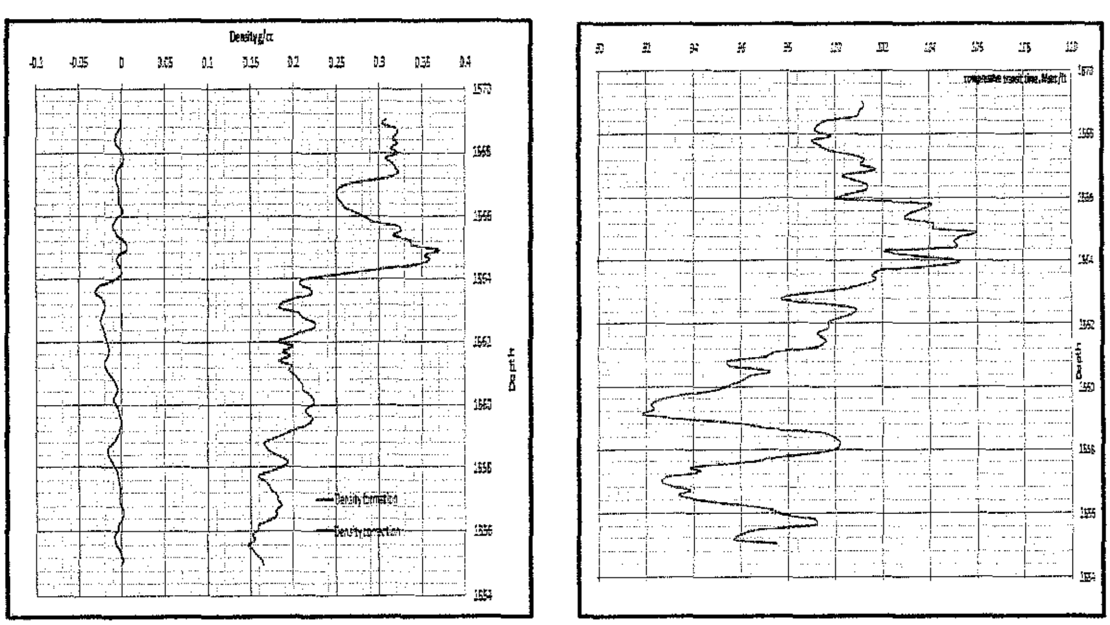


Figure 6 : Sonic Log

Then, correlate all the calibration measured and the calculated data:

$$UCS = \frac{-2c \times \cos\phi}{(1-\sin\phi)}$$ ....Equation 11

$$F = \frac{(UCS\log)}{(UCSmeasure)}$$

Thus, to get the rock strength at any area of sandstone:

UCS log * F

Next step is calculated the Critical Drawdown Pressure (CDP) and Critical Reservoir Pressure (CRP):

Poroelastic constant : $$A_p = \frac{(1-2\upsilon)\alpha}{(1-\upsilon)}$$ .... Equation 12

Where: α Biot's Effective Stress Constant. Porous & weak rock, α =1

v Poisson Ratio

Formation Collapse Strength, $u = c \times UCS$

Hence, $$CDP = \frac{1}{2-A_p}\left[2P_R - (3\sigma_1 - \sigma_3 - u)\right]$$ .... Equation 13

$$CRP = \frac{1}{2}(3\sigma_1 - \sigma_3 - u)$$ .... Equation 14

3.2 POISSON'S RATIO (n)

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio contains a minus sign so that normal materials have a positive ratio.

$n = - e_{trans} / e_{longitudinal}$

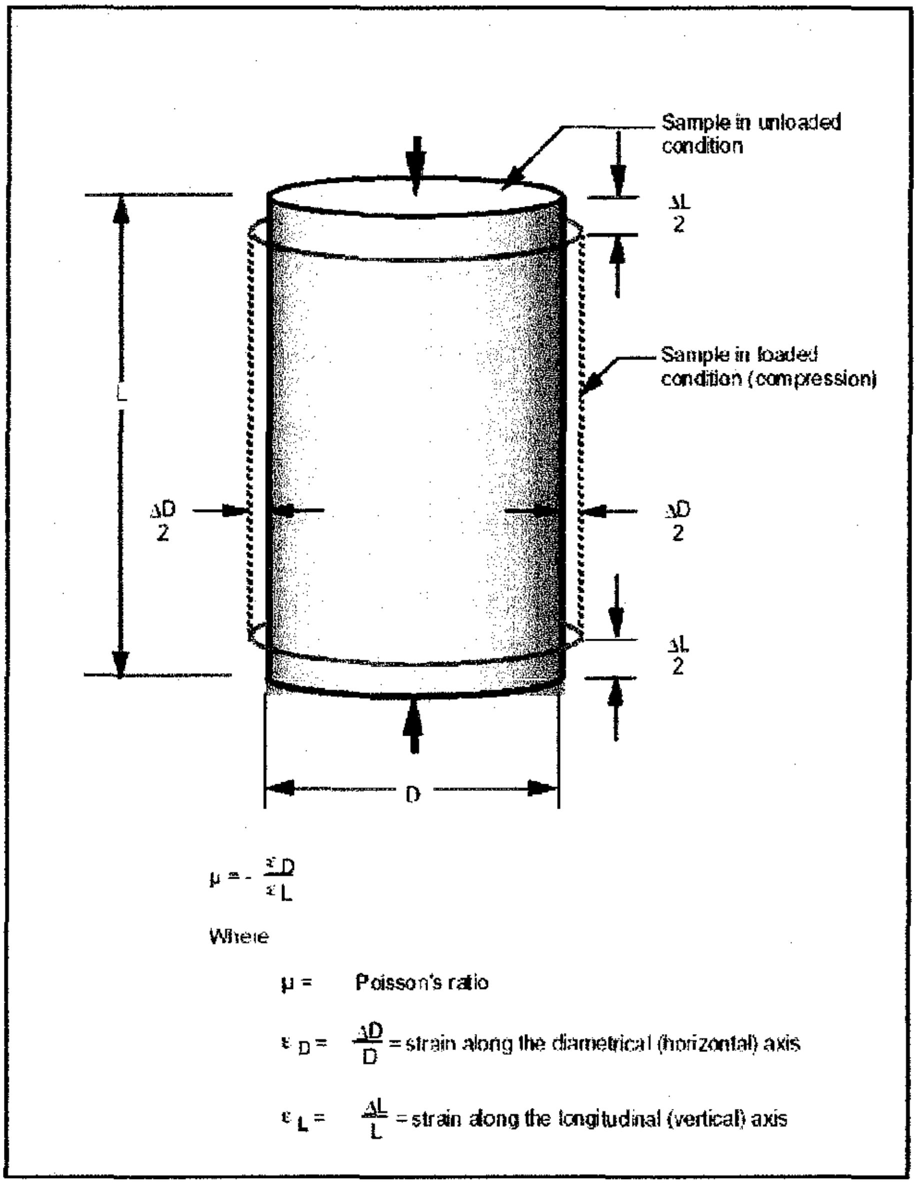


Figure 7: Poisson's Ratio

3.3 YOUNG MODULUS (E)

Young Modulus is a measure of the stiffness of an isotropic elastic material. It is defined as the ratio of the uniaxial stress over the uniaxial strain in the range of stress in which Hooke's Law holds. It can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material.

$$E \equiv \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L}$$

where

E = Young's modulus (modulus of elasticity)

F = Force applied to the object;

A_0 = Original cross-sectional area through which the force is applied;

ΔL = Amount by which the length of the object changes;

L_0 = Original length of the object.

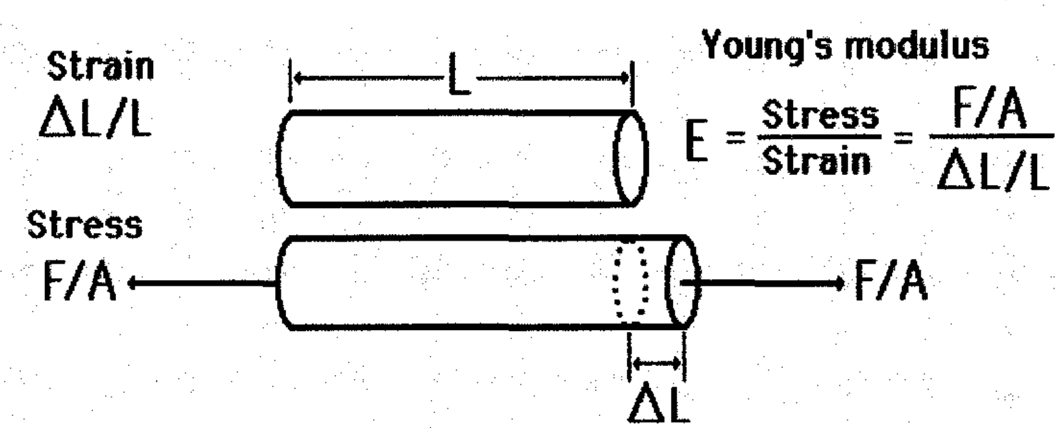


Figure 8: Young Modulus

3.4 MOHR'S COULOMB

Mohr–Coulomb theory is a mathematical model describing the response of brittle materials such as concrete, or rubble piles, to shear stress as well as normal stress. Most of the classical engineering materials somehow follow this rule in at least a portion of their shear failure envelope. Generally the theory applies to materials for which the compressive strength far exceeds the tensile strength.

In Geotechnical Engineering it is used to define shear strength of soils and rocks at different effective stresses.

In structural engineering it is used to determine failure load as well as the angle of fracture of a displacement fracture in concrete and similar materials. Coulomb's friction hypothesis is used to determine the combination of shear and normal stress that will cause a fracture of the material. Mohr's circle is used to determine which principal stresses that will produce this combination of shear and normal stress, and the angle of the plane in which this will occur. According to the principle of normality the stress introduced at failure will be perpendicular to the line describing the fracture condition.

It can be shown that a material failing according to Coulomb's friction hypothesis will show the displacement introduced at failure forming an angle to the line of fracture equal to the angle of friction. This makes the strength of the material determinable by comparing the external mechanical work introduced by the displacement and the external load with the internal mechanical work introduced by the strain and stress at the line of failure. By conservation of energy the sum of these must be zero and this will make it possible to calculate the failure load of the construction.

A common improvement of this model is to combine Coulomb's friction hypothesis with Rankine's principal stress hypothesis to describe a separation fracture.

The Mohr–Coulomb failure criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress. This relation is expressed as :

$$\tau = \sigma \ \tan(\phi) + c$$

Where

τ	=	shear strength,
σ	=	normal stress,
c	=	intercept of the failure envelope with the τ axis,
φ	=	slope of the failure envelope.

The quantity c is often called the **cohesion** and the angle φ is called the **angle of internal friction**. Compression is assumed to be positive in the following discussion. If compression is assumed to be negative then σ should be replaced with $-\sigma$.

If $\varphi = 0$,

The Mohr–Coulomb criterion reduces to the Tresca criterion. On the other hand, if $\phi = 90^\circ$ the Mohr–Coulomb model is equivalent to the Rankine model. Higher values of φ are not allowed.

From Mohr's circle we have:

$$\sigma = \sigma_m - \tau_m \sin\phi \ ; \quad \tau = \tau_m \cos\phi$$

Where:

$$\tau_m = \frac{\sigma_1 - \sigma_3}{2} \ ; \quad \sigma_m = \frac{\sigma_1 + \sigma_3}{2}$$

And σ_1 is the maximum principal stress and σ_3 is the minimum principal stress.

Therefore the Mohr–Coulomb criterion may also be expressed as

$$\tau_m = \sigma_m \sin\phi + c\cos\phi \ .$$

This form of the Mohr–Coulomb criterion is applicable to failure on a plane that is parallel to the σ_2 direction.

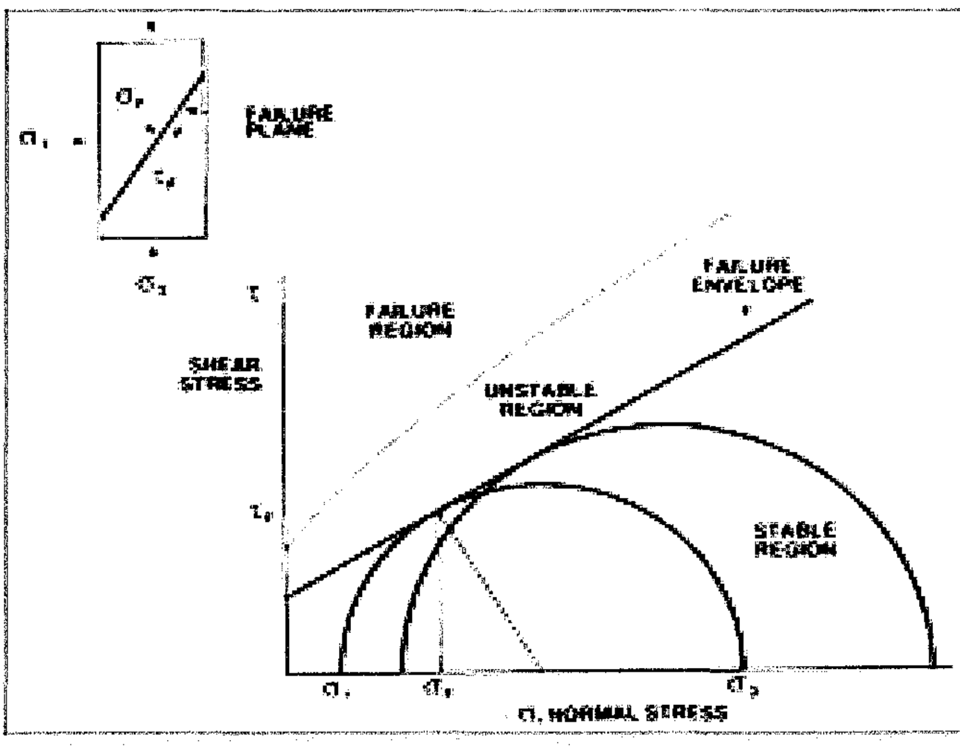


Figure 9: Mohr Coulomb Circle

CHAPTER 4

4.1 RESEARCH METHODOLOGY

4.1.1 Identify the data required in a complete evaluation for predicting sand production potential.

4.1.2 Analyze on the factor believed to influence a well tendency to produce sand production.

4.1.3 Testing the core by mechanical application to identify shear modulus, Poisson ratio, young modulus, Mohr coulomb, and compressive strength

4.1.4 Analyze from the SPE paper regarding the theory and case study that have been conducted at certain area possible to produce sand.

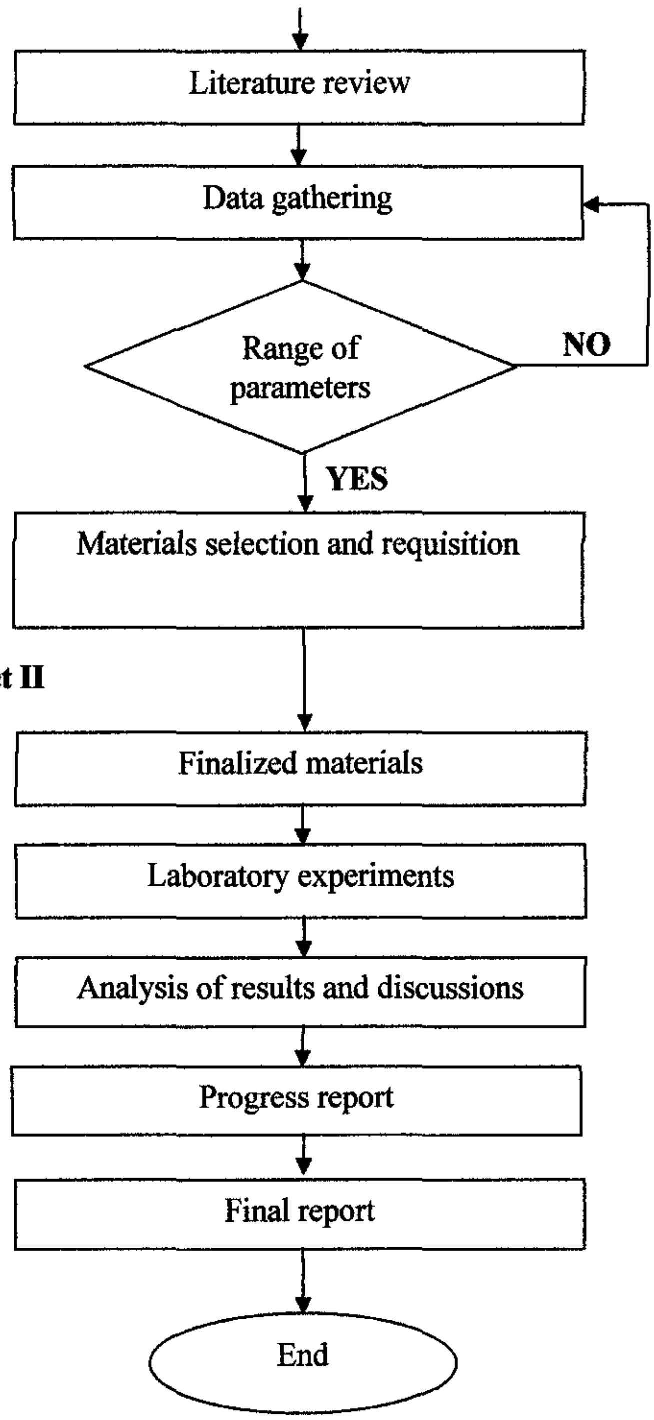
4.1.5 Analyze the well log data and in situ stress

4.1.6 Identify the theoretical modeling that required mathematical formulation of the sand failure mechanism which is compressive failure, tensile failure and erosion.

4.1.7 Designing the unconfined compressive strength (USC) laboratory testing for axial and tri-axial forces to identify the rock properties.

4.2 PROCEDURE IDENTIFICATION

Final Year Project I



Final Year Project II

4.3 PROJECT ACTIVITIES

No.	Subject / Activity	First Semester	Second Semester
1.	Project Proposal	/	
2.	Literature Review	/	
3.	Collecting and Analyzing Data	/	
4.	Compilation of Literature Review	/	
5.	Equipments Selection	/	
6.	Draft of Laboratory Works	/	
7.	Interim Report	/	
8.	Methodology of Laboratory Works		/
9.	Materials Selection and Preparation		/
10.	Laboratory Experiments		/
11.	Result Interpretation and Analysis		/
12.	Final Report		/

Table 4: Project activities

4.4 KEY MILESTONE

No.	Activities	Date/Week
1.	Gathering information and (material) soil selection	W1-W2
2.	Laboratory experiment	W3-W5
3.	Result interpretation and data analysis	W6-W8
4.	Submission of progress report	W8
5.	Pre EDX, seminar, poster exhibition and submission of finale report	W11
6.	*Engineering design exhibition*	W12
7.	Final oral presentation	W13
8.	Evaluation by external examiners	W14
9.	Submission of hardbound copies of report	W16

Table 5: Key milestone

4.6 GANTT CHART

No	Task Name	Week															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Material selection	■	■														
2	Laboratory experiment			■	■	■											
3	Result interpretation and data analysis						■		■	■							
4	Submission of progress report								■	■							
5	Pre EDX, seminar, poster exhibition and submission of finale report										■	■					
6	Engineering design exhibition												■				
7	Final oral presentation													■			
8	Evaluation by external examiners														■		
9	Submission of hardbound copies of report															■	■

Table 6: Gantt chart

]

CHAPTER 5

5.1 RESULT AND DISCUSSION

UNCONFINED COMPRESSIVE STRENGTH TEST ANALYSIS

Purpose:

The primary purpose of this test is to determine the unconfined compressive strength, which is then used to calculate the unconsolidated undrained shear strength of the clay under unconfined conditions. According to the ASTM standard, the unconfined compressive strength (q_u) is defined as the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. In addition, in this test method, the unconfined compressive strength is taken as the maximum load attained per unit area, or the load per unit area at 15% axial strain, whichever occurs first during the performance of a test.

Standard Reference:

ASTM D 2166 - Standard Test Method for Unconfined Compressive Strength of Cohesive Soil

Significance:

For soils, the undrained shear strength (s_u) is necessary for the determination of the bearing capacity of foundations, dams, etc. The undrained shear strength (s_u) of clays is commonly determined from an unconfined compression test. The undrained shear strength (s_u) of a cohesive soil is equal to one-half the unconfined compressive strength (q_u) when the soil is under the f = 0 condition (f = the angle of internal friction). The most critical condition for the soil usually occurs immediately after construction, which represents undrained conditions, when the undrained shear strength is basically equal to the cohesion (c). This is expressed as:

$$su = u = \frac{qu}{2}$$

Then, as time passes, the pore water in the soil slowly dissipates, and the intergranular stress increases, so that the drained shear strength (s), given by s = c + s'tan f , must be used. Where s' = intergranular pressure acting perpendicular to the shear plane; and s' = (s - u), s = total pressure, and u = pore water pressure; c' and φ' are drained shear strength parameters.

5.2 Experimental work

Objectives:

To determine an unconfined compressive strength of cylinder specimen of soil

Apparatus:

1) Mechanical Load Frame
2) Calibrated force-measuring device (load ring)
3) Platen with strain dial gauge
4) Dial gauge
5) Lever assembly for fitting to dial gauge
6) Apparatus for extruding and trimming the soil specimens
7) Clinometers or protractors
8) Stop clock

General Discussion:

A cylindrical specimen of soil is subjected to a steadily increasing axial load until failure occurs. In the unconfined test, the axial load is the only force or stress which is applied to the soil. Axial compression is applied to the specimen at constant rate of deformation.

Procedure:

A: Preparation of apparatus

1. The load frame is ensured stands firmly on a solid level bench top or support.
2. The attachment of the load ring to the cross head of the frame is checked out and is fitted at necessary extension pieces, and the upper platen, securely to the lower end of the ring.

3. The load ring dial gauge is checked securely held at the end of the stem makes contact with the adjustable stop on the ring. The lower platen is located centrally on the machine platen and the dial gauge is stated post vertically upright.
4. Level of lower platen is adjusted to allow enough clearance to insert the test specimen
5. The gear position which will give a platen speed between 0.05% and 2% of the specimen length per minute is selected. (the time to failure should not exceed 15 min)

   Note: Soft soils which require large deformations to failure will require somewhat rate of strain, whereas stiff or brittle materials which fail at small deformations will require lower rates of strain.

B: <u>Preparation of test specimen</u>

1. Cylindrical compression test of 38mm in diameter is take from a block sample of soft or fairly firm clay by pushing in a thin-walled 38mm sampling tube, which has a sharp cutting edge.

C: <u>Setting up specimen</u>

1. The specimen is placed centrally on the lower platen of the machine, and that specimen axis is checked in vertical.
2. The platen is wind up by hands until the specimen just makes contact with the top platen (this will be indicated by a frictional movement of a load dial gauge)
3. The strain dial gauge is adjusted on the pillar to read zero, or a convenient initial reading.

D: <u>Compression test</u>

1. The motor is switched on and the clock starts reading at the same time. The clock can be used to verify that the correct rate of train is being applied.
2. The readings at granular intervals are recorded every 0.2mm, of the strain dial readings.
3. Continue loading and taking the reading until it is certain that failure has been occurred.

4. The machine is stopped when the specimen is failed, allow the motor to stop completely and put it into reverse. The load dial gauge is read as a check on the initial reading under zero loads.
5. The machine platen is lowered far enough to enable the specimen to be removed.

   Note: If the machine speed is to be checked, record the time from the start also. When the rates of the increase of the load dial reading become small, fewer reading are need to be taken. If the load dial readings increase rapidly near that start of the test, take reading at granular intervals of load dial reading so that enough readings are taken to define the stress-strain curve before failure. At least 12 sets of reading should be obtained up to failure.

E: <u>Removing specimen</u>

1. The machine is stopped when the specimen is failed; allow stopping completely and putting into reverse; or winning down by hand until the load is taken off the specimen.
2. The load dial gauge is read as a check on the initial reading under zero loads.
3. The machine plate is lowered down far enough to enable the specimen to be removal.
4. The specimen is carefully removed from the base platen, keeping it together in one piece. It is plated on a small weight dry or moisture content container, together with any soil adhering to the upper and lower platens.

F: <u>Measurement of moisture content</u>

1. The container mass is weighted (m1)
2. The specimen and container is weighted to 0.1g (m2) and placed in standard drying oven overnight
3. The specimen is take out from the oven and weight the dry specimen and container ti 0.1g (m3)

G: <u>Plotting the stress-strain curve</u>

1. Calculated values of compressive stress are plotted as ordinate against corresponding value of strain (expressed as percentage) as abscissa, and draw the stress-strain curve through the points.

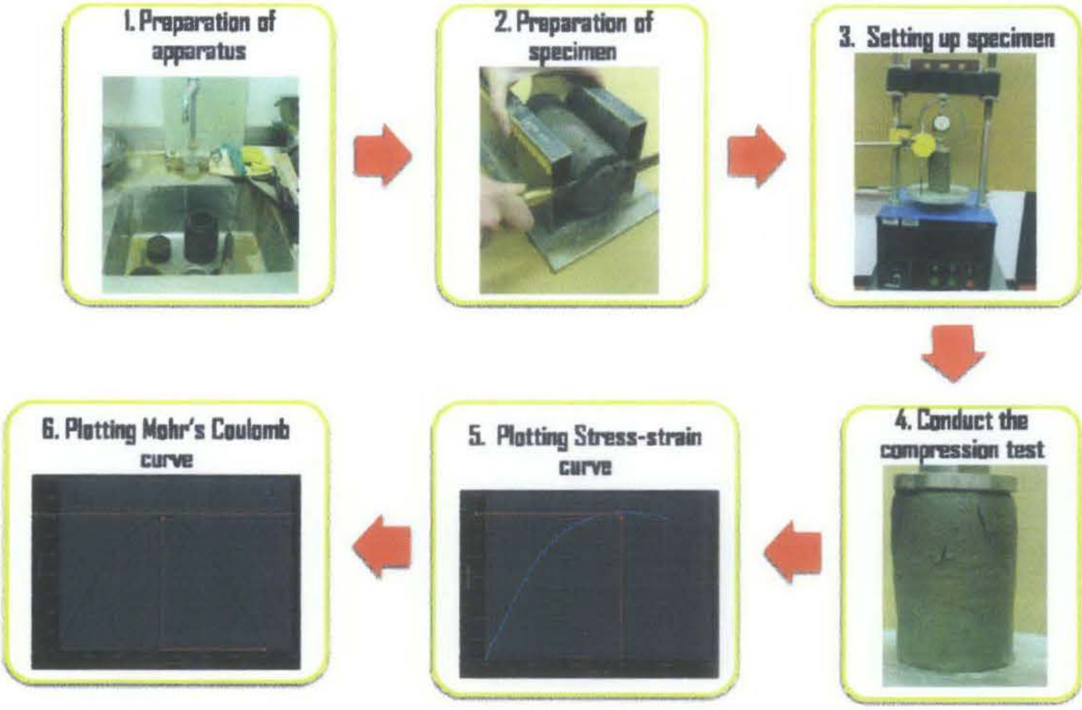


Figure 10: Laboratory procedure

Analysis:

1. Convert the dial readings the appropriate load and length units, and enter these values on the data sheet in the deformation and total load columns. (confirm that the conversion is done correctly, particularly proving dial gauge readings conversion into load)
2. Compute the sample cross section area, ⟶ $Ao = \frac{\pi}{4} \times (d)^2$
3. Compute the strain, ⟶ $e = \frac{L}{Lo}$
4. Compute the corrected area, ⟶ $A' = \frac{Ao}{1-e}$
5. Using A', compute the specimen stress, ⟶ $Sc = \frac{P}{A'}$
6. Compute the water content, W%
7. Plot the stress strain. Show q_u as the peak stress (or at 15% strain) of the best. Be sure that the strain is plotted on the abscissa.
8. Draw Mohr's circle using q_u from the last step and show the undrained shear strength, Su = c = cohesion = $q_u/2$

Result:

Diameter (d) : 7.29 cm

Length (Lo) : 14.78 cm

Mass : 1221.4 g

Moisture can number – Lid number	A
Mc = Mass of empty, clean can +lid (grams)	15.6
Mcms = Mass of can, lid, and dry soil (grams)	45.7
Mcds = Mass of can, lid and dry soil (grams)	39.5
Ms = Mass of soil solids (grams)	23.9
Mw = Mass of pore waters (grams)	6.2
W = Water content (W%)	25.94

Table 7: Moisture content determination

Area $Ao = \frac{\pi}{4} \times (7.27)^2$ $= 41.74\ cm^2$

Volume = $\frac{\pi}{4} \times (7.27)^2 \times 14.78$ $= 616.9\ cm^3$

Wet density = $\frac{1221.4}{616.9}$ $= 1.98\ g/cm^3$

Water content (W%) = 25.9%

Dry density (ρd) = $\frac{1.98}{1+\frac{25.9}{100}}$ $= 1.57\ g/cm^3$

Deformational unit : 1 unit = 0.10 mm

Load unit : 1 unit = 0.3154 lb

Deformation dial reading	Load dial reading	Sample deformation on ΔL (mm)	Strain Ɛ	% strain	Corrected area A'	Load, lb	Load, KN	Stress, KPa
0	0	0.0	0.000	0.000	41.740	0.000	0.000	0.000
20	4	0.2	0.001	0.135	41.797	1.262	56.118	1.343
40	9	0.4	0.003	0.271	41.853	2.839	126.267	3.017
60	12	0.6	0.004	0.406	41.910	3.785	168.355	4.017
80	19	0.8	0.005	0.541	41.967	5.993	266.563	6.352
100	21	1.0	0.007	0.677	42.024	6.623	294.622	7.011
120	24	1.2	0.008	0.812	42.082	7.570	336.711	8.001
140	26	1.4	0.009	0.947	42.139	8.200	364.770	8.656
160	29	1.6	0.011	1.083	42.197	9.147	406.859	9.642
180	33	1.8	0.012	1.218	42.255	10.408	462.978	10.957
200	36	2.0	0.014	1.353	42.313	11.354	505.066	11.937
250	45	2.5	0.017	1.691	42.458	14.193	631.333	14.870
300	54	3.0	0.020	2.030	42.605	17.032	757.600	17.782
350	64	3.5	0.024	2.368	42.752	20.186	897.896	21.002
400	74	4.0	0.027	2.706	42.901	23.340	1038.192	24.200
450	84	4.5	0.030	3.045	43.051	26.494	1178.488	27.374
500	93	5.0	0.034	3.383	43.201	29.332	1304.755	30.202
550	102	5.5	0.037	3.721	43.353	32.171	1431.022	33.008
600	112	6.0	0.041	4.060	43.506	35.325	1571.318	36.117
650	120	6.5	0.044	4.398	43.660	37.848	1683.555	38.560
700	129	7.0	0.047	4.736	43.815	40.687	1809.821	41.306
750	138	7.5	0.051	5.074	43.971	43.525	1936.088	44.031
800	144	8.0	0.054	5.413	44.129	45.418	2020.266	45.781
850	152	8.5	0.058	5.751	44.287	47.941	2132.503	48.152
900	160	9.0	0.061	6.089	44.446	50.464	2244.740	50.504
950	166	9.5	0.064	6.428	44.607	52.356	2328.917	52.209
1000	171	10.0	0.068	6.766	44.769	53.933	2399.065	53.588
1100	182	11.0	0.074	7.442	45.096	57.403	2553.391	56.621
1200	192	12.0	0.081	8.119	45.428	60.557	2693.688	59.295
1300	202	13.0	0.088	8.796	45.765	63.711	2833.984	61.924
1400	209	14.0	0.095	9.472	46.107	65.919	2932.191	63.595
1500	217	15.0	0.101	10.149	46.455	68.442	3044.428	65.536
1600	223	16.0	0.108	10.825	46.807	70.334	3128.606	66.840
1700	229	17.0	0.115	11.502	47.165	72.227	3212.784	68.118
1800	234	18.0	0.122	12.179	47.528	73.804	3282.932	69.073
1900	240	19.0	0.129	12.855	47.897	75.696	3367.109	70.299
2000	243	20.0	0.135	13.532	48.272	76.642	3409.198	70.625
2200	250	22.0	0.149	14.885	49.040	78.850	3507.406	71.522
2400	253	24.0	0.162	16.238	49.832	79.796	3549.495	71.230
2600	255	26.0	0.176	17.591	50.650	80.427	3577.554	70.633
2800	256	28.0	0.189	18.945	51.496	80.742	3591.583	69.745
3000	254	30.0	0.203	20.298	52.370	80.112	3563.524	68.045

Table 8: Unconfined compression test data

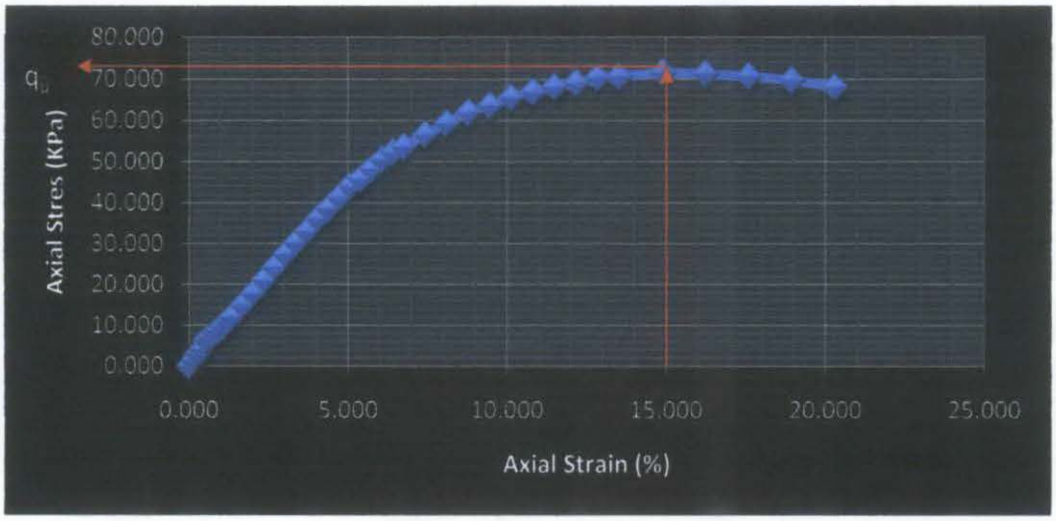


Figure 11: Stress-strain curve

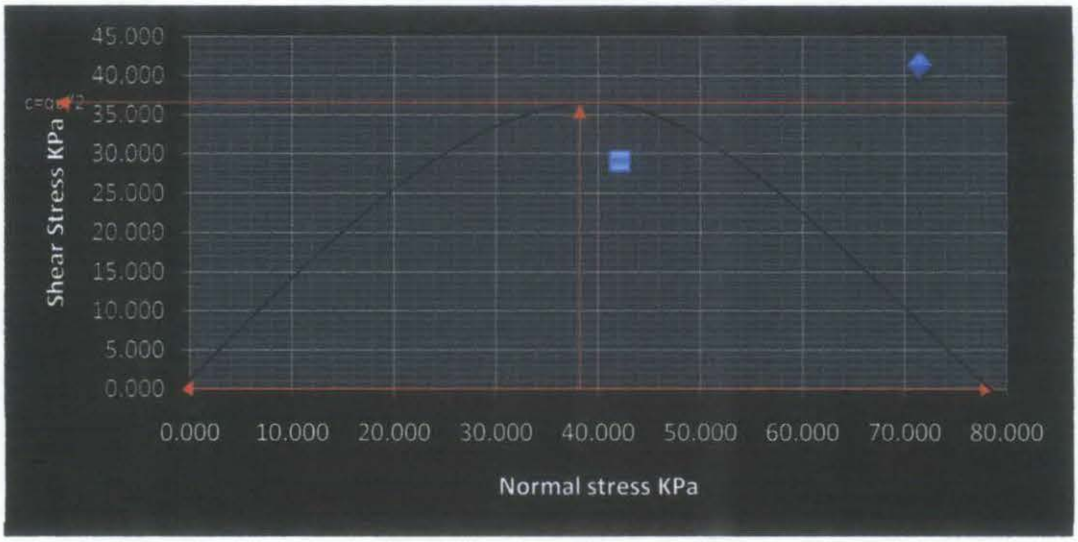


Figure 12: Plotted Mohr's Coulomb circle

From the graph above, the value of unconfined compressive strength is 72 KPa.

Thus, Su = C or cohesion is $q_u/2$ = 36 KPa

5.3 APPLICATION IN INDUSTRY

In this section the author study based on the case study that develop by the industry in predicting the sand production using the method of numerical modeling and calculation as the initial stage predicting the sand.

Data given from sonic log:

1) Compressive wave velocity, Vp = 100 μsec/ft or 3.048 km/s
2) Bulk density, ρbulk = 2.3 g/cc

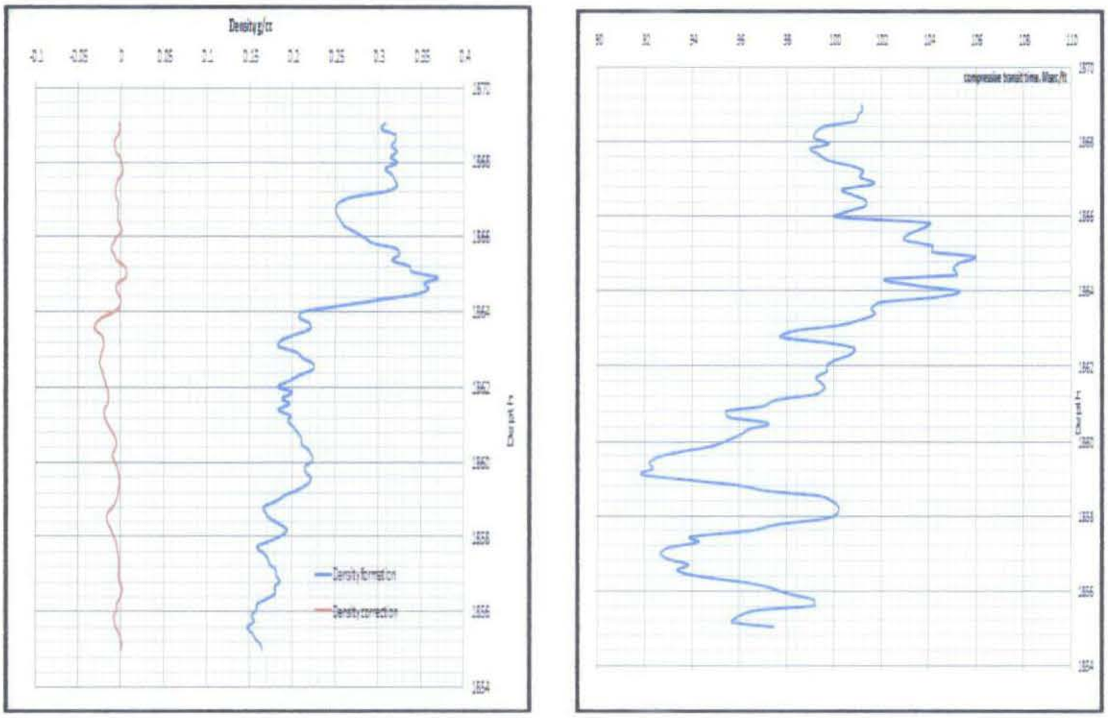


Figure 13: Log data for selecting depth to test the core

Step 1

Dynamic rock properties $E_D = 0.265V_P^{2.04}$

$$E_D = 0.265(3.048)^{2.04} = 2.574 km/s$$

Step 2

Static rock properties $E_S = 0.0293E_D^2 + 0.4533E_D$

$$E_S = 0.0293(2.574)^2 + 0.4533(2.574) = 1.361 km/s$$

Step 3

Derived rock properties $UCS = 2.28 + 4.1089E_S$

$$UCS = 2.28 + 4.1089(1.361) = 7.87 MPa$$

Step 4

Experimental work/ Laboratory test data analysis

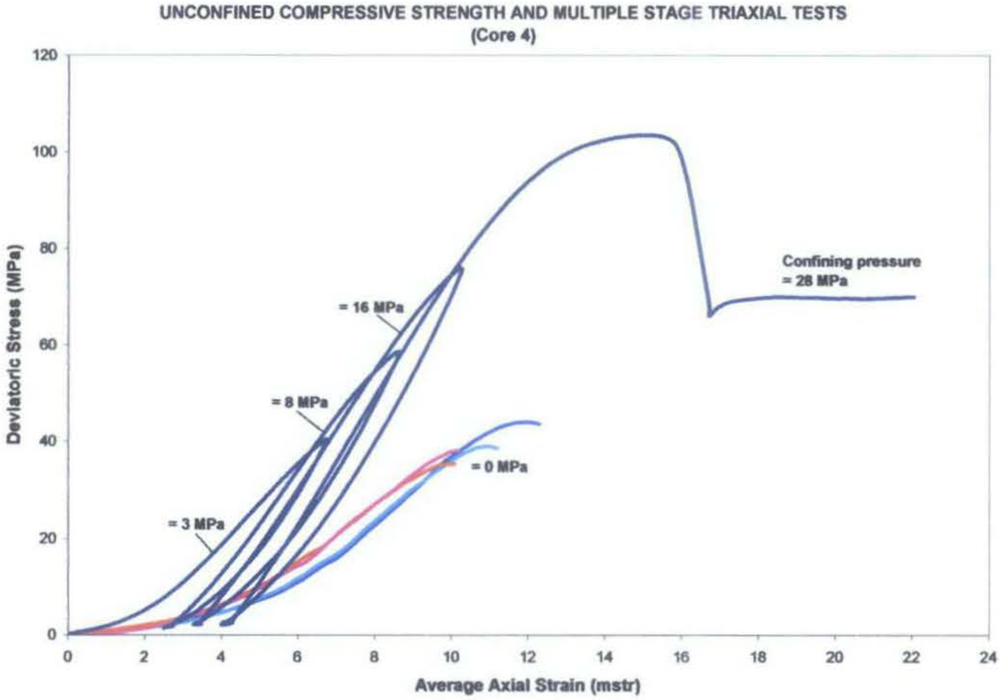


Figure 14: Stress-strain analysis graph

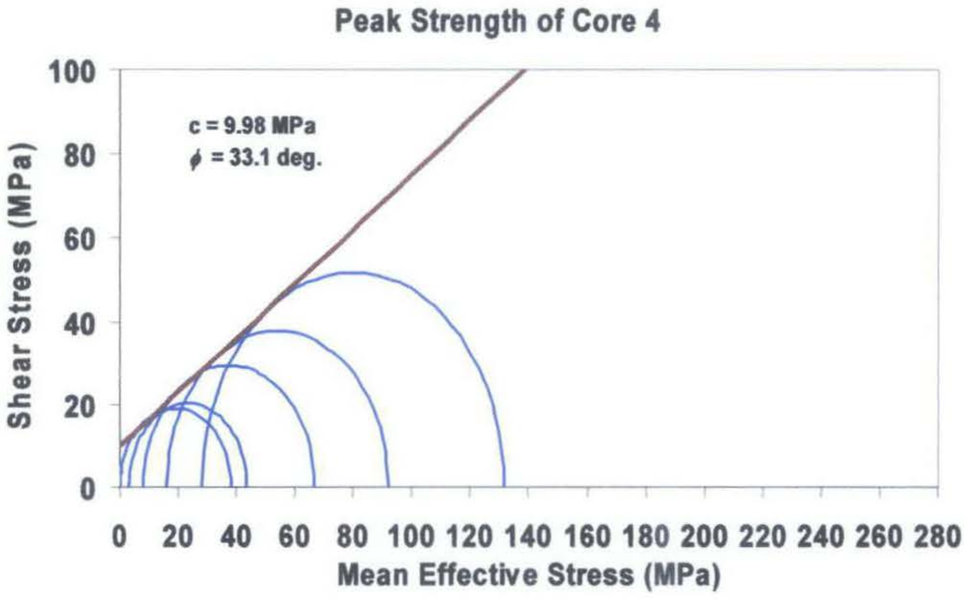


Figure 15: Plotted Mohr's Coulomb Circle

Step 5

Calibrate measured and calculate data $UCS = \frac{-2c \times \cos\phi}{(1-\sin\phi)}$

$$\sigma_1^{'} = 2c \cdot \tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right) + \sigma_3^{'} \tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right)$$

Result

Core Depth (mMDKB)	Young's Modulus (GPa)			Poisson's Ratio		
	Static Value	Dynamic Value	Calibration Factor	Static Value	Dynamic Value	Calibration Factor
1855.1 - 1855.28	8.89	14.6	0.609	0.23	0.33	0.697
1858.28 - 1858.36	12.32	15.23	0.809	0.38	0.33	1.152
1868.91 - 1869.10	10.38	12.38	0.838	0.32	0.33	0.970
Average			**0.752**			**0.939**

Table 9: Young Modulus and Poisson Ratio data

Core Depth (mMDKB)	Unconfined Compressive Strength (MPa)	Effective Cohesion (MPa)	Effective Angle of Internal Friction (degree)	Tensile Strength (MPa)
1855.1 – 1855.28	38.06	9.80	35.5	2.33
1858.28 – 1858.36	36.84	9.98	33.1	2.63
1868.91 – 1869.10	27.56	7.67	31.8	3.81

Table 10: UCS, cohesion, angle of friction and tensile strength data

Core Depth (mMDKB)	UCS (MPa)			Cohesion (MPa)		
	Measur ed	Correlated	Calibration Factor	Measured	Correlated	Calibration Factor
1855.1 - 1855.28	38.06	26.83	1.419	9.8	6.24	1.571
1858.28 - 1858.36	36.84	27.76	1.327	9.98	6.57	1.519
1868.91 - 1869.10	27.56	23.49	1.173	7.67	6.71	1.143
Average			**1.306**			**1.411**

Table 11: Corrected UCS and Cohesion

Core Depth (mMDKB)	Frictional Angle (°)			Tensile Strength (MPa)		
	Measured	Correlated	Calibration Factor	Measured	Correlated	Calibration Factor
1855.1 - 1855.28	35.5	40.07	0.848	2.33	2.24	1.04
1858.28 - 1858.36	33.1	39.33	0.796	2.63	2.31	1.139
1868.91 - 1869.10	31.8	30.51	1.052	-	-	-
Average			**0.899**			**1.089**

Table 12: Friction angle and tensile strength data

Sand	Depth (mKB)	Original reservoir pressure, Psi	Critical drawdowm pressure, CDP Psi	Critical reservoir pressure, CRP Psi
D	1219.74	1815.2	4345.65	-823.6
E	1683.41	2375.2	5653.55	-843.9
E	1864.61	2805.8	4370.3	313.2
F	2482.44	7479.1	4213.7	4883.6
D	1495.04	2114.1	2815.9	403.1
F	1925.26	3587.3	5684	78.3
D	1583.13	2263.5	4483.4	-426.6
E	1818.13	3168.3	5311.4	138.7
D	1689.66	2359.2	4827.1	-642.4
F	2234.03	5280.9	698.9	4827.1

Table 13: CDP and CRP data

Discussion

The final step in predicting the sand production in plotting the graph of flowing bottom hole pressure versus reservoir pressure and analysis on the critical drawdown pressure and critical reservoir pressure on that plotted graph. Illustrated as figure below:

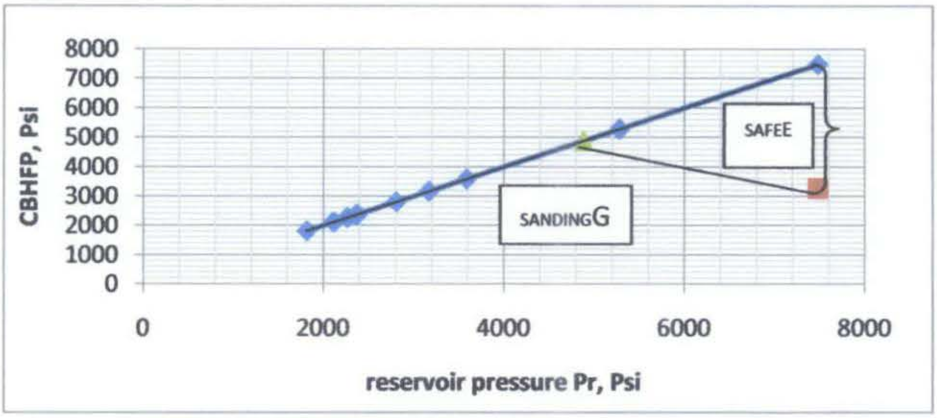


Figure 16: FBHP versus Pr graph

The CDP and CRP are plotted for the deepest targeted area which the depth is 2482.44 mKB where the CDP and CRP are 4213.7 and 4883.6 respectively. By plotting this value in the FBHP versus Pr graph, the area of sanding and are of safe is the illustrated as above.

Thus, this result will help a lot and be the target of all completion engineers to design the completion of the well in order to prevent from the sand problem. By having this research being conducted, lots of sand problem can be solved and not cause the major problem that will finally result in closed the well.

CHAPTER 6

6.1 CONCLUSION AND RECOMMENDATION

As the conclusion, being able to predict whether a well will produce fluids without producing sand or predicting that some type of sand control will be required has been the goal of many completion engineers and research projects. In spite of the fact that there have been a number of analytical techniques and guidelines developed to assist in determining if sand control is necessary, no technique has yet proven to be universally acceptable or completely accurate.

The most suitable technique that can simply be implemented in predicting the sand formation is by using the analytical modeling which calculates the rock compressive strength where maximum pressure applied before the rock failure. This analytical modeling can be completed by testing the core sample using thick-walled cylindrical approach and unconfined compressive strength. After completing the experiment on the compressive strength, the result data can be correlated with the real formation and production data of the well. This method known as calculating sand production prediction where we plotted the graph of reservoir pressure and flowing bottom hole pressure where we can find the critical draw down pressure at critical reservoir pressure.

The area under this condition will indicate the safe area where no sand will produce during the whole drilling and production operation.

As the recommendation, this project can be simply implemented as the first step of precaution action to avoid sand from producing and cause many problems to the equipment and the major disadvantages is will required high cost of removal and treatment of the sand such as sand control and equipment malfunction.

6.2 REFERENCES

1. JPT. November 1994 "sand Production Prediction" W.R. MOORE, SPE, BJ Services Co.

2. SPE 136980 "Practical Guideline for Predicting Sand Production" Samuel O. Osisanya, SPE, University of Oklahoma.

3. SPE 22792 "Sand Production Prediction Review : Developing an Integrated Approach" C.A.M. Veeken, D.R. Davies, C.J. Kenter, and A.P. Kooijman, Shell Research B.V.

4. SPE/ISRM 78234 "Sand Production Prediction of Gas Field- Methodology and Field Application" B. Wu, SPE and C.P. Tan, SPE, CSIRO Petroleum, Perth, Australia.

5. SPE 112394 " Sanding Study For Deepwater Indonesia Developing Wells-A Case History of Prediction and Production" Ian D. Palmer and Nigel G. Higgs, Higgs-Palmer technologies; Robert M. Mathers & Scott R. Herman, Chevron.

6. SPE 90273 "Sand Production Prediction: A New Set of Criteria for Modeling Based on Large Scale Transient Experiments and Numerical Modeling" Alireza Nouri, Dalhousie University; Hans Vaziri, BP-America inc; hadi Belhaj, Rafiqul Islam, Dalhousie University.

7. JCPT March 1998, Volume 37, No 3 "Modeling of Sand Production from Wells on Primary Recovery" B. TREMBLAY, G. SEDGWICK, Alberta Research Council.

8.SPE 24798 "Large Scale Laboratory Sand Production Test" A.P Kooijman, Koninklijke/Shell E&P Laboratorium; P.M Lalleck, Terra Tek Inc.

9. SPE Drill. & Completion 15(4), December 2000 "A New Concept of Sand Production Prediction: Theory and Laboratory Experiments" P.J van den Hoek, SPE, G.M.M. Hertogh, A.P Kooijman, SPE, Ph. De Bree, SPE, and C.J Kenter, SPE Shell Intl. E&P B.V