# EFFECT OF BENTONITE DRILLING FLUID ON SKIN RESISTANCE OF THE PILE

A Dissertation submitted in partial fulfillment of the requirement for the Award of degree of

## MASTER OF TECHNOLOGY

**IN**

## GEOTECHNICAL ENGINEERING

**BY**


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## CANDIDATE'S DECLARATION

I do hereby certify that the work presented is the report entitled "**Effect of bentonite drilling fluid on skin resistance of the pile**" in the partial fulfillment of the requirements for the award of the degree of "Master of Technology" in geotechnical engineering submitted in the Department of Civil Engineering, Delhi Technological University, is an authentic record of our own work carried out from December 2014 to June 2015 under the supervision of Dr. Amit Kumar Shrivastava (Assistant Professor), Department of Civil Engineering.

I have not submitted the matter embodied in the report for the award of any other degree or diploma.

Shubham Vishwakarma

Date: 29 June 2015 (2K13/GTE/19)

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## CERTIFICATE

This is to certify that above statement made by the candidate is correct to best of my knowledge.

Dr. Amit Kumar Shrivastava
(Assistant Professor)
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# ABSTRACT

Pile foundations are found as an economical and effective foundation system for high rise buildings. With increasing use of long straight shafts necessitated accurate assessment of uplift resistance. Since last 70 years, for the construction of bored cast-in-situ piles, bentonite has been used as a borehole stabilizer. The action of bentonite in stabilizing the sides of bore holes is primarily due to thixotropic property of bentonite which permits the material to have the consistency of a fluid when introduced into a hole. When left undisturbed it forms a jelly like membrane of low permeability on the excavated borehole wall around the soil particles, helping in its stabilization but in return reduces the frictional resistance of pile. To check the effect of bentonite support fluid on skin resistance of the pile, the project work has been carried out which includes laboratory as well as experimental works. In laboratory work, influence of various parameters such as concentration of bentonite, time without agitation, effect of addition of poly-fluid and alum and silt content on the rheological properties has been studied and the dissertation also presents the results of a set of bentonite–sand interface shear tests carried out using bentonite support fluids, and a real life problem of pile is physically modeled and pull out test has been performed on a fabricated laboratory setup. The field test on modeled concrete piles has shown reduction in uplift capacity of the pile due to the formation of soft filter cake.

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# CHAPTER 1
# INTRODUCTION

## 1.1 Preamble

Improvement in load carrying capacity of pile foundation in recent time has been of primary concern for various researchers. Since the load-carrying capacity of pure friction pile is a function of the shaft area in contact with the soil thus it requires a large length of pile to provide adequate load carrying capacity which is not feasible in some cases, to solve the problems the end bearing concept came into the picture.

Driven piles are mostly used in cohesionless soil such as sands of medium to low density to increase the density and thus the shear strength and are generally used in an area, where ground conditions showing loose deposits of sands. Numerous investigators have given greatest attention on the behavior of pile or pile group foundation over the last few decades. In case of cohesionless soil, the inside vertical face of the excavated borehole may not be stable unless supported. In bored piles such support is needed which provided either in the form of temporary or permanent casings system, as required. For the temporary casing a borehole stabilizers is used while taking out the casing.

Since last 70 years bentonite drilling fluids have been used for the construction of diaphragm walls and bored piles. In this application, the bentonite suspension must be capable of forming a filter cake or an impermeable membrane on the sides of the excavations to prevent loss of fluid into the ground and provide a surface layer against which the pressure of the fluid can act in order to resist external pressures from the soil and groundwater.

W. Michael and O'Neill (2001) have quoted that the thixotropic nature of bentonite is mainly responsible for the stabilization of the sides of bore holes, which permits bentonite slurry have the consistency of a fluid when it poured into a hole. When left undisturbed it forms a jelly like membrane on the excavated borehole wall and when agitated it becomes a fluid again. In the case of a cohesionless soil, if a positive differential head is maintained between the column of slurry in the borehole and the piezometric surface in the cohesionless soil, the slurry penetrates the soil. The bentonite slurry penetrations into sides under positive differential head and after a while form a jelly. The bentonite suspension then gets deposited on the sides of the excavated borehole and makes the surface impervious and provides a plastering effect. With the passage of time gel becomes thicker and more impermeable and gets more swell. This formation of a filter cake is necessary for a stable excavation in granular soils.

For pile foundation, the ultimate bearing capacity is the sum of end bearing resistance as well as frictional resistance around the shaft, but various researchers have shown that with the use of bentonite as a borehole stabilizer, the frictional resistance offered by the pile is found to be reduced due to the formation of a soft layer. In fine grained silty soils, pile capacity had reduced when the piles installed using bentonite slurry compared to other installation methods. This effect appears to be largely due to the presence of a thin soft layer of bentonite slurry left at the interface of concrete-soil as quoted by D. Brown (2002).

This project presents the results of a laboratory and field investigation into the effect of bentonite support fluids on the skin resistance between sand and cast in situ concrete pile which includes theoretical as well as experimental works. Tests are carried out by varying the concentration of slurry and friction resistance between pile and soil due to presence of bentonite slurry is estimated from the pullout test.

### 1.2 Objective of Dissertation

The objective of this study is to analyze the effect of bentonite drilling fluid on skin resistance of pile through theoretical and experimental work and to study the rheology of drilling fluid. The first portion of this study consisted of laboratory work and the second portion consisted of field work. A modeled bored cast in-situ piles were made and then analyzed for uplift capacity determination and parametric study is performed onto it. The main objective of the present dissertation work can be achieved through the following studies:

a) Effect of concentration of bentonite on viscosity, density and pH of suspensions.
b) Effect of passage of time on viscosity, density and pH of bentonite suspensions.
c) Effect of pH on viscosity and density of bentonite suspensions.
d) Effect of poly-fluid and alum on viscosity, density and pH of bentonite slurry.
e) Effect of a layer of bentonite slurry (placed along failure plane) on shear strength parameters in direct shear test.
f) Effect of bentonite drilling fluid on frictional resistance of pile through experimental work.

### 1.3 Scope of the Project

The project topic is "*Effect of bentonite drilling fluid on skin resistance of the pile*". For the effective stabilization of sides of the borehole, bentonite is one of the common mineral slurry which is easily available. Due to the swelling characteristics in water bentonite have received greatest attention in the field. Combinations of bentonite and water can perform a large number of jobs because rheological properties of the solutions change as the water to bentonite proportion changes. The results of the present study will allow using optimum content of the bentonite concentration.

The properties of the drilling fluid such as Marsh viscosity, pH and density of fluid affects its stabilizing action thus the effect of parameters on the rheological properties of fluid studied in this project work will help us in better understanding of the subject. It can provide a material for industry in terms of a better drilling fluid which can stabilize the soil along with minimizing the cost of the project. Bentonite slurry have another operational advantage that of preventing the loss of the fluid into permeable strata, bentonite will generally form a filter cake on the face of such a formation, thus retaining the slurry in the hole. The soft layer formation is necessary to keep the soil intact in the borehole, but it results a reduction in the overall ultimate load carrying capacity of the pile, to check this effect, the project has been carried out. The pull out test for determining the uplift capacity of the bored cast in-situ model concrete piles with different concentration of bentonite drilling fluid will explain the performance of pile foundation and the frictional resistance it offers while resisting the heavy structural loads.

### 1.4 Types of Bentonite

Based on the isomorphous replacement bentonite is categorized as:

a) Natural Calcium Bentonite
b) Natural Sodium Bentonite
c) Sodium Activated Bentonite

**Natural Sodium Bentonite:** Sodium bentonite is a kind of expansive clay. This is generally used in installation process of pile foundations and is characterized by very high swelling ability, high liquid limit and low filter loss. The predominant exchangeable cation in natural sodium bentonite is the sodium cation but there may also be significant amounts of other cations present.

**Natural Calcium Bentonite:** In this type of bentonite calcium is the predominant exchangeable cation. It has much lower swelling ability and liquid limit, and fluid loss is much higher than natural sodium bentonite.

**Sodium-Activated Bentonite:** This type of bentonite is produced by the addition of soluble sodium carbonate to calcium bentonite. Due to this, a base exchange of calcium ions with sodium ions takes place on the surfaces of the clay particles. Result of this bentonite exhibiting many of the typical characteristics of a natural sodium bentonite.

## 1.5 Use of Bentonite Support Fluids in Civil Engineering

Now a days bentonite support fluids are mostly used in civil constructions.

a) One of the main uses of bentonite drilling fluid is to support the sides of excavations for diaphragm walls. In this application, the bentonite fluid must be capable of forming a filter cake on the side excavated wall to prevent loss of fluid into the ground.
b) Bentonite drilling fluids are also widely used in the construction of cast in-situ bored piles. Application is similar to that for diaphragm wall.
c) Another widely used application is in the construction of cut-off walls below ground to form barriers to groundwater or to surround areas of contaminated land where leachates must be contained.
d) Bentonite support fluids are also used to support the excavation face in front of tunneling machines.

## 1.6 Organization of Dissertation

The report is subdivided into 7 chapters. *Chapter 1* states the importance of the matter and aim of the study. *Chapter 2* presents the review of the literature available on this topic. The methodology, characteristics of fluid laboratory work and theory involved in this dissertation work is discussed in *Chapter 3* and *Chapter 4*. *Chapter 5* includes the experimental program for this study. The results and the observations are enlisted in *Chapter 6.* Finally in *Chapter 7* summary and conclusions of the dissertation work are discussed.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Preamble

In this dissertation work, various papers are referred and they are enlisted in the bibliography. This chapter is subdivided into three major categories i.e. rheological properties of bentonite suspension, effect of drilling fluid on frictional resistance of the pile and uplift capacity of the pile. Each category includes reviewing of at least one pioneer paper pertaining to its topic.

## 2.2 Rheological Properties of Bentonite Suspension

Numerous researchers have worked on the rheological properties of water – bentonite mixtures. The rheological properties of bentonite-water systems are not yet fully understood. Akther et Al. (2007) quoted that the complex behavior of this drilling fluid system is due to the anisometric bentonite particles exposing different crystal faces which vary both in charge and the magnitude of the surface potential. In suspension the bentonite particles are oriented with negative faces in association with the positive edges to form a three dimensional ‘house of cards’ structure. When the suspension is stirred it gets broken and the system becomes more fluid. When the suspension is left for some time, the broken bonds are reformed and it forms gels again. This is called thixotropic nature of the fluid and it increases with increase in concentration of bentonite.

### 2.2.1 Drilling Fluid Viscosity

**Paul F. Luckham and Sylvia Rossi (1999)** said that the viscosity of both untreated and anionic polymer treated bentonite suspensions increased with increasing solution pH. Effect of pH on viscosity of the clay suspension is due to the changes in the surface charge and double-layer structure with pH of the solution. A regular arrangement of the particles was found in high pH conditions and in turn to increase viscosity.

**Akther et Al. (2007)** have selected two commercial bentonites. They made a homogeneous solution bentonite of 100 ml of solution at different concentrations of NaCl and at different pH values (2, 7 and 12) by agitated via magnetic stirring for 30 min to allow dispersion and left the solution for 8 h 15 min to achieve homogeneity and measured the viscosity of homogeneous suspensions. They concluded that the viscosity of bentonite suspension treated with an anionic polymer CMC (carboxymethyl cellulose) generally showed greater viscosity than the untreated sample in all solution-testing conditions and also revealed that viscosity of both untreated and CMC-treated bentonite solution increased with increasing solution pH. CMC is very effective in increasing the viscosity of bentonite-based drilling fluids only under neutral and alkaline conditions.

**Vassilios C. Kelessidis et Al. (2007)** checked the influence of pH between 7.5 to 10.5, for 5% and 6.42% bentonite suspensions. They prepared a bentonite – water suspension using Wyoming bentonite which is a natural sodium montmorillonite bentonite, each bentonite suspensions was left for 16 hr at room temperature for full hydration and adjusted the pH of the suspension using 0.1 M NaOH and 0.1 M HCl solutions and measured the pH values by Inolab pH meter. Viscosity of the suspensions was obtained with a continuously varying rotational speed. Based on the analysis they concluded that addition of salt NaCl decreases the viscosity for all three studied bentonite concentrations at all shear rates, over the range of electrolyte concentrations from 0.0 M to 1.0 M that was happened due to compression of the electric double layer which disturbed the network structure.

### 2.2.2 Filtercake Thickness

**K. Ilamparuthi and V. Kishor Kumar (2011)** fabricated a setup to determine the cake thickness which consists of sampler tube and slurry tank. They prepared the sample by filling the sand in sampler tube at the density of 1.61 $gm/cm^3$ and filled the slurry tank at required viscosity without causing disturbance to the sample. They kept the slurry in the tank for 4 hours and allowed it to penetrate through vertical and horizontal samples. They concluded that Marsh viscosity of the bentonite slurry increases as the specific gravity increases exponentially after the specific gravity of 1.04 and also observed filter cake thickness increases as the specific gravity increases of the solution increases.

### 2.2.3 Mechanism of Bentonite Support Fluid

**Majano, R.E. and O'Neill (1994)** quoted that the thixotropic nature bentonite is primarily responsible for stabilizing the sides of bore holes. The thixotropic property of bentonite suspension permits the material to have the consistency of a fluid when it introduced into a hole.

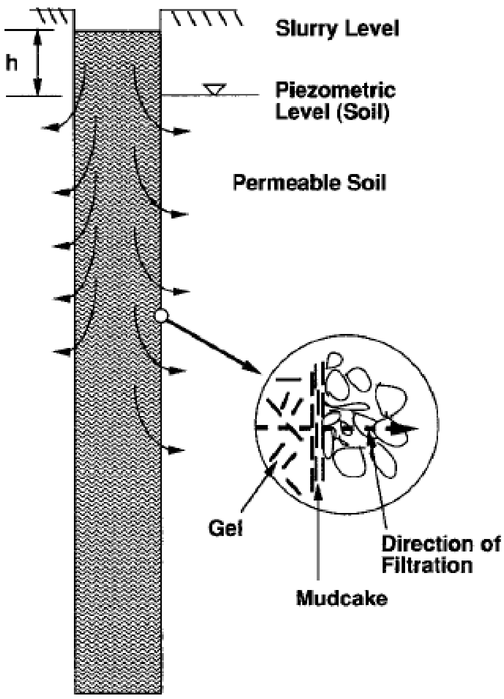


**Fig.2.1 Filtration of bentonite slurry [10]**

When left undisturbed it forms a jelly like membrane on the excavated borehole wall and when agitated it becomes a fluid again. If a positive differential head in the case of a granular soil, is maintained between the column of slurry in the borehole and the piezometric surface in the granular soil, leads to the slurry penetration into the soil as shown in Fig.2.1. The bentonite suspension penetrations into sides under positive head and after a while form a jelly. The bentonite suspension then gets deposited on the sides of the hole and makes the surface impervious and imparts a plastering effect.

### 2.3 Effect of Drilling Fluid on Frictional Resistance of the Pile

**Majano, R.E. and O'Neill (1994)** examined the issue of concrete-soil perimeter load transfer in drilled shafts in clean sands through laboratory studies. They concluded the effectiveness of polymer fluid over bentonite slurry as former have shown greater friction angle, in terms of $\delta$, even at very low concentration whereas bentonite didn't even at high concentration.

**Carlos Lam et Al. (2010)** carried out a field test comprising the construction and testing of three piles in east London. They compare the performance of pile under two different drilling fluids of polymer and bentonite. Three bored piles one under conventional bentonite slurry and other two were under a synthetic polymer fluid with diameter of 1.2m and length of pile of 27m were installed at the test location. The concrete cube test results show that both bentonite and the polymer fluids, if allowed to mix with concrete, have a similar degree of impact on compressive strength and elastic modulus and they also found that the two piles under polymer slurry significantly outperformed the pile under bentonite slurry at the maximum proof load.

**K. Ilamparuthi and V. Kishor Kumar (2011)** have made a bored cast in situ model pile of grade M30 and of diameter 75mm and embedment length of 400mm in the test tank. They maintained the slurry in the pile hole for 4 hours before concreting taken place so that the filter cake has to be formed. And they performed the pull out test on the model pile after 7 days of concreting to determine the load versus displacement response. Based on the result they found that the "Ktanδ" values are varies 2.36 to 2.61 depending on the case. The "Ktanδ" values obtained with bentonite slurry and polymer slurry are less by 17.5% and 9.5% respectively while comparing with the value obtained without slurry.

**Carlos Lam et Al. (2014)** presents the results of a set of concrete–sand interface shear tests carried out using both polymer and bentonite support fluids, with water as a reference fluid. They made a medium sized shear box with dimensions such that the upper and lower halves of the box are respectively 100 mm and 70 mm high and plan dimensions of 175 mm by 275 mm, and the gap between the two halves of the box is adjustable, with fluid controlled system. For the analysis of interface shear strength they filled the top half of the box with fresh concrete and lower half with sand before pressurized with bentonite or polymer fluid and applied a constant shear force. They concluded that the shearing resistance under bentonite slurry decreases as the filtration time increases this is due to formation of soft filter cake, and that after 24 hours of filtration the resistance approaches that of the filter cake and also concluded that interface shear strength between concrete and sand decreases linearly with the square root of the filtration time, until it reaches the strength of the pure filter cake.

### 2.4 Uplift Capacity of the Pile

With the increasing use of straight piles to resist uplift loads necessitated accurate assessment of uplift resistance for safe and economical design of pile foundations. Unlike the prediction of load carrying capacity of piles under compressible loads very few papers are available to predict the behavior of piles under uplift loads. Several studies have concluded that shaft resistance is about the same for uplift and compression loads. However, O'Neill and Reese reported that the shaft resistance in tension could be 12–25%

smaller than shaft resistance obtained from compression test due to Poisson’s ratio effect. Poulos and Davis recommended that when estimating the uplift capacity of piles takes it as 2/3 of the downward shaft resistance as quoted by K. E. Gaaver (2013). Many theories have been developed to find the net uplift capacity of a bored pile (D.R. Levacher et al. 1985; Chattopadhyay and Pise 1986) and validated through experimental measurements.

# CHAPTER 3

# METHODOLOGY AND DRILLING FLUID CHARACTERIZATION

To understand the effect of drilling fluid on skin resistance of the pile laboratory and field work analysis is performed. The laboratory work serves primarily as background for the field work. Primary investigation is concerned with the determination of the slurry properties which influence the filter cake is studied. The aim of the investigation is to provide information that will assist in the development of specifications for the construction of drilled shafts when bentonite slurry is used in the construction. The second portion of investigation consisted of field work which could be compared with the laboratory work that could serve as a basis for recommendations concerning slurry-construction of drilled shafts.

The series of data collection and methodology carried out is presented in the form of a flow chart:

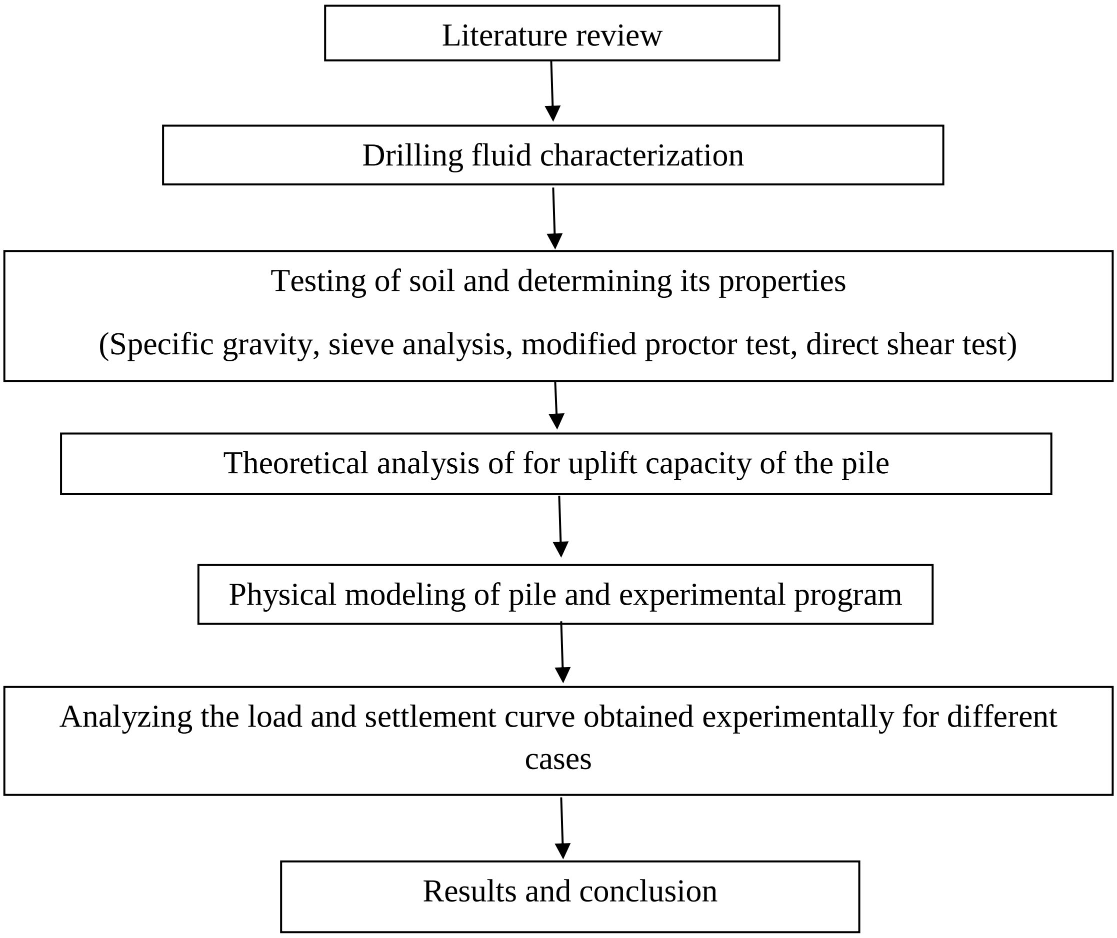


**Fig 3.1 Flow chart for the methodology**

### 3.1 Chemical Composition of Bentonite

Characterization of the chemical composition of the bentonite sample was conducted at the Nano-Technology laboratory of Delhi technological university, using SCM-EDX instruments. Scanning electron microscope (SCM) produces high-resolution images of small particles in which electron beam is focused on areas of small particles on the surface to be studied. When electrons interact with the atoms emits low energy secondary electrons which results in the sample producing signals in the form of images that contain information about the sample surface morphology and particle size.

Energy dispersive X-ray spectroscopy (EDX) gives the information about chemical composition on mineral of the sample. In EDX, high energy electrons beam or beams of X-rays are focused onto the surface of sample. The incident beam may excite the electron in an inner shell, due to which it ejects out leaving an electron hole. This hole is then filled by the electron from higher energy outer shell and thus the difference in energy is released in the form of characteristic X-ray depending on the atomic structure of the sample.

### 3.2 Need of Specification of Bentonite Slurry

Since last 70 years, for the construction of bored cast-in-situ piles, bentonite has been used as a borehole stabilizer. However, the use of bentonite has not always in under ideal conditions. If any testing is done, it consists merely of density, viscosity and pH measurements. Concern has arisen as to the integrity of the bentonite slurry and the finished construction. This concern has led to the development of various specifications. One of the specifications has given by Indian standard 2911: 2010. As per IS code [15] for the piling work, bentonite powder and bentonite slurry should satisfy the following requirements:

**Table 3.1: Properties of bentonite suspension for piling work**

| Properties | Specifications |
|---|---|
| Liquid limit | Greater than or equal to 400% |
| Density of freshly prepared bentonite | 1.03-1.10g/ml |
| Marsh viscosity | 30-60 stoke |
| pH | 9-11.5 |
| Specific gravity | 2-2.2 |

### 3.3 Rheological Properties of Bentonite Fluid

Quality of bentonite suspension is very useful for stabilizing the bore hole made for installation of bored piles. Generally, sodium bentonite is used as a drilling fluid during the installation of bored piles. The bentonite slurry should have a low viscosity and contain the minimum possible amount of particles in suspensions if it is to be displaced by concrete placed through a tremie method. The engineering properties of bentonite slurry include viscosity and density was determined in laboratory. Sand content and pH are also determined. Measurement of these characteristics is done in the determination of the slurry's ability to build up a filter cake. These properties are influenced by the amount of bentonite present, the method and duration of mixing, time without agitation, and the amount of impurities present.

#### 3.3.1 Effect of Bentonite Concentration on Viscosity, Density and pH of the Slurry

The purpose of this investigation consists for a number of reasons. First, when density of slurry is high aids in preventing sloughing of the soil surrounding the excavated borehole because as the density of the slurry increases the pressure created by the slurry also increases. Second, if the viscosity of the slurry is too great, the slurry will not flow easily and if the viscosity is too low, an effective filter cake may not formed. And third, very dense slurry may be difficult for concrete to displace which results in slurry inclusions in the concrete leads to degradation of concrete quality.

In order to investigate the effect of concentration of bentonite, solution of 1 litre is prepared by taking 1 litre of water and varying concentration i.e. (2%, 4%, 5%, 6%, and 9%) of bentonite by weight. The bentonite powder was mixed thoroughly with water to form fully dispersed lump free uniform slurry for which a jar apparatus shown in Fig.3.2 which is a mechanical device for proper mixing of slurry was used and the solution was rotated at 250 rpm for 30 minutes.

Viscosity of the prepared solutions has been measured by Marsh funnel shown in Fig.3.3 as Marsh viscosity i.e. the time taken by one litre solution upto a marked level to pass through the Marsh-funnel. A pre – calibrated hydrometer as shown in Fig.3.5 was used to determine the density of the slurry. The pH of suspensions was noted using the electronic pH meter as shown in Fig.3.4 after neutralizing it in a buffer solution of pH value of 7.0. The change in viscosity, density and pH of bentonite suspension was checked after 2 hours of sample preparation.

**Fig. 3.2 Jar apparatus for mixing**

**Fig. 3.3 Marsh funnel apparatus**


**Fig. 3.4 pH meter**

**Fig. 3.5 Hydrometer**

### 3.3.2 Effect of pH Variation on the Slurry Viscosity and Density

The purpose of this investigation is performed due to the following reasons. The pH of the slurry should be kept in a range so that it would have no adverse effects on the pile reinforcement, casing, or concrete.

In order to increase the pH value of solution, sodium hydroxide NaOH was added at different concentrations of (0.01%, 0.1%, 0.5%, and 1%). In this investigation first bentonite fluids of 4% concentrations were formed after mixing them for 30 min. at 250 rpm and the rheological properties mentioned above were determined just after the mixing of these solutions. After that pH of the prepared solutions was changed by adding the NaOH and the solutions were mixed again at the rate of 250 rpm for 30 min. And change in viscosity and density of bentonite suspension was checked just after mixing of the solutions.

### 3.3.3 Effect of Passage of Time on the Slurry Viscosity, Density and pH

Bentonite with time gains the strength due to its thixotropic nature and thus, to determine its effect the test was conducted. In this investigation a suspension of 1.5 litres was prepared by taking 6% of bentonite by weight and 1.5 litre of water to make 4% concentration of solution. And the solution was mixed thoroughly at the rate of 250 rpm for 30 min. After 30 min of mixing 1 litre of the solution was taken to check the viscosity, density and pH of the solution at different interval of time.

### 3.3.4 Effect of Poly-fluid and Alum on the Rheological Properties of the Slurry

To reduce the density of drilling fluid poly-fluid and alum were added as coagulants which interact with bentonite particles make them settles. Before concreting these settled particles can be removing easily using any suitable construction technique. To check this effect the test was performed.

In which a different concentration i.e. (0.01%, 0.1%, 0.5%, 1%, and 2%) of alum and poly-fluid (polyacrylamide) containing (15% of solid and rest of water) were added in the 4% bentonite concentration of the solutions and the solutions were mixed again at the rate of 250 rpm for 30 min. After 30 min of mixing, instantaneously pH, viscosity and density of the suspensions were measured. And the solution of 1% concentration of poly-fluid and alum was left for 24 hours. The settlement of bentonite particles were checked at an interval of 15 min, 1 hour and 20 hours. And thereafter no settlements were obtained up to next 4 hours and the properties of top fluid were checked.


**Fig. 3.6 Effect of poly-fluid and alum**

### 3.3.5 Effect of Addition of Silt Content on the Rheological Properties of the Slurry

This investigation is performed to check effect of presence of silt or sand content on the rheology of the slurry. The presence of silt or sand leads to increase the density of the slurry and this may cause the slurry to be difficult to circulate and to be displaced. Also, as the slurry is displaced by concrete which is placed through a tremie, silt may collect on the reinforcement of the pile; this may hindered the proper bonding between concrete and reinforcement.

In this investigation first initial properties of the fluid were determined. Thereafter, 5% silt content was added in in the 4 and 6% concentration of the bentonite solution jars and the solution was mixed at the rate of 250 rpm for 30 min. viscosity, density and pH of the suspensions were observed instantaneously and after 2 hours.

# CHAPTER 4
# LABORATORY WORK AND THEORETICAL ANALYSIS

## 4.1 Soil Properties

To determine the properties of the excavated soil from Noida site, used as foundation soil for pile foundation model, different tests were performed in the laboratory.

### 4.1.1 Specific Gravity

The specific gravity of soil solids is defined as the ratio of the mass of a given volume of solids to the mass of an equal volume of water. Specific gravity is determined as per [16].

$$G = \frac{(M_2 - M_1)}{((M_2 - M_1) - (M_3 - M_4))}$$

Where, $M_1$ = Weight of empty pycnometer bottle

$M_2$ = Weight of pycnometer bottle + soil sample

$M_3$ = Weight of pycnometer bottle + soil sample + water

$M_4$ = Weight of pycnometer bottle + water (fully filled)

**Table 4.1: Calculation of specific gravity of the soil**

| | **Sample 1** | **Sample 2** | **Sample 3** |
|---|---|---|---|
| **$M_1$ (g)** | 696.50 | 697.03 | 697.10 |
| **$M_2$ (g)** | 896.45 | 896.90 | 897.18 |
| **$M_3$ (g)** | 1690.82 | 1689.73 | 1689.88 |
| **$M_4$ (g)** | 1565.20 | 1565.00 | 1565.09 |
| **G** | 2.69 | 2.659 | 2.654 |
| **$G_{avg}$** | $\frac{2.69 + 2.659 + 2.654}{3} = 2.67$ | | |

The value of the specific gravity of the soil tested is taken as average value of the three samples i.e. **G = 2.67.**

### 4.1.2 Dry Sieve Analysis Test

The dry sieve analysis of the soil sample was carried out to find the particle size distribution [17]. The sieves of different size were arranged in decreasing size from top to bottom and the mass retained on each sieve was noted. The Table 4.2 shows the calculation of percentage finer particles for each sieve and Fig. 4.1 shows the gradation curve for the soil.

**Table 4.2: Result data for sieve analysis of the soil**

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| **Sieve size** | **Mass retained (g)** | **% Mass retained (3) = ((2)/1000) x100** | **Cumulative % retained** | **% Finer (N) (5) = 100 - (4)** |
| **4.75 mm** | 17.06 | 1.706 | 1.706 | 98.294 |
| **2.36 mm** | 28.96 | 2.896 | 4.602 | 95.398 |
| **1.18 mm** | 48.44 | 4.844 | 9.446 | 90.554 |
| **0.60 mm** | 32.53 | 3.253 | 12.699 | 87.301 |
| **0.425 mm** | 126.95 | 12.695 | 25.394 | 74.606 |
| **0.300 mm** | 567.33 | 56.733 | 82.127 | 17.873 |
| **0.150 mm** | 143.32 | 14.332 | 96.459 | 3.541 |
| **0.075 mm** | 14.08 | 1.408 | 97.867 | 2.133 |
| **Pan** | 21.34 | 2.134 | 100 | |

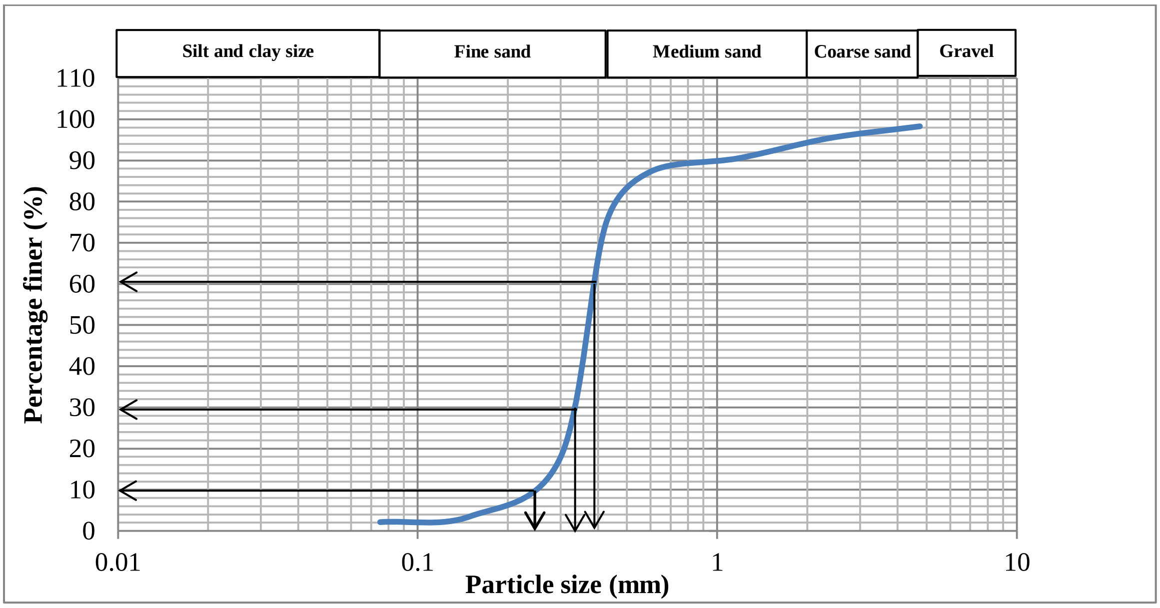


**Fig. 4.1 Grain size distribution curve**

From the semi-log graph plotted between percentage finer and sieve size (on log scale) as shown in Fig.4.1, the value of $D_{10}$= 0.25mm, $D_{30}$= 0.34mm, $D_{60}$= 0.39mm.

Where, $D_{10}$ = particle size such that 10 percent of sample is finer than this size

$D_{30}$ = particle size such that 30 percent of sample is finer than this size

$D_{60}$= particle size such that 60 percent of sample is finer than this size

$C_u$, the coefficient of uniformity and $C_c$, the coefficient of curvature are given as :

$$C_U = \frac{D_{60}}{D_{10}} = \frac{0.39}{0.25} = 1.56$$

$$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}} = \frac{0.34^2}{0.25 \times 0.39} = 1.19$$

As more than 50% particles are retained on 75μ IS sieve, the soil is coarse grained soil. And more than 50% particles are passes through 4.75 mm IS sieve, the soil is sandy soil. Based upon the $C_c$ and $C_u$ value soil is classified as poorly graded sand i.e. SP as per [18].

### 4.1.3 Modified Proctor Compaction Test

The maximum dry unit weight of the soil corresponding to the optimum moisture content is obtained through the modified proctor test, in which the sample is placed in five layers and each layer is compacted by giving 56 blows with the drop hammer. The plot is made between the water content and the dry density and the maximum value of the density gives the corresponding value of optimum water content. And it was obtained from the compaction curve as the maximum dry unit weight equal to **18.38kN/m$^3$** at an optimum moisture content of **11.8%.**

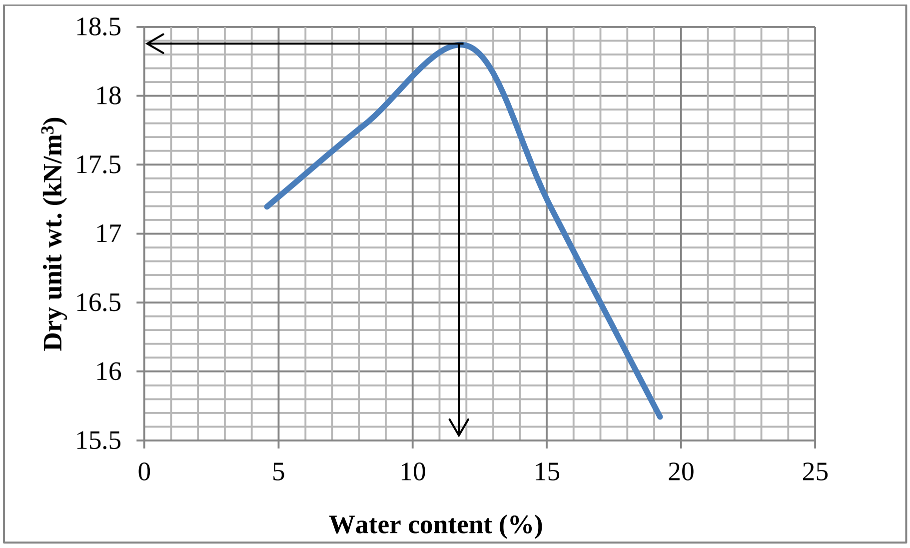


**Fig. 4.2 Graph of compaction curve**

### 4.1.4 Direct Shear Test

The direct shear test as per [19] was conducted on the soil sample to obtain the angle of internal friction of the soil (ϕ) and the cohesion (c) using the direct shear apparatus with mould of size 60mm x 60mm. The test was conducted for three different normal loadings of 50kN/m$^2$, 100kN/m$^2$ and 150kN/m$^2$. The horizontal displacement corresponding to different shear force is noted and curves are plotted for different normal loadings. The curves provides the maximum shear force at which the soil sample failed and the corresponding shear stress is calculated and plotted against the normal stress to give the value of c and ϕ.

The shear force versus horizontal displacement curve and shear stress versus normal stress curves obtained for different normal loadings are shown in Fig.4.3 and Fig.4.4 respectively.

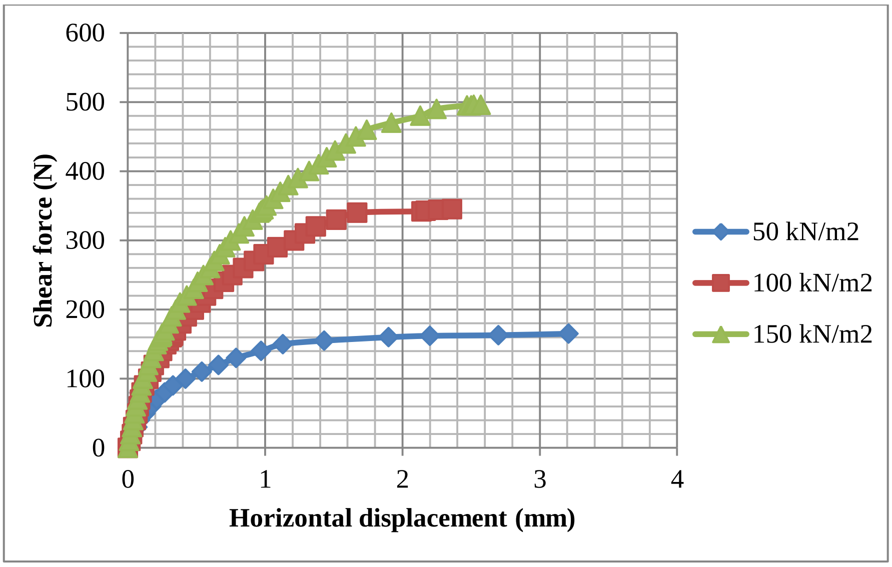


**Fig. 4.3 Shear force vs. horizontal displacement curve for different loading conditions**

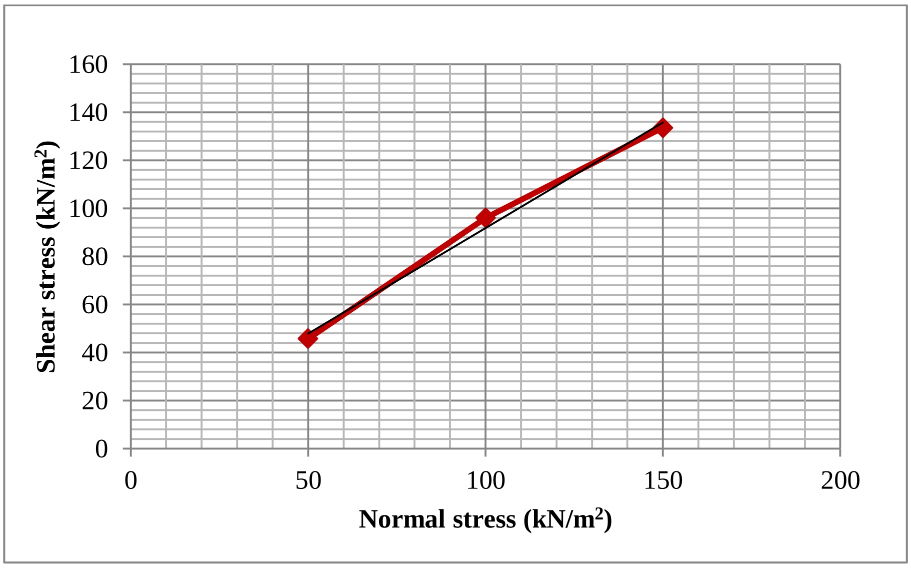


**Fig. 4.4 Shear stress versus normal stress curve**

The cohesion ‘c’ and angle of internal friction ϕ are obtained from the plot of shear stress versus normal stress curve of the given soil are as follows: $c = 4.07$ kN/m$^2$ and $\phi = 41.28^o$.

### 4.2 Properties of Bentonite

To determine the engineering properties of bentonite powder collected from Kutch region, Gujrat, India, used for drilling fluid as a borehole stabilizer, different tests were performed in the laboratory. This bentonite has a dark reddish brown colour due to presence of iron oxides.

#### 4.2.1 Liquid Limit

The liquid limit is the water content at which the soil behaves practically like a liquid, but has small shear strength. It flows to close the groove in just 25 blows in Casagrande's liquid limit device [20] shown in Fig. 4.5. The liquid limit of the bentonite is the water content corresponding to N = 25, as obtained from the plot shown in Fig.4.6 is equal to **498%**.

**Table 4.3: Calculation of water content for liquid limit of the bentonite**

| Water content added (%) | Mass of empty can ($M_1$) (g) | Mass of can + wet soil ($M_2$) (g) | Mass of can + dry soil ($M_3$) (g) | Actual Water content (w) (%) |
|---|---|---|---|---|
| 325 | 6.00 | 14.30 | 7.85 | 348.60 |
| 400 | 5.38 | 18.76 | 7.85 | 441.70 |
| 425 | 5.93 | 13.47 | 7.20 | 493.70 |
| 450 | 6.40 | 16.25 | 8.03 | 504.29 |
| 475 | 5.49 | 13.39 | 6.78 | 512.40 |
| 500 | 4.76 | 11.61 | 5.80 | 558.60 |
| 525 | 5.17 | 11.92 | 6.15 | 588.75 |

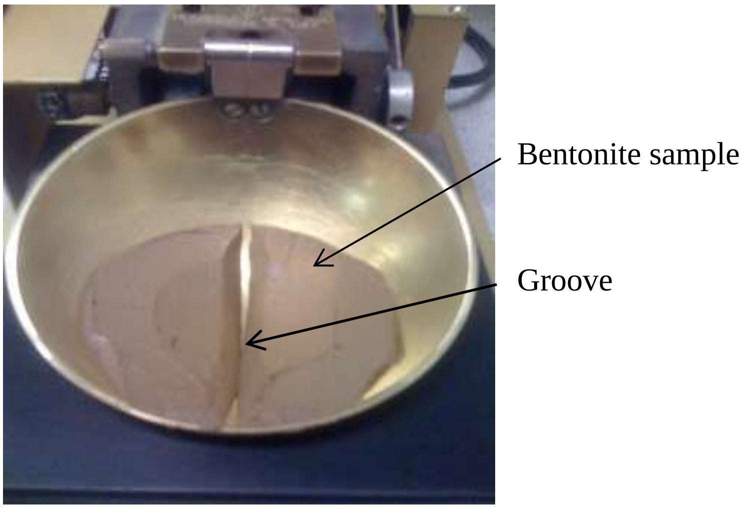


**Fig. 4.5 Liquid limit apparatus**

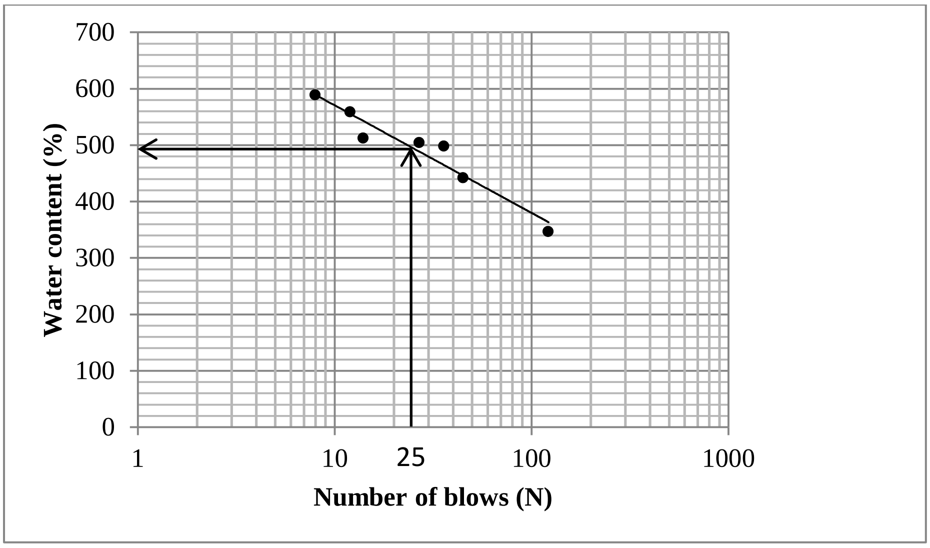


**Fig. 4.6 Flow curve of bentonite sample**

### 4.2.2 Shrinkage Limit

The shrinkage limit of a soil is the water content when the water is just sufficient to fill all the pores of the soil, and soil is just saturated. At the shrinkage limit volume of soil does not decrease when the water content is reduced below the shrinkage limit [21]. Table 4.4 shows the calculation for shrinkage limit for bentonite sample which comes out to be 12%.

**Table 4.4: Calculation for shrinkage limit of bentonite sample**

| Sl. No. | Observations and calculations | Determination |
|---|---|---|
| **Observation** | | |
| **1** | Mass of empty mercury dish | 21.02g |
| **2** | Mass of mercury dish, with mercury equal to volume of the shrinkage dish | 233.18g |
| **3** | Mass of mercury = (2) – (1) | 212.16g |
| **4** | Volume of shrinkage dish $V_1$= (3)/13.6 | 15.6cm$^3$ |
| **5** | Mass of shrinkage dish | 31.10g |
| **6** | Mass of shrinkage dish + wet bentonite sample | 51.58g |
| **7** | Mass of wet bentonite sample $M_1$ = (6) – (5) | 20.48g |
| **8** | Mass of shrinkage dish + dry bentonite sample | 42.10g |
| **9** | Mass of dry bentonite sample $M_s$ = (8) – (5) | 11.00g |
| **10** | Mass of mercury displaced by dry pat | 101.2g |
| **11** | Volume of dry pat $V_2$ = (10)/13.6 | 7.44cm$^3$ |
| **Calculation** | | |
| **13** | Shrinkage limit = $\frac{(M_1-M_S)-(V_1-V_2)\rho_w}{M_S} \times 100$ | 12% |

**Fig. 4.7 Shrinkage limit apparatus**

**Fig. 4.8 Shrinkage dish with bentonite sample**

### 4.2.3 Plastic Limit

Plastic limit of a soil is the water content below which the soil stops behaving as a plastic material. It begins to crumble when rolled into threads of 3mm diameter. To determine the plastic limit of the bentonite sample 30g of sample was taken and thoroughly mixed it with water and divided it into two equal parts. Roll the sample with finger on a glass plate until a thread of 3mm diameter was formed. When the crumbling occurs at the thread of 3mm of diameter, the crumbled sample was taken for the determination of water content. The plastic limit of the bentonite sample is computed in Table 4.4 which is equal to 54.36%.

**Table 4.5: Calculation for plastic limit of bentonite sample**

| Sl. No. | Observations and calculations | 1 | 2 |
|---|---|---|---|
| 1 | Mass of empty can = $M_1$ | 4.74g | 5.53g |
| 2 | Mass of can + wet bentonite sample = $M_2$ | 11.10g | 13.20g |
| 3 | Mass of can + dry bentonite sample = $M_3$ | 8.91g | 10.44g |
| 4 | Mass of water = $M_2 – M_3$ | 2.19g | 2.76g |
| 5 | Mass of dry sample = $M_3 – M_1$ | 4.17g | 4.91g |
| 6 | Water content, $w = \frac{(4)}{(5)} \times 100$ % | 52.52% | 56.21% |
| Avg. value of water content = 54.36% | | | |

### 4.2.4 Sand Content

Sand content of the bentonite sample was computed by placing 20g of the sample in a 75μ IS sieve. The sample was allowed to drain in running water and the retained particles on sieve were then dried to obtain the sand content present in bentonite sample. Table 4.4

shows the calculation for sand content in bentonite sample which was come out to be 0.53%.

**Table 4.6: Calculation for sand content in bentonite sample**

| Sl. No. | Observation | 1 | 2 |
|---|---|---|---|
| **1** | Mass of 75µ empty sieve | 333.19g | 333.21g |
| **2** | Mass of 75µ empty sieve + mass of dry soil retained | 333.31g | 333.30g |
| **3** | Mass of dry soil (3) = (2) – (1) | 0.12g | 0.09g |
| **4** | Sand content in % | 0.60% | 0.45% |
| **5** | Sand content = $\frac{0.60+.45}{2}$ = 0.53% | | |

## 4.3 Effect Bentonite Slurry on Shear Parameters of Soil

Laboratory investigations were conducted for the analysis of effect of a soft layer of bentonite filter-cake on the interface between soil and soil. For this purpose direct shear test mould was used consists of pre-defined failure plane. Two phases were considered in this laboratory investigation. The first phase of the investigations consisted of application of bentonite fluid on lower half of compacted soil and the formation of the filter cake on the compacted soil. Factors influencing the filter-cake growth such concentration of bentonite slurry were varied to determine the effect of filter cake on the shear parameters such as ‘c’ and ‘ϕ’ value of the soil. The second phase consisted of placement of soil onto the filter cake and application of the load on the shear box. When the soil is sheared along predefined failure plane, then the horizontal force gives the frictional value between the soil particles around the failure plane.

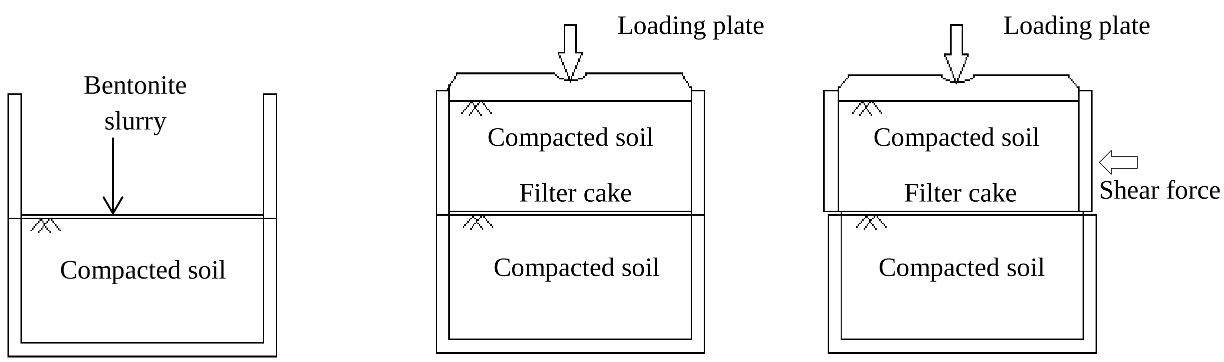


**Fig. 4.9 Sketch diagrams showing arrangement of the interface direct shear mould during: (a) soil placement and application and filtration of slurry; (b) placement of soil in upper half of the mould; (c) shear force application**

### 4.3.1 Sample Preparation and Load Application

The effect of bentonite slurry on frictional resistance of soil was computed by performing the direct shear test. It consists of a predefined failure plane. For performing the direct shear test sample preparation was the first step of the testing procedure and consisted of mixing the soil with water at optimum moisture content (11.8%) until a uniform mixture was obtained. Then the soil was compacted into the lower half of the mould. 10 ml of the slurry with different concentration of bentonite was poured on lower half of the compacted soil in lower part of the direct shear mould. The prepared mould was kept undisturbed for 30 min as shown in Fig.4.11 and thereafter the upper half of the mould was filled with soil and was weighed to obtain the bulk unit weight of the compacted soil, this was done to achieve same density for each case.

After the preparation of sample, the mould were placed in direct shear testing machine and normal loads were applied through a static weight hanger and the soil is sheared gradually by applying horizontal force. Each sample was tested for three normal stresses i.e. 50kN/m$^2$, 100kN/m$^2$ and 150kN/m$^2$ obtain maximum shear stress values corresponding to different normal loadings.

**Fig. 4.10 Placement of bentonite layer on lower half of compacted soil**

**Fig. 4.11 Sample after 30 min placement of bentonite layer**

## 4.4 Theoretical Analysis

Many investigations have been conducted to study the behavior of short piles or pile group subjected to axial compressive, uplift, inclined, or lateral loads over the last few decades. In spite of that, a few researches carried out the test on piles subjected to uplift load over shallow to short embedment depths in cohesionless soil.

To find the net uplift capacity of the bored piles many theories have been developed and validated through experimental measurements. These theories differ based on assumptions that they have taken with regard to the shape and extent of the failure surface. Chattopadhyay and Pise (1986) assume a curved failure surface within the soil.

### 4.4.1 Meyerhof's Methods

Ignoring the weight of the pile he suggested an expression for the pull-out resistance as,

$$\boldsymbol{Q_u = 0.5K_u p\gamma L^2 \tan\delta} \qquad \text{...…… Eq. 3.1}$$

Where, p = perimeter of the shaft.

ϒ = unit weight of the soil

L = length of the pile

δ = soil - pile friction angle

$K_u$ = uplift coefficient and can vary with in 0.5 to 1 depending on soil properties, type of pile and method of installation [5].

### 4.4.2 Nabil F. Ismael's Method

Assuming lateral earth pressure increases linearly over the length of the pile, the uplift capacity can be obtained from the following formula:

$$\boldsymbol{Q_u = 0.5\,\gamma L^2\pi\, D\, K_u\, tan\,\phi + W_p} \qquad \text{………Eq. 3.2}$$

Where, ϒ = unit weight of the soil

L = length of the pile

D = diameter of the pile

$W_p$ = weight of the pile

$K_u$ = coefficient of lateral earth pressure in uplift depends on SPT value [8]

### 4.4.3 Kulhawy et Al.'s Method

They assumed the cylindrical failure surface within the soil. The uplift capacity can be obtained from the following formula:

$$\boldsymbol{Q_u = 0.5\pi dK\gamma L^2 \tan\delta} \qquad \text{………Eq. 3.3}$$

Where, K = Coefficient of earth pressure, and K = $K_a$ for loose sand K =$\sqrt{K_p}$ for dense sand. Here, $K_a$ and $K_p$ are active and passive earth pressure coefficient respectively [13].

### 4.4.4 IS Code Method

The uplift capacity of a pile is given by sum of the frictional resistance and the weight of the pile. Uplift capacity can be obtained from static formula by ignoring end-bearing term and adding weight of the pile as follows,

$$Q_u = \sum K\, P_D \tan\delta\, A_s + W_p \qquad \text{.........Eq. 3.4}$$

Where, $P_D$ = effective overburden pressure at pile tip

$A_s$ = surface area of pile shaft

δ = soil - pile friction angle obtained by taking δ equal to ϕ values

K = coefficient of earth pressure depends on the nature of soil strata, type of pile and method of construction. For driven piles in loose to dense sand with ϕ between 30° and 40°, K values is varying from 1 to 1.5 as per [15].

# CHAPTER 5
# PHYSICAL MODELING AND FIELD EXPERIMENT

## 5.1 Experimental Program

The purpose of the investigation was to show the effect of bentonite fluid, used as a borehole stabilizer, on the frictional resistance of soil-concrete interface. For which field test was performed. In which three bored cast in-situ concrete piles were casted in the steel tank, which was pre-filled with soil collected from Noida region. One of the piles was casted without any drilling fluid and other two were casted under different concentration of bentonite drilling fluid. And after 7 days of casting the test was performed to obtain the uplift capacity of the pile. To achieve the objective of the project experimental work were performed with defined procedure. The description of experimental setup and procedure for the experiment work is mentioned below.

### 5.1.1 Steel Tank

The size of the steel tank, located in Delhi Technological University, for the experimental work is 1.5m in length, 0.90m wide and 0.60m deep. It consisted of a steel girder consisting of two hooks, resting above it on the ground surface. Steel tank was suitable for performing the pull-out test. Pulley was clamped in the hook provided in the steel girder. During casting of piles care was taken so that there has no effect of sides of steel tank on the zone of reactions (2.5 times diameter) transferred by the pile during uplifting [24].

### 5.1.2 Measuring Devices

For measuring the settlement, one dial gauge, with 0.01mm least count were fitted near the center of the pile. Dial gauge was fixed with the girder using a magnetic stand. The loads of known weights were applied on the loading pan and the corresponding settlements were noted down from the dial gauge.

### 5.1.3 Equipment Used

For carrying out the experiments, different equipment was used, for the proper setup to obtain best results. The equipment, as listed in Table 5.1, were used to ensure proper compaction of soil, horizontal level of soil, verticality of piles and proper measuring.

**Table 5.1: List of equipment used for experimental work**

| Equipment | Quantity | Specification |
|---|---|---|
| Steel Hammer | 2 | Weighing 11.5 kg each |
| Weighing Machine | 1 | For weighing soil |
| Cement | 1 | 43 grade OPC |
| Spirit Level | 1 | Horizontal as well as vertical |
| Measuring tape | 1 | For marking distances |
| Pulley | 2 | To carry out pull out test |
| String | 1 | To connect pile and loading pan |
| Loading Pan | 1 | To apply dead load |
| Hollow PVC pipe | 1 | Used as casing |

### 5.1.4 Concrete Mix

The concrete mix, for the casting of pile, was formed as per [22], to obtain a M40 grade of concrete. The cubes were tested after 7 and 28 days, and their strength was obtained about 35 MPa at 28 days. But the prepared mix was not workable enough to cast the pile of diameter 4.5cm as the size of the aggregate were large enough to be placed.

In order to form a concrete mix having good strength as well workable enough to cast the pile, cement and sand (stone-dust) ratio of 1:2.5 and water-cement ratio of 0.45 was selected and 5% silica flume was added, as it is used to enhance the strength of the concrete. The average strength of cubes after 7 days and 28 days of casting was found to be 17.1MPa and 28MPa.

**Fig.5.1 Prepared concrete cubes**

**Fig.5.2 Universal testing machine**

## 5.2 Pile Modelling

The length and diameter of the pile i.e. 0.35m and 0.045m respectively, for model concrete pile, were selected such that the effect of the edges of the tank should not lie in the zone of influence of pile due to loading.

## 5.3 Design of Pulley System

The uplift capacity of the piles was determined by conducting pull-out tests using a pulley system. The size of the string and the pulley were selected such that they should bear enough load. The theoretical analysis of model pile has given a maximum uplift capacity of 0.266 kN. This load was increased by a factor of safety of 3, and the design load was taken as 0.80 kN.

### 5.3.1 Wire Rope Calculation

The rope must have enough breaking strength so that it should not break in tension during the application of load. The required breaking strength of the rope was calculated as:

Load on rope = 0.80 kN

Factor of safety = Zp x Cdf = 3.5 x 1.5 = 5.25 (as per IS: 3177/1999)

Number of falls = 2

Type of bearing = Roller bearing

Efficiency of bearing = 98%

Hence, load (L) on each fall of wire rope with consideration of pulley efficiencies,

$$L = \frac{0.80}{2} \times \frac{1 - 0.98}{1 - 0.98^2} = 0.20\ kN$$

Where, 0.98 is the pulley efficiency.

The required breaking strength of the rope = 0.20 x 5.25 kN = 1.05 kN (i.e. 107 kg). Thus, a wire rope of suitable strength and diameter were selected to perform the pull-out test.

### 5.3.2 Equalizing Pulley Calculation

As per Indian standard, IS: 3177/1999, cl: 8.5.2, the required root diameter ($R_d$) of equalizing pulley can be calculated as:

Rd = 8 x diameter of rope x Cdf

Rd = 8 x 3 x 1.5 mm = 36 mm i.e. 0.036 m

Therefore, two standard pulleys with root diameter of 4cm i.e. 0.04 m were selected for the experimental test.

### 5.4 Schematic Diagram of Experimental Setup

The sketch diagram of the experimental setup, shown in Fig 5.3 and Fig 5.4 represents overall setup for the pull out test and top view of the steel tank with location of concrete pile respectively.

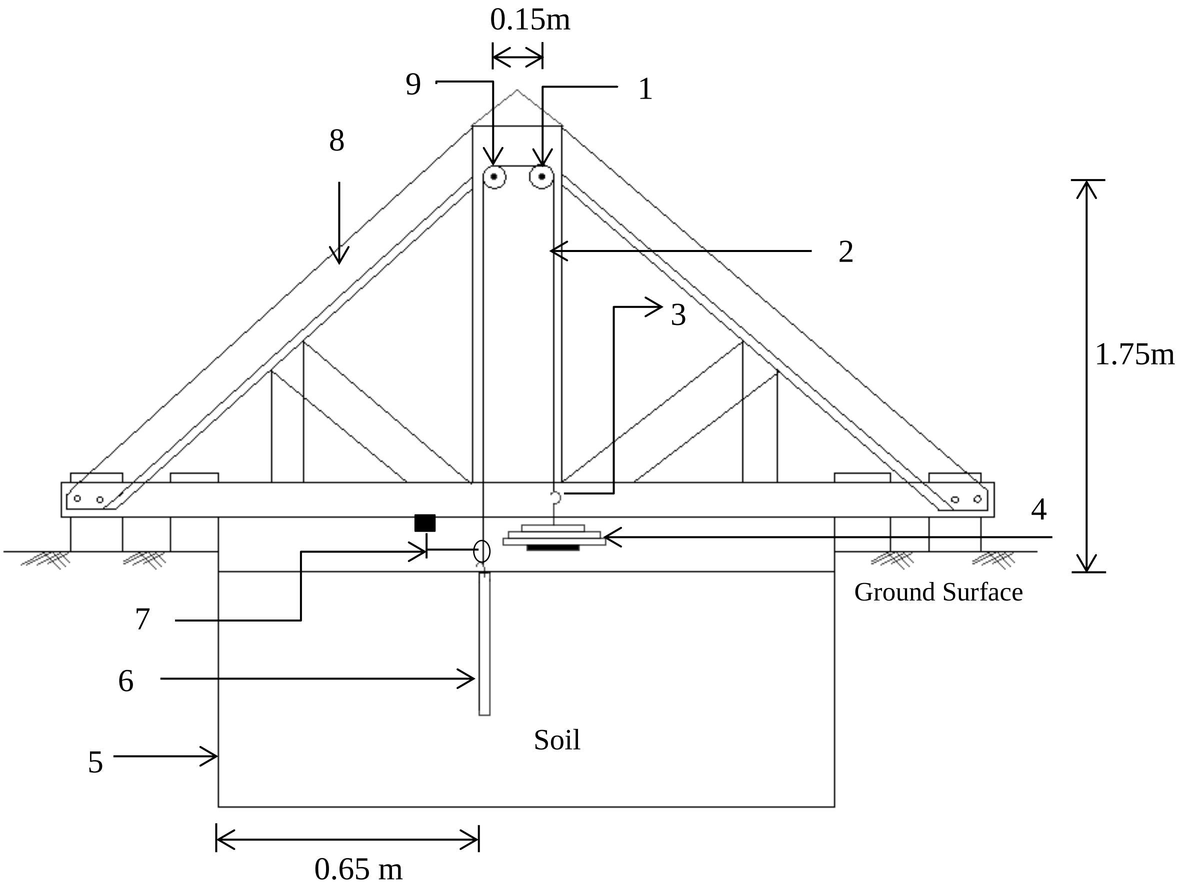


**Fig.5.3 Experimental setup**

**Legends**

1. Pulley 1
2. String
3. Loading pan
4. Dead weight
5. Steel tank
6. Bored cast in-situ concrete pile
7. Dial Gauge with magnetic stand
8. Girder
9. Pulley 2

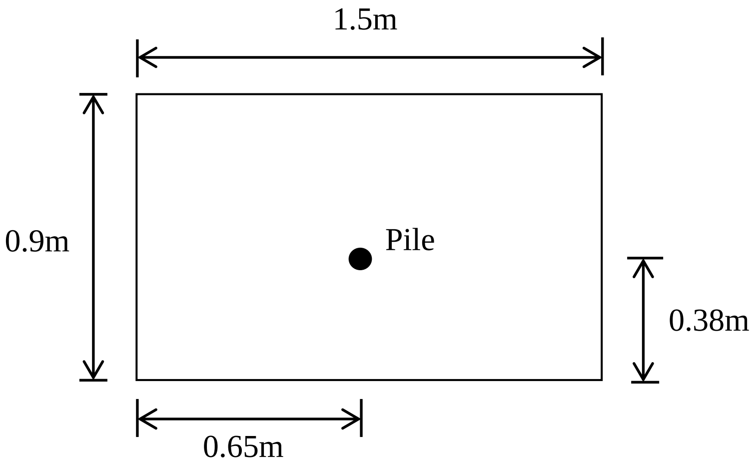


**Fig.5.4 Top view of the tank**

(a) (b)

(c) (d)

**Fig.5.5 Experimental program; (a) Levelling of compacted soil; (b) Concreting for pile without use drilling fluid; (c) Borehole stabilization using bentonite slurry; (d) Typical pull out setup**

## 5.5 Testing Program

a) The markings, at a distance of 15 cm, 30 cm, 45 cm and 55 cm from the bottom of the steel tank were made, on the sides of the tank.

b) Soil, was weighed using weighing machine, and was compacted in layers, using steel hammers, at different marked levels which gave overall bulk unit weight of 15.85kN/m$^3$ i.e. a density of 1.61 g/cm$^3$.

c) The top surface of soil (55 cm from the bottom of the tank) was leveled using a spirit level and once the top surface was leveled, markings were made, using the measuring tape depending upon location of the pile.

d) For the first case i.e. without any drilling fluid, borehole was formed by hammering the PVC pipe into the soil, taking care of its verticality and center, and the soil collected inside the pipe was taken out.

e) A concrete, with cement and sand (stone dust) ratio of 1:2.5 and water-cement ratio of 0.45 with 5% silica flume was formed that was gave a compressive strength of 17.1MPa at 7 days, and the pile was casted, and reinforced with 2mm diameter wires with a hook was fitted at the top of the pile.

f) After 7 days of casting of pile, a setup was made as shown in Fig.5.3 and loads were applied and corresponding settlements were recorded after 2-3 min of each loading until there was no change in the settlement reading observed.

g) The settlement readings were noted till the pile pulled out from the soil.

i) For the next case i.e. the case in which borehole was stabilized using drilling fluid, the soil was disturbed and again compacted and leveled.

j) Bentonite slurry of 4% and 6% concentration were poured in the excavated borehole, for their respective cases and were kept undisturbed for two hours in order to produce a layer of filter cake on the inside wall of excavation, thereafter concreting was done.

k) Repeat the steps mentioned above in order to obtain a curve between load and displacement for the pull out test.

# CHAPTER 6
# RESULTS AND DISCUSSION

## 6.1 Characteristics of Bentonite Powder

Morphology of the bentonite which was obtained from scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) was performed to characterize and quantify the chemical elements exist within bentonite sample.

### 6.1.1 Scanning Electron Microscopy (SEM)

Fig.6.1 shows the morphology of the bentonite used in the work which was obtained from Scanning Electron Microscopy (SEM) performed in Nano-Technology laboratory DTU. Fig.6.1(a) shows that particles present in bentonite sample are of irregular size and shape and having large voids. Fig.6.1(b) was taken at 10 µm, it can be observed that it has agglomerated due to the presence of water in the atmospheric condition. This demonstrates the hygroscopic nature of bentonite.

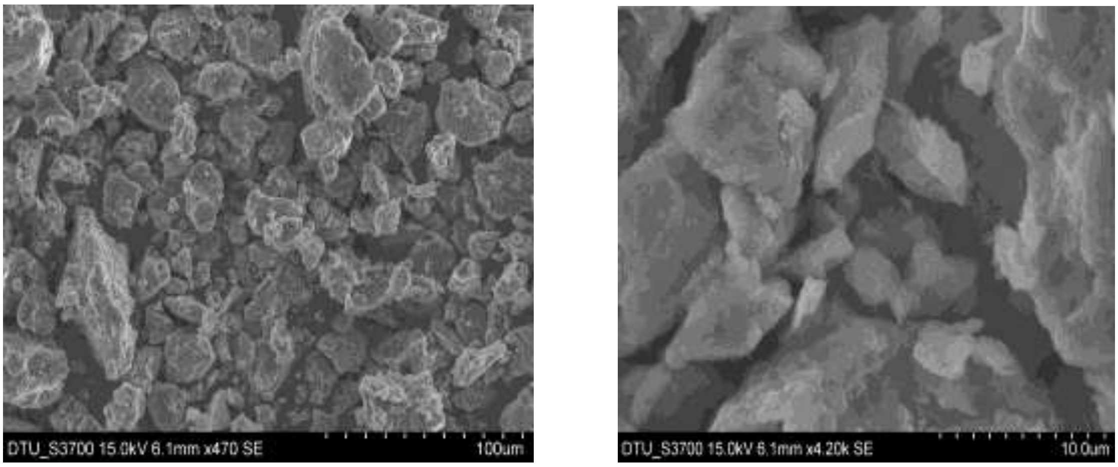


**Fig. 6.1 Morphology of bentonite sample (a) image of bentonite sample at 100 µm; (b) image of bentonite sample at 10 µm**

### 6.1.2 Energy Dispersive X-Ray Spectroscopy (EDX)

Fig.6.2 shows the spectrum of bentonite as obtained using an energy-dispersive X-ray spectrometer (EDX) which is attached to a SEM. The spectrum obtained from the EDX shows that there are traces of sodium ions in bentonite samples which indicates that the bentonite used in work is a type of sodium bentonite.

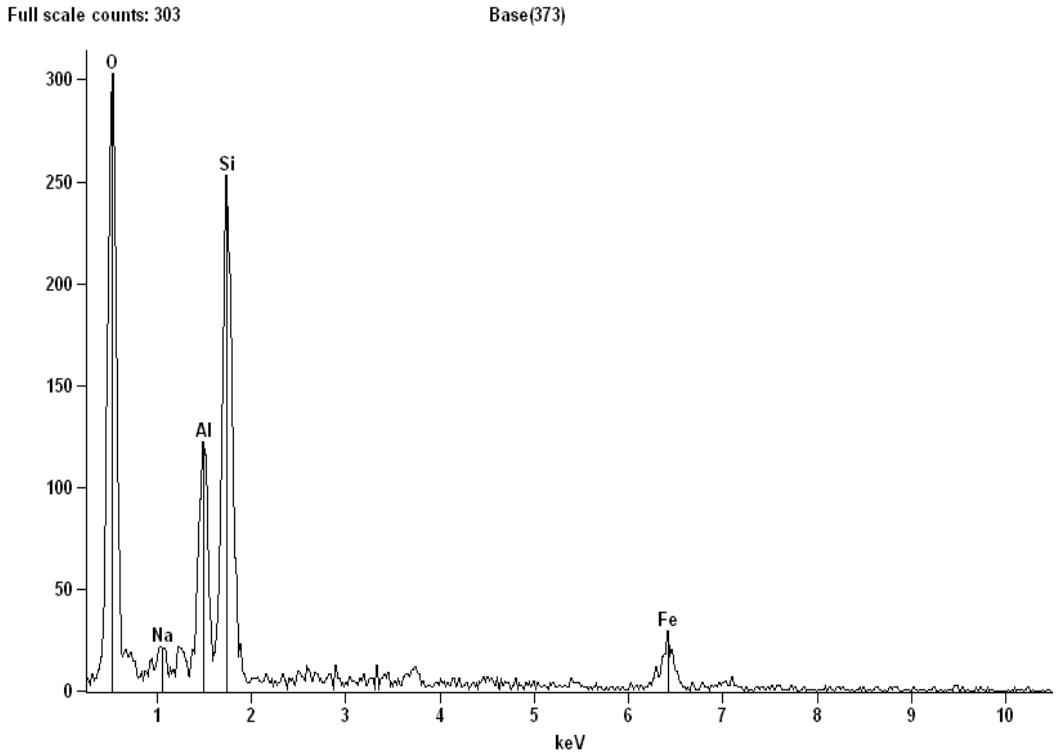


**Fig.6.2 Spectrum of bentonite powder**

**Table 6.1: Quantitative results obtained from EDX**

| *Element Line* | *Net Counts* | *Int. Cps/nA* | *Weight %* | *Weight % Error* | *Atom %* | *Atom % Error* | *Formula* | *Standard Name* |
|---|---|---|---|---|---|---|---|---|
| ***O K*** | 2693 | --- | 44.12 | +/- 0.88 | 62.33 | +/- 1.25 | O | |
| ***Na K*** | 106 | --- | 1.34 | +/- 0.19 | 1.31 | +/- 0.19 | Na | |
| ***Al K*** | 1000 | --- | 9.14 | +/- 0.49 | 7.65 | +/- 0.41 | Al | |
| ***Si K*** | 2647 | --- | 25.81 | +/- 0.69 | 20.77 | +/- 0.56 | Si | |
| ***Si L*** | 0 | --- | --- | --- | --- | --- | | |
| ***Fe K*** | 362 | --- | 19.59 | +/- 2.22 | 7.93 | +/- 0.90 | Fe | |
| ***Fe L*** | 151 | --- | --- | --- | --- | --- | | |
| ***Total*** | | | 100.00 | | 100.00 | | | |

## 6.2 Rheological Properties of Bentonite Drilling Fluid

The rheological properties of bentonite fluid such as viscosity, density in addition with pH of the slurry were determined. And factors influencing to these properties such as time without agitation, addition of coagulating agents, and impurities which may degrade the quality of fluid were also checked.

### 6.2.1 Effect of Concentration of Bentonite

The result tabulated in Table 6.2, were obtained from the experimental work to check the effect of increase in bentonite concentration in water sample. It was observed that with the addition of bentonite in the water, pH of water increased but pH has not affected by addition of more concentration of bentonite into it, whereas the viscosity of fluid increases with increase in concentration of bentonite as shown in Fig.6.3. It was also observed that density of fluid increases exponentially with the addition of the bentonite as shown in Fig.6.4. The Marsh funnel viscosity of bentonite slurry is less than 60 seconds for the suspensions varying from 2 to 5 % concentration of bentonite. In general low density of fluid will not offer adequate strength and high density has a problem of filter cake formation in addition to displacement of slurry by concrete. As per IS 2911-2: 2010 guidelines which recommended a range of 30 to 60 sec for the viscosity, so that an average viscosity i.e. 4% concentration of bentonite suspension has been adopted in all other tests.

**Table 6.2: Effect of bentonite concentration on fluid properties**

| Bentonite (%) | pH | Viscosity (s) | Density (g/cm$^3$) |
|---|---|---|---|
| **0** | 7.1 | 36.40 | 1 |
| **2** | 9.2 | 40.00 | 1.005 |
| **4** | 9.3 | 46.88 | 1.03 |
| **5** | 9.3 | 57.51 | 1.1 |
| **6** | 9.3 | 72.31 | 1.2 |
| **9** | 9.3 | 122.00 | - |

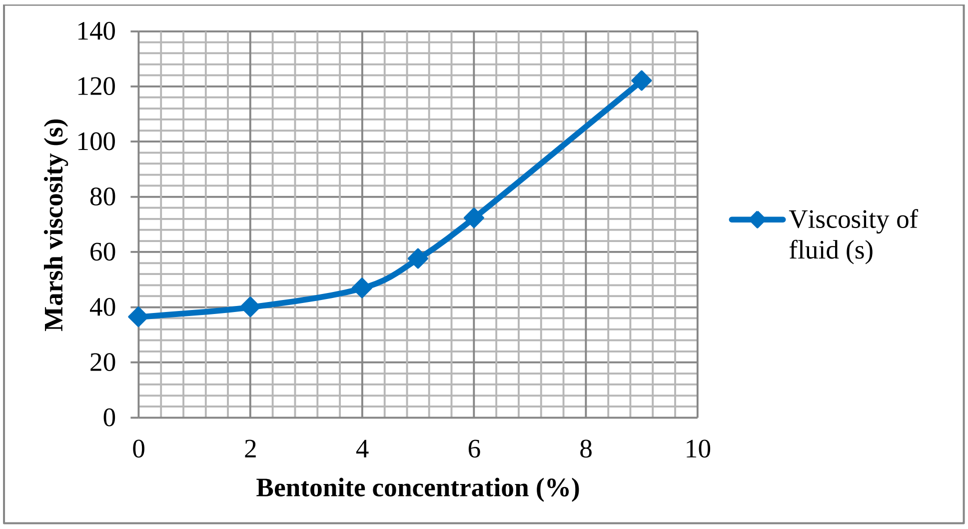


**Fig.6.3 Variation of viscosity with increase in bentonite concentration**

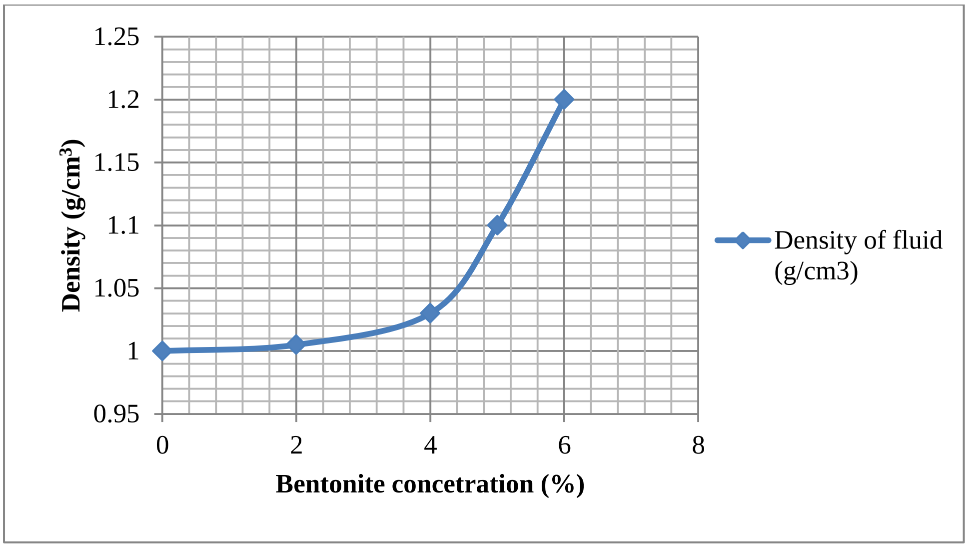


**Fig.6.4 Variation of density with increase in bentonite concentration**

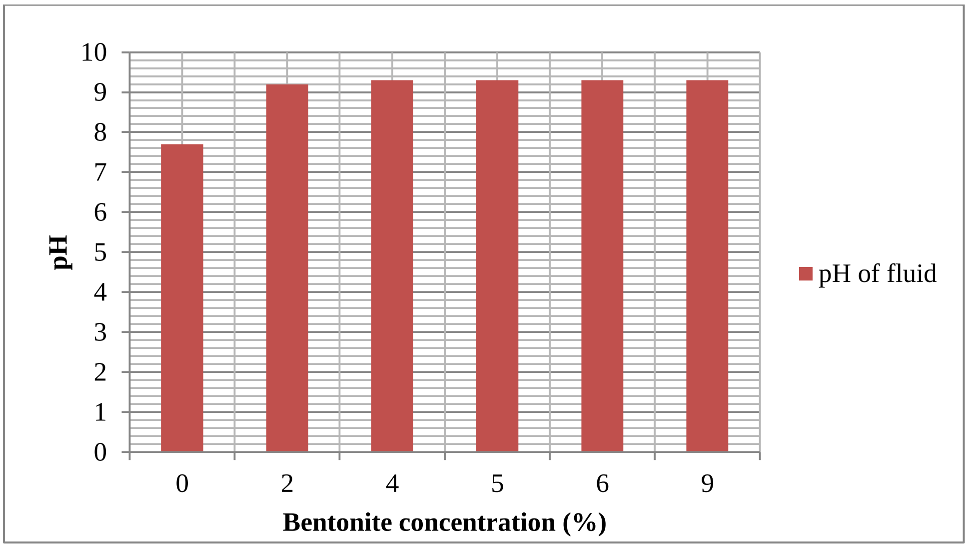


**Fig.6.5 Variation of pH of fluid with increase in bentonite concentration**

### 6.2.2 Effect of Variation of pH of the Fluid

To check this effect pH of prepared solutions of 4% bentonite concentration has changed with the addition of sodium hydroxide NaOH at different concentrations of (0.01%, 0.1%, 0.5%, and 1%). The experimental results as tabulated in Table 6.3, shows the effect of increase of pH on the Marsh viscosity and density of fluid. Fig.6.6 shows that Marsh viscosity increases as the pH changes from 9.3 to 9.6 and thereafter it decreases. It can be inferred from the literature that clay minerals have two types of electric charges.

Permanent charges on the face of particle and variable charges on broken edges, these permanent charges do not vary with pH but the charges on edges get disturbed due to variation of pH depending on $H^+$ or $OH^-$ ions. As the solutions get alkaline the broken edges of bentonite particles become negatively-charged. This leads to a stable dispersion (dispersed) of the sample due to electrostatic repulsion between the same charges on basal surface thus the viscosity increases. Fig.6.7 shows that the density of fluid increases as the pH increases.

**Table 6.3: Effect of increase of pH on fluid properties**

| 4% Concentration bentonite slurry | | | |
|---|---|---|---|
| **NaOH (%)** | **pH** | **Viscosity (s)** | **Density (g/cm$^3$)** |
| **0** | 9.3 | 45.54 | 1.025 |
| **0.01** | 9.4 | 50.21 | 1.03 |
| **0.1** | 9.6 | 63.10 | 1.04 |
| **0.5** | 10.1 | 61.41 | 1.05 |
| **1** | 10.6 | 60.52 | 1.05 |

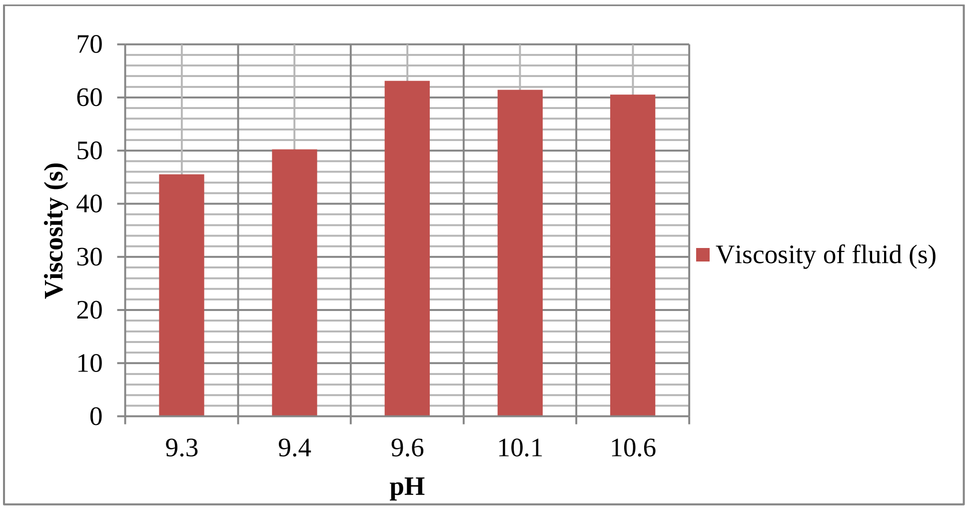


**Fig.6.6 Variation of viscosity with increase in pH of the fluid**

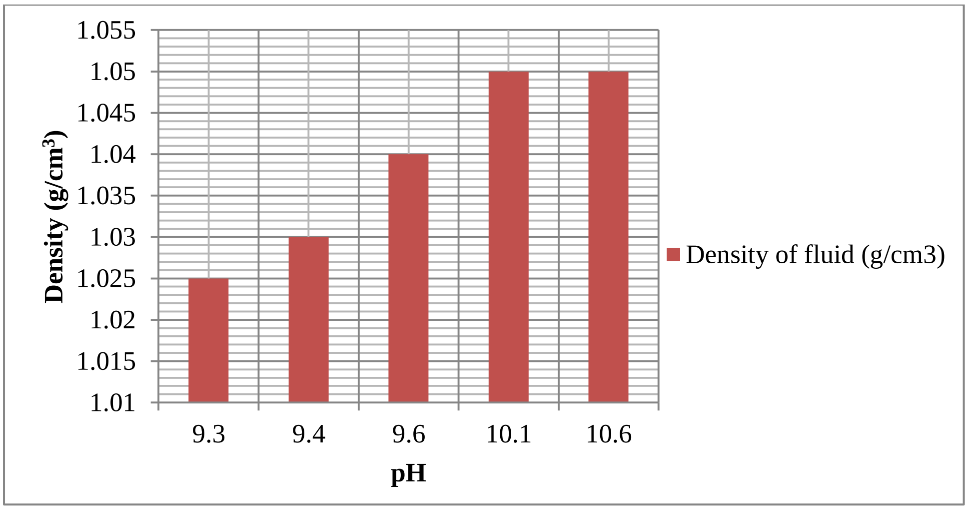


**Fig.6.7 Variation of density with increase in pH of the fluid**

### 6.2.3 Effect of Passage of Time on Fluid Properties

Table 6.4, shows the result obtained from this laboratory experiment. Fig.6.8 shows the effect of time without agitation on the Marsh funnel viscosity of 4% concentration of bentonite slurry. From the result it can be observed that viscosity of fluid increases as the time passage, because bentonite particles have tendency to get swell with time and with time gains the strength due to its thixotropic nature. Similar effect was also observed on the density of fluid which was also increases with the passage of time as shown in Fig.6.9. pH of the slurry with time as shown in Fig.6.10 is slightly decreases after 5 hours but the effect was not significant.

**Table 6.4: Effect of passage of time on fluid properties**

| 4% Concentration bentonite slurry | | | |
|---|---|---|---|
| **Time after mixing** | **pH** | **Viscosity (s)** | **Density (g/cm$^3$)** |
| **0** | 9.3 | 45.20 | 1.025 |
| **0.5h** | 9.3 | 45.60 | 1.025 |
| **1h** | 9.3 | 46.32 | 1.03 |
| **2h** | 9.3 | 47.54 | 1.03 |
| **5h** | 9.3 | 48.69 | 1.04 |
| **24h** | 9.2 | 51.5 | 1.07 |
| **48h** | 9.1 | 52.32 | 1.10 |

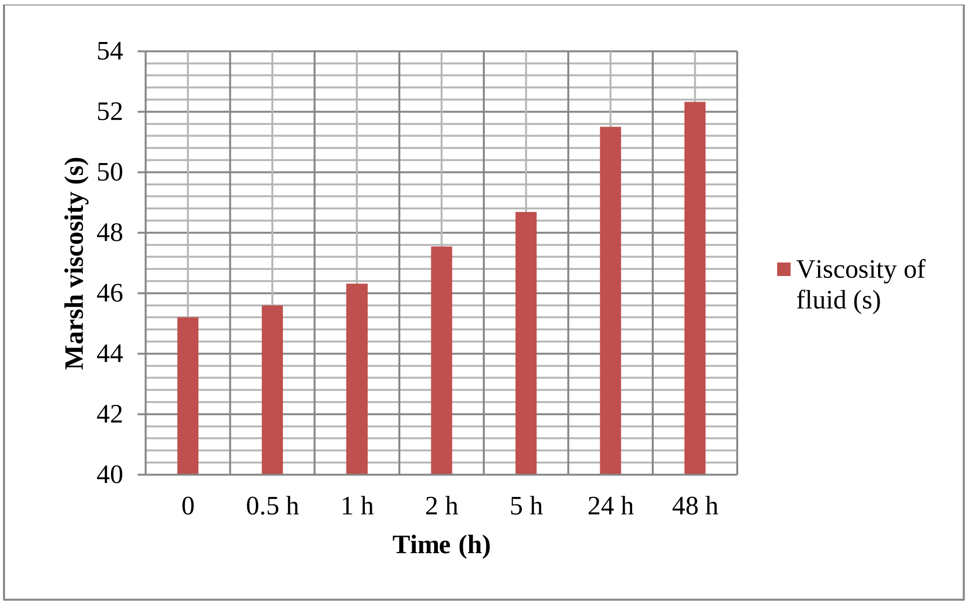


**Fig.6.8 Variation of viscosity of the fluid with passage of time**

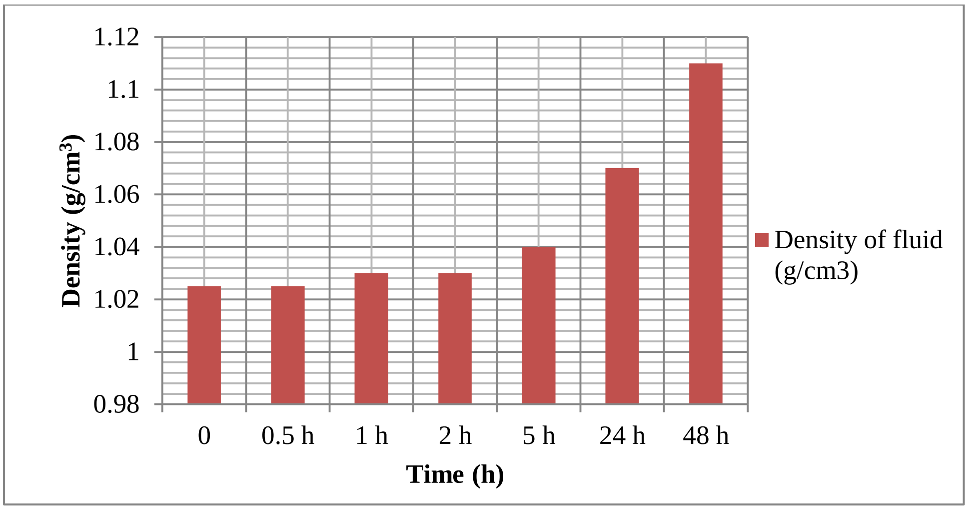


**Fig.6.9 Variation of density of the fluid with passage of time**

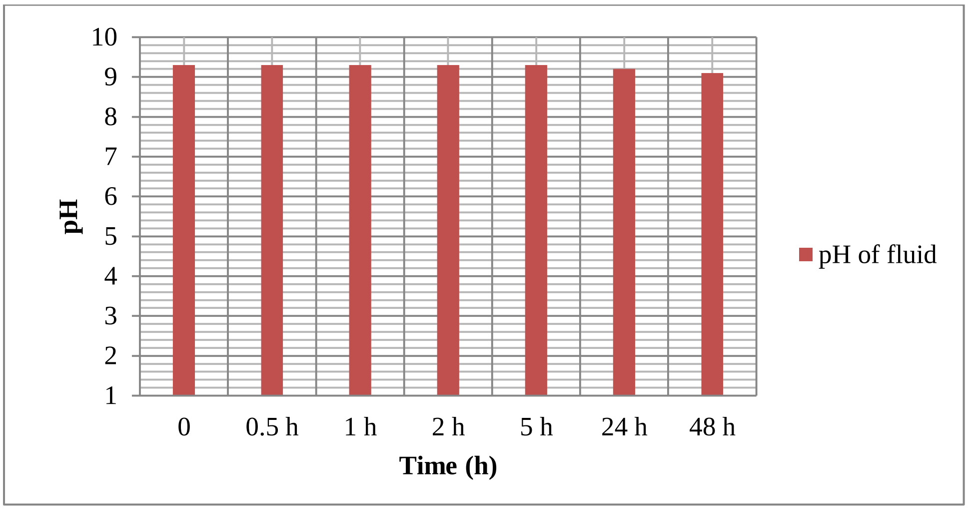


**Fig.6.10 Variation of pH of the fluid with passage of time**

### 6.2.4 Effect of Silt Content on Fluid Properties

Table 6.5 and 6.6 shows the results of effect of addition of silt content on rheological properties of fluid. For this investigation two different concentration of drilling fluid was taken for the observation.

**Table 6.5: Effect of silt content on 4% bentonite concentration of fluid**

| Time after mixing | Silt content added (%) | 4% Concentration of bentonite | | | Silt content added (%) | 4% Concentration of bentonite | | |
|---|---|---|---|---|---|---|---|---|
| | | pH | Viscosity (s) | Density ($g/cm^3$) | | pH | Viscosity (s) | Density ($g/cm^3$) |
| **0** | 0 | 9.3 | 45.41 | 1.025 | 5 | 9.0 | 53.15 | 1.06 |
| **2h** | 0 | 9.3 | 47.10 | 1.03 | 5 | 9.0 | 54.67 | 1.10 |

From the result it is observe that pH of solution was decreased as the silt content added in the solution as shown in Fig.6.11 and Fig.6.14. And it was also observed that viscosity and density of fluid also increases. For the lower concentration i.e. 4% bentonite concentration Marsh viscosity of solution was increased from 47.10 sec to 54.67 sec after 2 hours as shown in Fig.6.12. But at higher concentration of bentonite solution, as selected (6% bentonite solution) it was difficult to get Marsh funnel viscosity because with the addition of impurities it may clog the funnel, it can be inferred from the result as shown in Fig.6.15. Fig.6.13 and Fig.6.16 shows that increment in density with the addition of silt for both lower and higher concentration of fluid. It necessitates that when slurry is to be circulated, if it is possible to remove most of the impurities through the use some suitable mechanism so that it may not degrade the quality of the product.

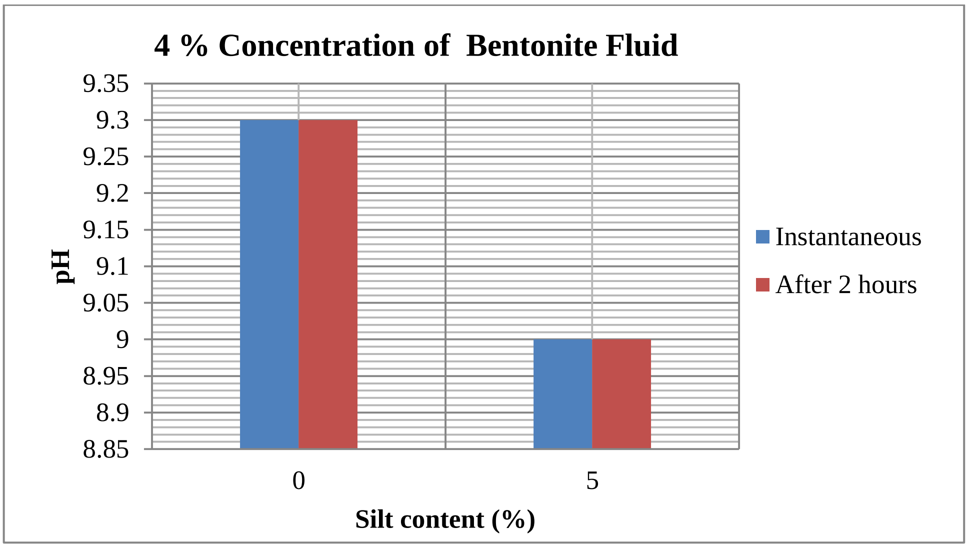


Fig.6.11 Variation of pH of the 4% bentonite fluid with addition of silt

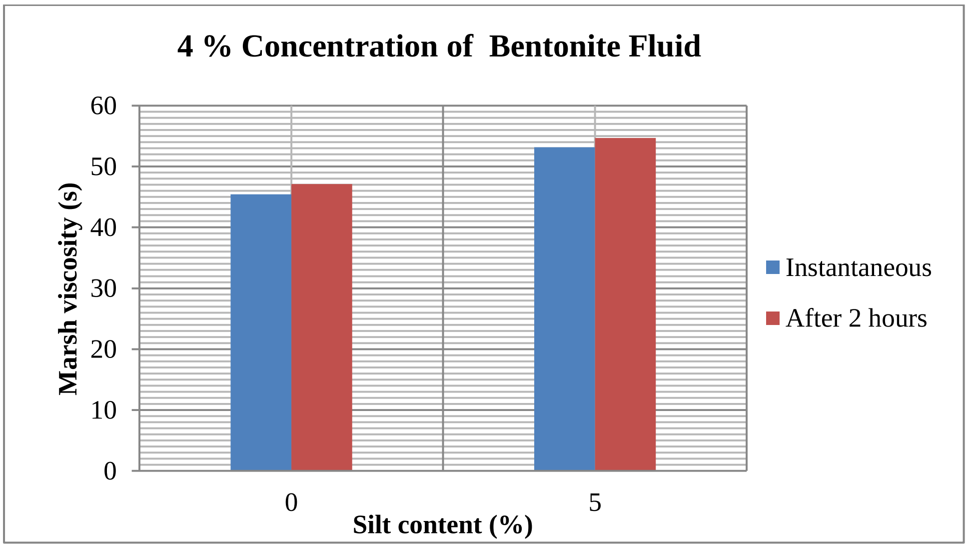


Fig.6.12 Variation of viscosity of the 4% bentonite fluid with addition of silt

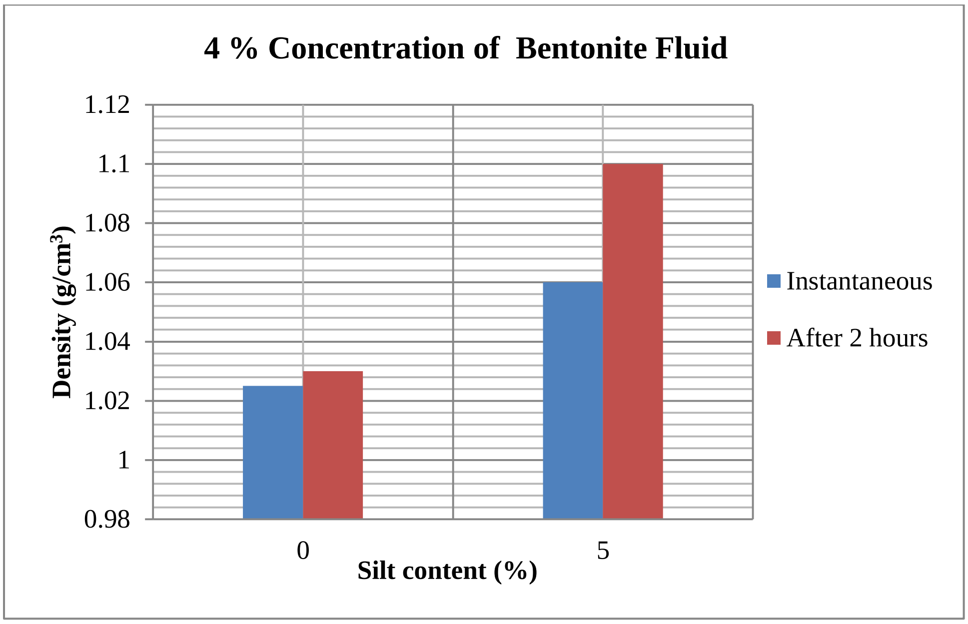


**Fig.6.13 Variation of density of the 4% bentonite fluid with addition of silt**

**Table 6.6: Effect of silt content on 6% bentonite concentration of fluid**

| Time after mixing | Silt content added (%) | 6% Concentration of bentonite | | | Silt content added (%) | 6% Concentration of bentonite | | |
|---|---|---|---|---|---|---|---|---|
| | | pH | Viscosity (s) | Density ($g/cm^3$) | | pH | Viscosity (s) | Density ($g/cm^3$) |
| **0** | 0 | 9.3 | 71.23 | 1.2 | 5 | 9.0 | - | 1.21 |
| **2h** | 0 | 9.3 | 73.10 | 1.2 | 5 | 9.0 | - | 1.23 |

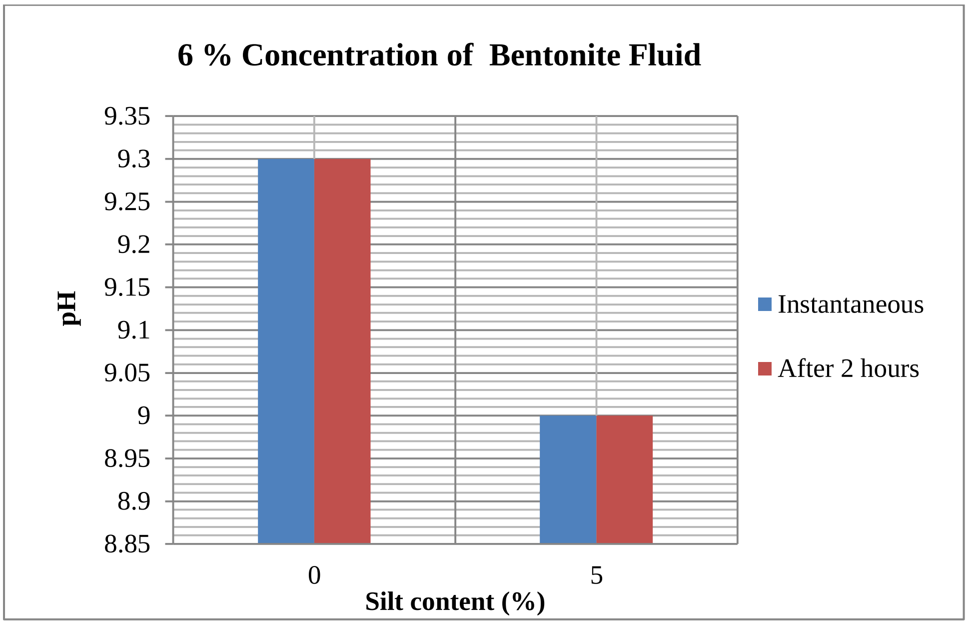


**Fig.6.14 Variation of pH of the 6% bentonite fluid with addition of silt**

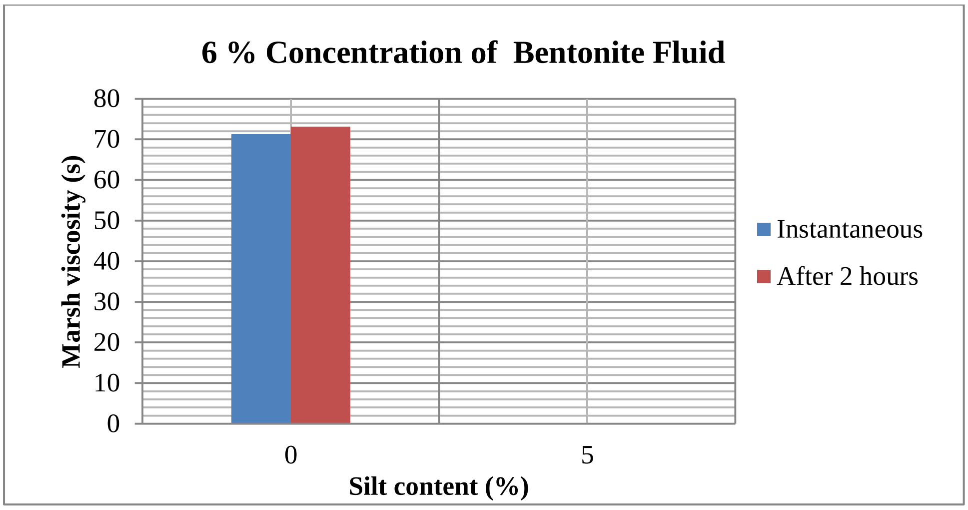


**Fig.6.15 Variation of viscosity of the 6% bentonite fluid with addition of silt**

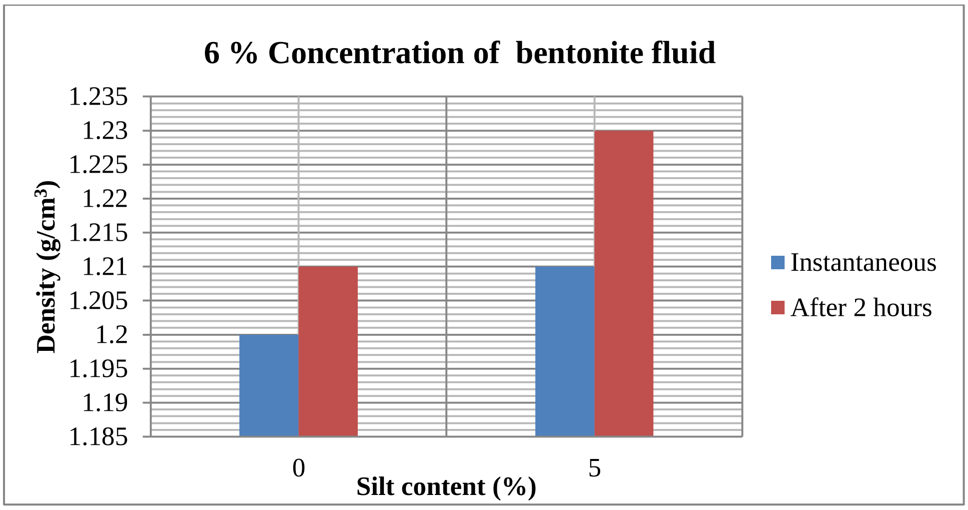


**Fig.6.16 Variation of density of the 6% bentonite fluid with addition of silt**

### 6.2.5 Effect of Addition of Poly-fluid and Alum on Fluid Properties

Table 6.7 shows a result of effect of addition of coagulating agents on the bentonite fluid properties. From the experimental work it was observed that Marsh viscosity of the solution increases with addition of poly-fluid whereas viscosity of fluid decreased with addition alum as shown in Fig.6.18. It can be inferred from the result and literature that poly-fluid act as a viscosity modifier that can increase the viscosity of fluid in alkaline conditions. Poly-fluid anions are attached on positively-charged clay particles thus prevent the edge-face contacts due to which viscosity increases. But in case of alum electric double layer get compressed due to which network structure may disrupts thus viscosity decreases. Table 6.8 shows results of flocculation of particle with time. Long chain poly-fluid molecules lubricates the soil particles which thus settle down in coarse of time and can be removed using suitable construction technique. Rate of settlement in case of poly-fluid was faster than that observed in alum. Density and Marsh viscosity of top fluid was noted down as 1.005g/cm$^3$ and 38sec respectively after 24hours i.e. came close to the properties of water. Fig.6.17 shows the acidic behavior of alum when added in the fluid system whereas poly-fluid has shown no significant effects on the pH value.

**Table 6.7: Effect of coagulating agents on 4% bentonite concentration of fluid**

| 4% Concentration of bentonite fluid | | | | | |
|---|---|---|---|---|---|
| Addition of poly-fluid | | | Addition of alum | | |
| Poly-fluid (%) | pH | Viscosity (s) | Alum (%) | pH | Viscosity (s) |
| **0** | 9.2 | 46 | **0** | 9.2 | 45.89 |
| **0.01** | 9.2 | 47.13 | **0.01** | 9.1 | 45.68 |
| **0.1** | 9.1 | 48.32 | **0.1** | 7.8 | 45.62 |
| **0.5** | 9.0 | 52.25 | **0.5** | 6.5 | 44.1 |
| **1** | 8.9 | 53.77 | **1** | 6.1 | 42.7 |
| **2** | 8.7 | 55.10 | **2** | 5.5 | 40.91 |

**Table 6.8: Effect of coagulating agents with time on 4% bentonite fluid**

| Observed settlement under two different coagulating agents | | |
|---|---|---|
| Time | 1% Poly-fluid concentration | 1% Alum concentration |
| | Settlement (mm) | Settlement (mm) |
| **0** | 0 | 0 |
| **15 min** | 6 | 32 |
| **1 h** | 11 | 42 |
| **20 h** | 16 | 46 |

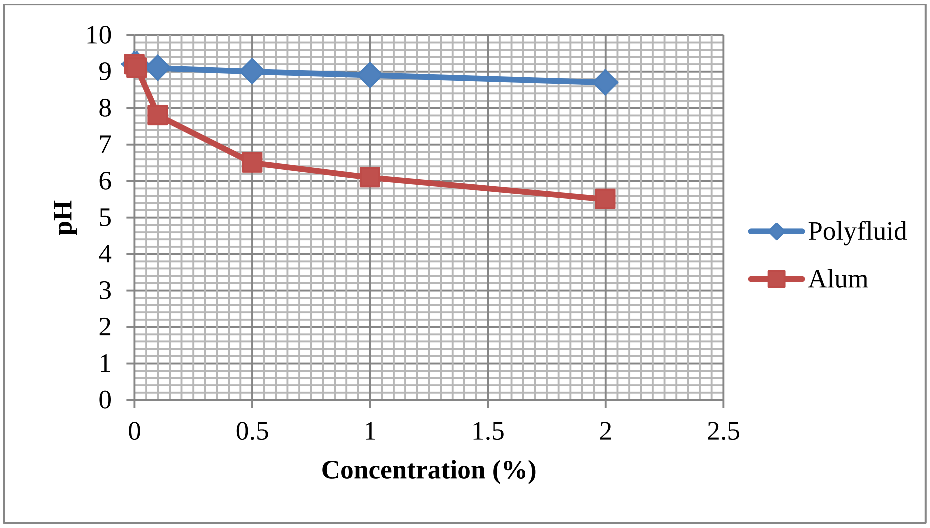


**Fig.6.17 Variation of pH with addition of two different coagulating agents in the fluid**

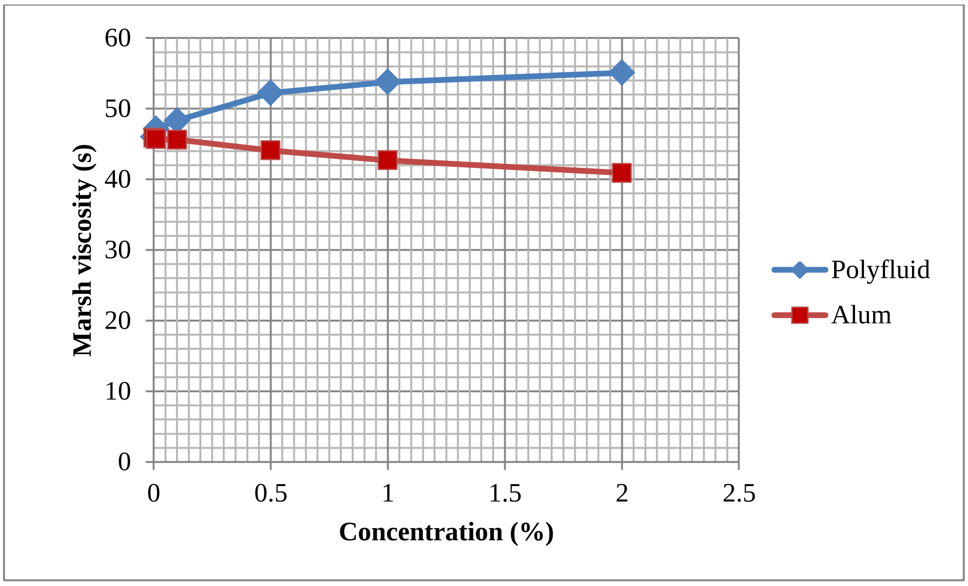


**Fig.6.18 Variation of viscosity with addition of two different coagulating agents in the fluid**

### 6.3 Effect of Concentration of Bentonite Fluid on Shear Parameters

As the bentonite concentration was increased, the internal angle of friction 'ϕ' and cohesion 'c' decreased drastically suggesting the formation of a soft filter cake. This results in decrease in the shear strength of soil, causing it to lose its frictional resistance. As the cohesion value is very much less than 1MPa thus it has been neglected while calculating uplift capacity of the pile.

Fig.6.19 represents the result of direct shear test for different concentration of bentonite fluid. It shows that the shear strength of the soil is reduced significantly with higher bentonite concentration.

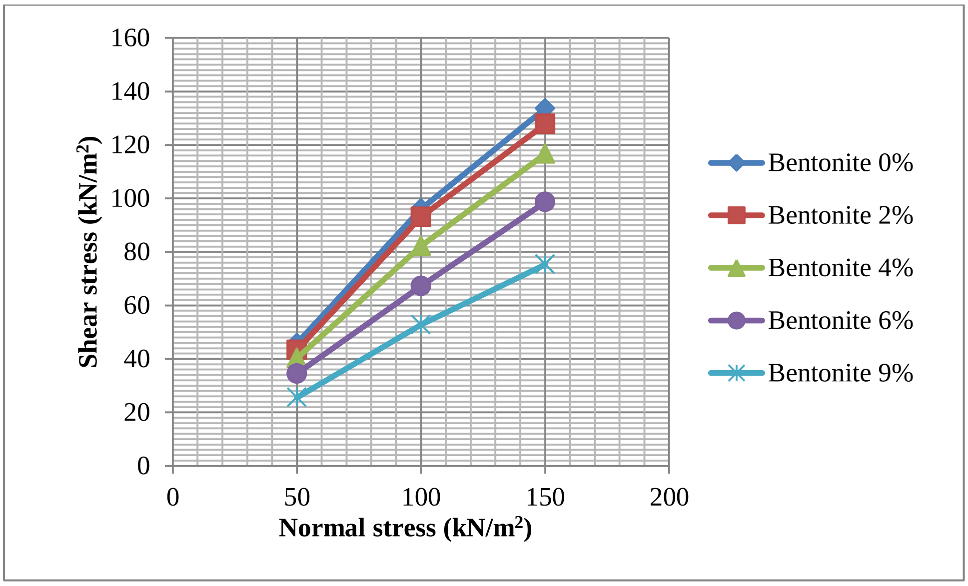


**Fig.6.19 Curve for shear stress vs. normal stress response of different concentration of bentonite fluid**

**Table 6.9: Result data of direct shear test**

| Bentonite concentration (%) | $\phi^o$ | c ($kN/m^2$) |
|---|---|---|
| **0** | $41.28^o$ | 4.07 |
| **2** | $40.17^o$ | 3.61 |
| **4** | $37.38^o$ | 3.28 |
| **6** | $32.68^o$ | 2.58 |
| **9** | $26.44^o$ | 1.47 |

## 6.4 Theoretical Calculation for Uplift Capacity of Pile

Different theories were used to theoretically calculate the uplift capacity of both modeled and prototype concrete piles. The results presented in Table 6.10 and Table 6.11 was obtained using direct shear test results and suggests that net uplift capacity of pile decreases as the bentonite concentration used as drilling fluid increases due to the formation of a soft layer of bentonite filter cake.

**Table 6.10: Theoretical result of uplift capacity of modeled concrete pile**

| Method applied | Bentonite concentration (%) | | | | |
|---|---|---|---|---|---|
| | 0% | 2% | 4% | 6% | 9% |
| | $Q_{mt}$ (kN) | $Q_{mt}$ (kN) | $Q_{mt}$ (kN) | $Q_{mt}$ (kN) | $Q_{mt}$ (kN) |
| **Meyerhof** | 0.121 | 0.116 | 0.105 | 0.088 | 0.068 |
| **Nabil F. Ismael** | 0.194 | 0.187 | 0.171 | 0.145 | 0.116 |
| **Kulhawy et al.** | 0.266 | 0.249 | 0.212 | 0.161 | 0.110 |
| **IS Code** | 0.194 | 0.187 | 0.171 | 0.145 | 0.116 |

**Table 6.11: Theoretical result of uplift capacity of prototype concrete pile**

| Method applied | Bentonite concentration (%) | | | | |
|---|---|---|---|---|---|
| | 0% | 2% | 4% | 6% | 9% |
| | $Q_{pt}$ (kN) | $Q_{pt}$ (kN) | $Q_{pt}$ (kN) | $Q_{pt}$ (kN) | $Q_{pt}$ (kN) |
| **Meyerhof** | 406.49 | 390.92 | 353.79 | 297.07 | 230.29 |
| **Nabil F. Ismael** | 654.96 | 631.59 | 575.87 | 490.78 | 390.58 |
| **Kulhawy et al.** | 898.35 | 840.47 | 714.65 | 543.63 | 370.77 |
| **IS Code** | 654.96 | 631.59 | 575.87 | 490.78 | 390.58 |

### 6.5 Experimental Results of Uplift Capacity of Modeled Pile

Fig.6.20 shows the load versus displacement response of the pile obtained during uplift of the pile for different bentonite concentration used as a drilling fluid. Result shows that uplift capacity obtained, without use of any drilling fluid is higher than that obtained using drilling fluid due to the effect of soft filter cake formation on the side of the excavated borehole. From the experiment it was also realized that in all the cases with or without use of drilling fluid failure occurs within 2.5 to 3.5 mm displacement.

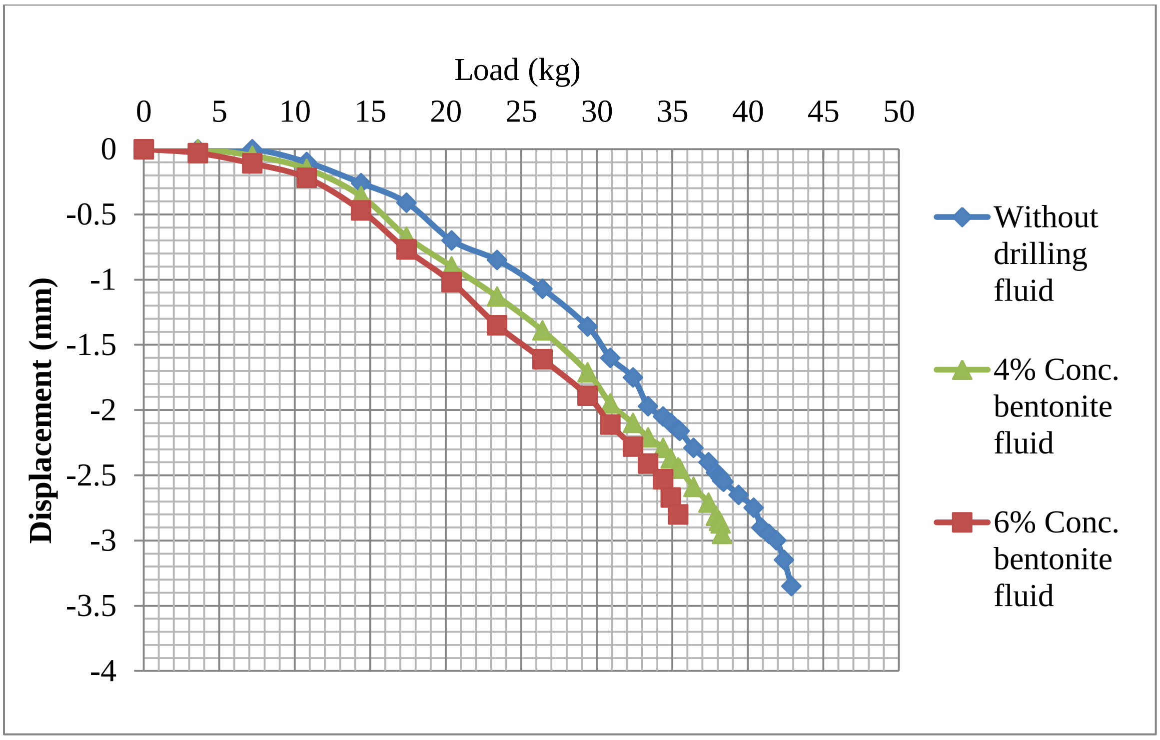


**Fig.6.20 Load - displacement curve during uplift for different bentonite concentration as drilling fluid**

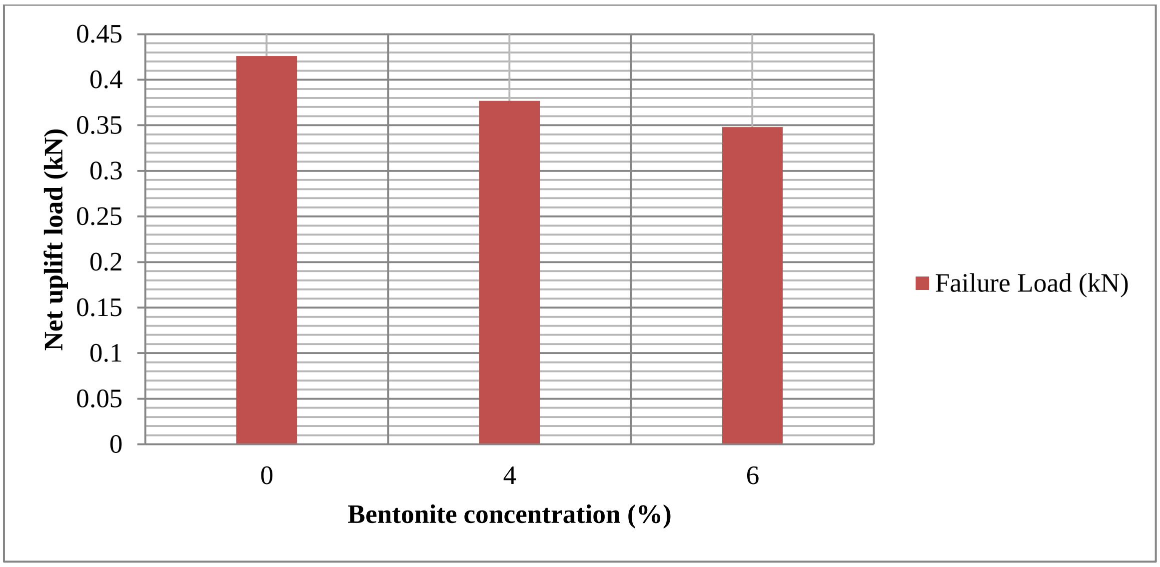


**Fig.6.21 Net uplift load for different bentonite concentration as drilling fluid**

**Table 6.12: Experimental results of frictional resistance of modeled concrete pile**

| Case | Uplift capacity (kN) | Weight of pile (kN) | Frictional Resistance $P_{me}$ (kN) | | | |
|---|---|---|---|---|---|---|
| | | | IS code | Meyerhof | Kulhawy | N. Ismael |
| No drilling fluid | 0.426 | 0.0133 | 0.413 | 0.426 | 0.426 | 0.413 |
| Bentonite fluid concentration (4%) | 0.377 | 0.0131 | 0.364 | 0.377 | 0.377 | 0.364 |
| Bentonite fluid concentration (6%) | 0.348 | 0.0125 | 0.336 | 0.348 | 0.348 | 0.336 |

## 6.6 Determination of Uplift Capacity of Prototype Pile

Table 6.13 shows the calculation for determination of a constant K – factor which is called earth pressure coefficient during uplift using Indian standard code method, from the frictional resistance obtained from experiment. Result shows that 'K' is increases as the angle of internal friction decreases.

Using this K – factor as obtained from different cases frictional resistance of prototype pile has been calculated as tabulated in Table 6.13. Similarly this K – factor has been calculated using different methods for uplift. For the determination of net uplift capacity of prototype pile using different methods a scale of 1:15 was taken as the size of actual pile with diameter 0.045m and embedment length of 0.35m was casted. Result shows that frictional of pile was decreased when we used drilling fluid due to the formation of a soft filter cake. About 11.8 % in case of lower concentrated bentonite fluid and 18.7 % in case of higher concentrated fluid, reduction in frictional resistance were observed for prototype pile from the case of no drilling fluid used.

### 6.6.1 IS Code Method

**Table 6.13: K – Factor from IS code method using experimental result**

| Indian Standard Code Method | | | | | |
|---|---|---|---|---|---|
| Case | $P_{me}$ (kN) | $\phi^o$ | $P_D$ (kN/m$^2$) | $C = K_1 \tan\delta$ | $K_1$ |
| No drilling fluid | 0.413 | 41.28 | 2.774 | 3.01 | **3.43** |
| Bentonite fluid concentration (4%) | 0.364 | 37.38 | 2.774 | 2.65 | **3.47** |
| Bentonite fluid concentration (6%) | 0.336 | 32.68 | 2.774 | 2.44 | **3.81** |

**Table 6.14: Frictional resistance for prototype pile using IS code method**

| Indian Standard Code Method | | | | |
|---|---|---|---|---|
| **Case** | **$K_1$** | **tanδ = tanϕ** | **$P_D$ ($kN/m^2$)** | **$P_{pe}$ (kN)** |
| No drilling fluid | 3.43 | 0.8778 | 41.606 | 1392.86 |
| Bentonite fluid concentration (4%) | 3.47 | 0.7639 | 41.606 | 1228.16 |
| Bentonite fluid concentration (6%) | 3.81 | 0.6415 | 41.606 | 1132.31 |

### 6.6.2 Meyerhof's Method

**Table 6.15: K – Factor from Meyerhof's method using experimental result**

| Meyerhof's Method | | | | | |
|---|---|---|---|---|---|
| **Case** | **$P_{me}$ (kN)** | **ϕ°** | **Perimeter (m)** | **C = $K_1$tanδ** | **$K_2$** |
| No drilling fluid | 0.426 | 41.28 | 0.1414 | 3.01 | **3.53** |
| Bentonite fluid concentration (4%) | 0.377 | 37.38 | 0.1414 | 2.65 | **3.59** |
| Bentonite fluid concentration (6%) | 0.348 | 32.68 | 0.1414 | 2.44 | **3.95** |

**Table 6.16: Frictional resistance for prototype pile using Meyerhof's method**

| Meyerhof's Method | | | | |
|---|---|---|---|---|
| **Case** | **$K_2$** | **tanδ = tanϕ** | **Perimeter (m)** | **$P_{pe}$ (kN)** |
| No drilling fluid | 3.53 | 0.8778 | 2.121 | 1434.75 |
| Bentonite fluid concentration (4%) | 3.59 | 0.7639 | 2.121 | 1272.37 |
| Bentonite fluid concentration (6%) | 3.95 | 0.6415 | 2.121 | 1174.50 |

### 6.6.3 Kulhawy et Al.'s Method

**Table 6.17: K – Factor from Kulhawy et al.'s method using experimental result**

| Kulhawy et al.'s Method | | | | | |
|---|---|---|---|---|---|
| **Case** | **$P_{me}$ (kN)** | **ϕ°** | **Perimeter (m)** | **C = $K_1$tanδ** | **$K_3$** |
| No drilling fluid | 0.426 | 41.28 | 0.1414 | 3.01 | **3.53** |
| Bentonite fluid concentration (4%) | 0.377 | 37.38 | 0.1414 | 2.65 | **3.59** |
| Bentonite fluid concentration (6%) | 0.348 | 32.68 | 0.1414 | 2.44 | **3.95** |

**Table 6.18: Frictional resistance for prototype pile using Kulhawy et al.'s method**

| Kulhawy et al.'s Method | | | | |
|---|---|---|---|---|
| Case | $K_3$ | tanδ = tanϕ | Perimeter (m) | $P_{pe}$ (kN) |
| No drilling fluid | 3.53 | 0.8778 | 2.121 | 1437.75 |
| Bentonite fluid concentration (4%) | 3.59 | 0.7639 | 2.121 | 1272.37 |
| Bentonite fluid concentration (6%) | 3.95 | 0.6415 | 2.121 | 1174.50 |

### 6.6.4 Nabil F. Ismael's Method

**Table 6.19: K – Factor from Nabil F. Ismael's method using experimental result**

| Nabil F. Ismael's Method | | | | | | |
|---|---|---|---|---|---|---|
| Case | $P_{me}$ (kN) | Weight of pile (kN) | ϕ° | $P_D$ ($kN/m^2$) | C = $K_1$tanδ | $K_4$ |
| No drilling fluid | 0.413 | 0.0133 | 41.28 | 2.774 | 3.01 | **3.43** |
| Bentonite fluid concentration (4%) | 0.364 | 0.0131 | 37.38 | 2.774 | 2.65 | **3.47** |
| Bentonite fluid concentration (6%) | 0.336 | 0.0125 | 32.68 | 2.774 | 2.44 | **3.81** |

**Table 6.20: Frictional resistance for prototype pile using Nabil F. Ismael's method**

| Nabil F. Ismael's Method | | | | |
|---|---|---|---|---|
| Case | $K_4$ | tanδ = tanϕ | $P_D$ ($kN/m^2$) | $P_{pe}$ (kN) |
| No drilling fluid | 3.43 | 0.8778 | 41.606 | 1392.86 |
| Bentonite fluid concentration (4%) | 3.47 | 0.7639 | 41.606 | 1228.16 |
| Bentonite fluid concentration (6%) | 3.81 | 0.6415 | 41.606 | 1132.31 |

## 6.7 Comparison of Frictional Resistance between Theoretical and Experimental Results

Table 6.21 shows theoretical calculation for determination of frictional resistance of prototype pile. In which weight of the pile has been reduced from theoretically calculated uplift capacity of pile in case of IS code and Nabil. F. Ismael methods. Whereas in case of Meyerhof and Kulhawy's methods frictional resistance are same as that theoretically calculated uplift capacity of the prototype pile. Table 6.22 and Table 6.23 shows the calculation of increment factor '$I_f$', which is the ratio of frictional resistance calculated experimentally and that of calculated theoretically.

It can be observed that frictional resistance obtained from the experimental results are about 1.3 times higher from theoretical values from IS code and Nabil. F. Ismael method, while this increment being about 2.7 times from Meyerhof and almost twice from Kulhawy's method.

**Table 6.21: Theoretical frictional resistance calculation for prototype pile**

| Method Applied | Weight of pile (kN) | Theoretical Friction Resistance (kN) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Bentonite concentration (%) | | | | | |
| | | No drilling fluid | | 4% | | 6% | |
| | | $Q_{pt}$ | $P_{pt}$ | $Q_{pt}$ | $P_{pt}$ | $Q_{pt}$ | $P_{pt}$ |
| **Meyerhof** | 45.088 | 406.49 | 406.49 | 353.79 | 353.79 | 297.07 | 297.07 |
| **N. Ismael** | 45.088 | 654.96 | 609.87 | 575.87 | 530.78 | 490.78 | 445.69 |
| **Kulhawy et al.** | 45.088 | 898.35 | 898.35 | 714.65 | 714.65 | 543.63 | 543.63 |
| **IS code** | 45.088 | 654.96 | 609.87 | 575.87 | 530.82 | 490.78 | 445.69 |

**Table 6.22: Calculation for increment factor $I_f$**

| Case | IS Code Method | | | Meyerhof's Method | | |
|---|---|---|---|---|---|---|
| | $P_{pt}$ (kN) | $P_{pe}$ (kN) | $I_{f_1} = \frac{P_{pe}}{P_{pt}}$ | $P_{pt}$ (kN) | $P_{pe}$ (kN) | $I_{f_2} = \frac{P_{pe}}{P_{pt}}$ |
| No drilling fluid | 609.87 | 1392.86 | **2.28** | 406.49 | 1437.75 | **3.53** |
| Bentonite fluid concentration (4%) | 530.82 | 1228.16 | **2.31** | 353.79 | 1272.37 | **3.59** |
| Bentonite fluid concentration (6%) | 445.69 | 1132.31 | **2.54** | 297.07 | 1174.50 | **3.95** |

**Table 6.23: Calculation for increment factor $I_f$**

| Case | Nabil F. Ismael's Method | | | Kulhawy's Method | | |
|---|---|---|---|---|---|---|
| | $P_{pt}$ (kN) | $P_{pe}$ (kN) | $I_{f_3} = \frac{P_{pe}}{P_{pt}}$ | $P_{pt}$ (kN) | $P_{pe}$ (kN) | $I_{f_4} = \frac{P_{pe}}{P_{pt}}$ |
| No drilling fluid | 609.87 | 1392.86 | **2.28** | 898.35 | 1437.75 | **1.60** |
| Bentonite fluid concentration (4%) | 530.82 | 1228.16 | **2.31** | 714.65 | 1272.37 | **1.78** |
| Bentonite fluid concentration (6%) | 445.69 | 1132.31 | **2.54** | 543.63 | 1174.50 | **2.16** |

## 6.8 Determination of Modification Factor

Modification factor is taken as the ratio of constant K-factor obtained from experiment and that K-factor given by different methods that applied in the project.

**Table 6.24: Calculation for modification factors**

| Case | IS Code Method | | | Meyerhof's Method | | |
|---|---|---|---|---|---|---|
| | $K_{IS}$ | $K_1$ | $F_1 = \frac{K_1}{K_{IS}}$ | $K_M$ | $K_2$ | $F_2 = \frac{K_2}{K_M}$ |
| No drilling fluid | 1.5 | 3.43 | **2.29** | 1 | 3.53 | **3.53** |
| Bentonite fluid concentration (4%) | 1.5 | 3.47 | **2.31** | 1 | 3.59 | **3.59** |
| Bentonite fluid concentration (6%) | 1.5 | 3.81 | **2.54** | 1 | 3.95 | **3.95** |

**Table 6.25: Calculation for modification factors**

| Case | Kulhawy's Method | | | Nabil F. Ismael's Method | | |
|---|---|---|---|---|---|---|
| | $K_K$ | $K_3$ | $F_3 = \frac{K_3}{K_K}$ | $K_M$ | $K_4$ | $F_4 = \frac{K_4}{K_N}$ |
| No drilling fluid | 2.21 | 3.53 | **1.59** | 1.5 | 3.43 | **2.29** |
| Bentonite fluid concentration (4%) | 2.02 | 3.59 | **1.78** | 1.5 | 3.47 | **2.31** |
| Bentonite fluid concentration (6%) | 1.83 | 3.95 | **2.16** | 1.5 | 3.81 | **2.54** |

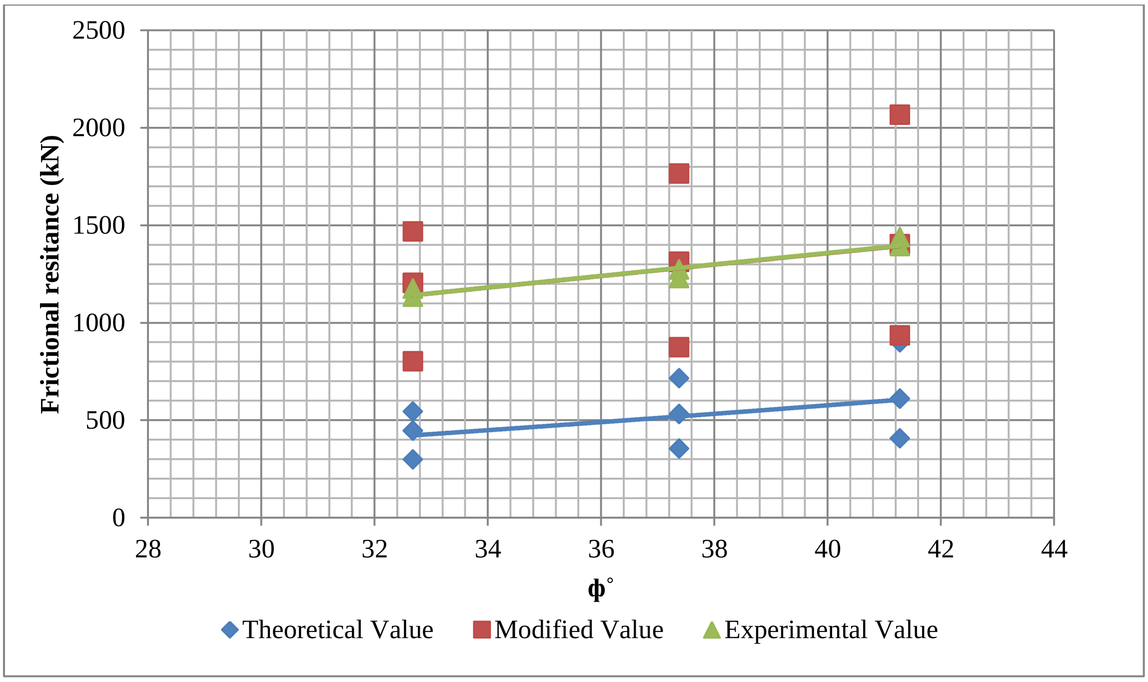


**Fig.6.22 Frictional resistance of prototype pile for different ϕ value**

**Table 6.26: Calculation for proposed modification factors**

| Case | Method Applied | | | | $F_{proposed}$ (From Graph) |
|---|---|---|---|---|---|
| | IS code | Meyerhof | Kulhawy | Nabil F. Ismael | |
| | $F_1$ | $F_2$ | $F_3$ | $F_4$ | |
| No drilling fluid | 2.29 | 3.53 | 1.59 | 2.29 | **2.3** |
| Bentonite fluid concentration (4%) | 2.31 | 3.59 | 1.78 | 2.31 | **2.47** |
| Bentonite fluid concentration (6%) | 2.54 | 3.95 | 2.16 | 2.54 | **2.7** |

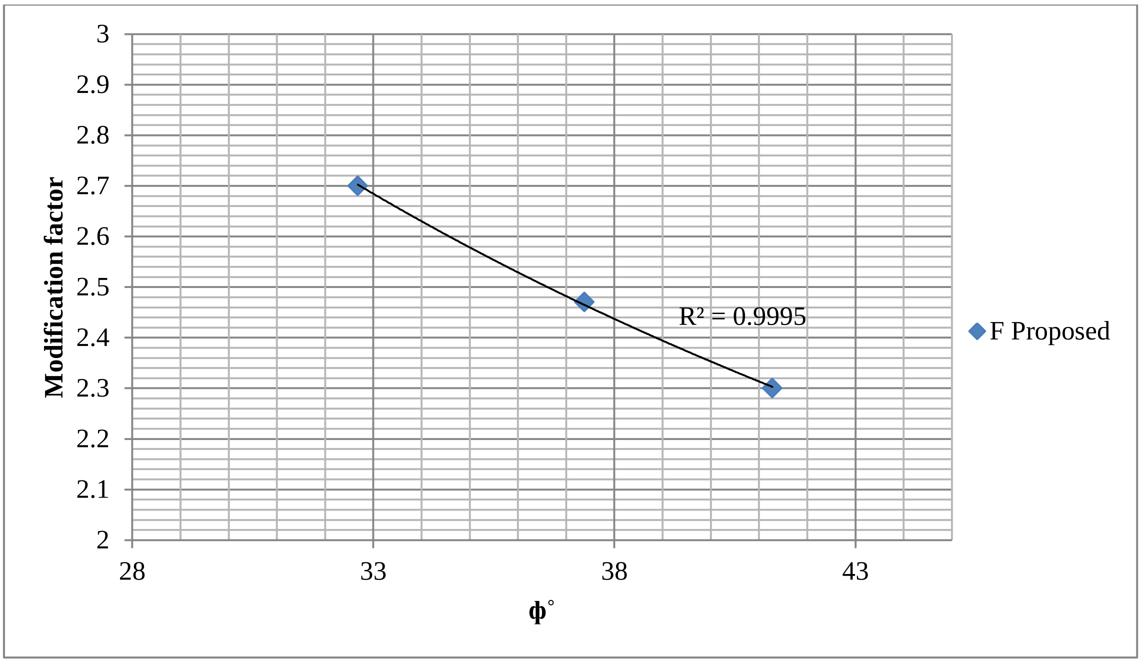


**Fig.6.23 Proposed value of modification factor for different ϕ value**

Table 6.24 and Table 6.25 show the results of obtained modification factors from different methods using experimental results. Table 6.26 shows proposed value of modification factor obtained from the Fig.6.22 by applying method of interpolation in the curve which is obtained as 2.3 to 2.7 for $32<\phi<42$. Fig.6.23 shows the variation of modification factor with varying value of ϕ. The modification factor was higher for Meyerhof's method i.e. the frictional resistance for pile is underestimated by this method than the actual value observed in the field.

## 6.9 Proposed K- Factor

Based on obtained value of K from experimental work using as a reference value, a constant 'K' has been proposed using the relation $A_i$ x $K_p$.

Table 6.27: Calculation for constant $A_i$ – factor

| Case | φ | IS Code Method | | Meyerhof's Method | |
|---|---|---|---|---|---|
| | | $K_1$ | $A_1$ | $K_2$ | $A_2$ |
| No drilling fluid | 41.28 | 3.43 | **0.7** | 3.53 | **0.72** |
| Bentonite fluid concentration (4%) | 37.38 | 3.47 | **0.85** | 3.59 | **0.88** |
| Bentonite fluid concentration (6%) | 32.68 | 3.81 | **1.04** | 3.95 | **1.18** |

Table 6.28: Calculation for constant $A_i$ – factor

| Case | φ | Kulhawy's Method | | N. Ismael's Method | |
|---|---|---|---|---|---|
| | | $K_3$ | $A_3$ | $K_4$ | $A_4$ |
| No drilling fluid | 41.28 | 3.53 | **0.72** | 3.43 | **0.7** |
| Bentonite fluid concentration (4%) | 37.38 | 3.59 | **0.88** | 3.47 | **0.85** |
| Bentonite fluid concentration (6%) | 32.68 | 3.95 | **1.18** | 3.81 | **1.04** |

Table 6.29: $A_i$ – factors for different φ value

| Considering Weight of Pile | | Without Considering Weight of Pile | |
|---|---|---|---|
| φ | $A_1 = A_4$ | φ | $A_2 = A_3$ |
| 41.28 | **0.7** | 41.28 | **0.72** |
| 37.38 | **0.85** | 37.38 | **0.88** |
| 32.68 | **1.04** | 32.68 | **1.18** |

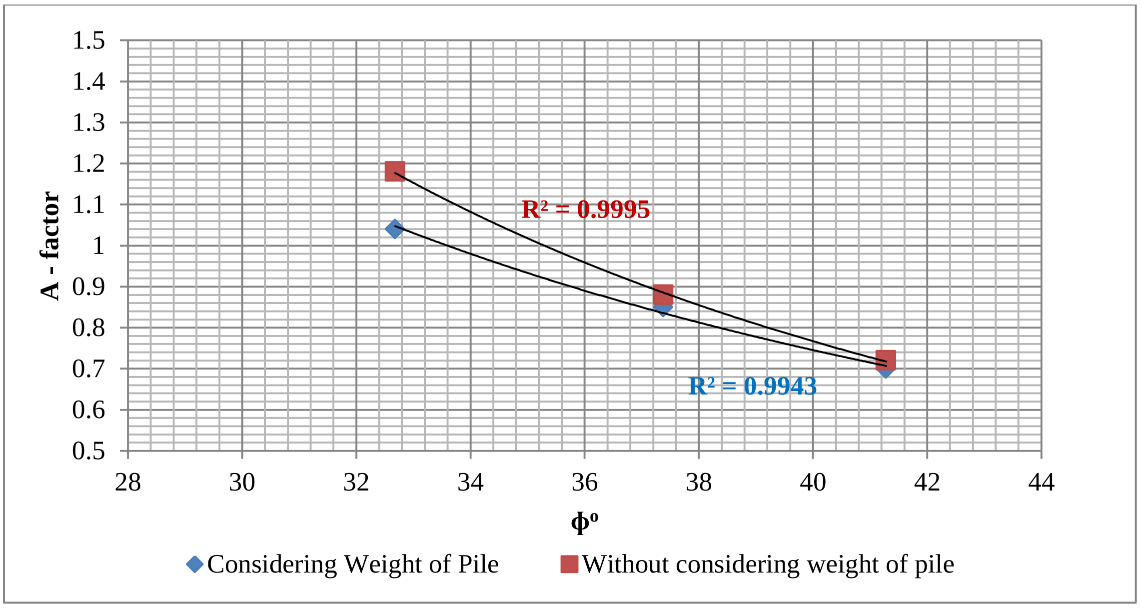


**Fig.6.24 Proposed value of A – factor for different φ value**

Where, $K_p$ = Passive earth pressure coefficient, i.e. $K_p = \frac{1+\sin\phi}{1-\sin\phi}$

$A_i$ = A constant depends on ϕ value, called as A – factor

And ϕ = Angle of internal friction

The K value can be active earth pressure coefficient, earth pressure coefficient at rest or passive earth pressure coefficient as quoted by various researchers, but from our experimental results K has found to be more close to passive earth pressure coefficient.

Table 6.27 and Table 6.28 shows the calculation for A – factor from different methods used in the dissertation. $A_1$ and $A_4$ has been calculated using IS Code and Nabil. F. Ismael methods, whereas $A_2$ and $A_3$ from Meyerhof and Kulhawy's methods respectively. The values of $A_1$ and $A_2$ differs from each other as for the former, weight of the pile has been deducted from the uplift capacity, whereas from the later the frictional resistance was equal to the uplift capacity. Fig.6.24 shows the variation of A - factor with angle of internal friction ϕ depending on the case whether weight of the included or not.

# CHAPTER 7
# CONCLUSIONS

The main objective of this dissertation work is to investigate the effect of bentonite drilling fluid on the skin resistance of the pile through theoretical as well as experimental analysis. Before performing experimental work, rheological properties of bentonite drilling fluid has been determined to optimize the solution to be used for field work. Three basic properties of drilling fluid are considered: Viscosity of fluid, density of fluid and pH of the fluid. For each property, different cases are performed and analyzed.

In the field work pullout capacity of the physically modeled concrete pile was determined using pre-fabricated pullout test setup and the main conclusions drawn from this dissertation work are as follows:

1. As the bentonite concentration in the fluid increases the Marsh viscosity and density of the fluid increases exponentially whereas pH has not affected by addition of more concentration of bentonite into it. From the laboratory results it has been concluded that bentonite concentration above 5% has Marsh viscosity and density exceeds from 60 sec and 1.1g/cm$^3$ respectively, so that a better range of 2 to 5% of bentonite can be used as drilling fluid.
2. Marsh viscosity of the fluid increases as the pH changes from 9.3 to 9.6 and thereafter it decreases slightly for the 4% bentonite concentration of drilling fluid. Density of the 4% bentonite fluid increases as the pH increases from 1.025g/cm$^3$ to 1.05g/cm$^3$.
3. Marsh viscosity of 4% bentonite fluid increases as the time passage, because bentonite particles have tendency to get swell with time and with time gains the strength due to its thixotropic nature. Similar effect was also observed on the density of fluid which is also increases with the passage of time. A slight decrement in pH (9.3 to 9.1) of the suspensions observed after 5hours, but the effect is not significant.
4. With the addition of 5% silt in lower and higher concentration of bentonite fluid density increases. Density of 4% bentonite fluid increases from 1.03 to 1.1 after 2 hours with the addition of 5% silt into it. For higher concentration of bentonite fluid, it got difficult to find Marsh viscosity as 5% silt was added. It necessitates

that when slurry is to be circulated, if it is possible to remove most of the impurities through the use some suitable mechanism.

5. Marsh viscosity of the fluid increases with the addition of poly-fluid whereas viscosity decreases with the addition of alum just after the mixing. pH of the slurry drastically decreases from 9.2 to 5.5 with the addition of alum while slight reduction in pH (9.2 to 8.7) is obtained with addition of poly-fluid. When the solutions, added with 1% poly-fluid and other added with 1% alum is left for some time, bentonite particles get settles faster in case of poly-fluid and viscosity and density of top fluid observed close to the water. Before concreting these settled particles can be removing easily using any suitable construction technique.

6. The effect of bentonite slurry on frictional resistance of soil was computed by performing the direct shear test. With the placement of bentonite fluid from lower to higher concentration on the pre-defined failure surface in direct shear test, the angle of internal friction '$\phi$' decreased drastically from $41.28^o$ to $26.44^o$ suggesting the formation of a soft filter cake. This results in decrease in the shear strength of soil, causing it to lose its frictional resistance.

7. From the experimental result it can be seen that uplift capacity of the pile decreases with the use of bentonite drilling fluid as compared to that obtained without use of drilling fluid. Uplift capacity is decreases about 11.8% in case of 4% bentonite drilling and 18.7% in case of 6% bentonite fluid, respect to without drilling fluid case.

8. From comparison of theoretical uplift capacity and experimental result it is concluded that different theories have underestimate the frictional resistance of the pile in direct tension. Frictional resistance obtained from the experimental results shows it is more approximate to the theoretical result obtained from Kulhawy's method.

9. Based on obtained value of K from experimental work, it is concluded that K (earth pressure coefficient) is much closer to passive earth pressure coefficient $K_p$, i.e. 0.7 to 1.18 times $K_p$ with $\phi$ varies from $41.28^o$ to $32.68^o$.

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