DRILLING FLUIDS IN BORED PILE CONSTRUCTION

A Thesis

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Submitted by:

Md Riyadul Islam

Student No. 0904093

&

Arnab Datta

Student No. 0904102

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Dr. Syed Fakrul Ameen

Professor

Department of Civil Engineering

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Dedicated to

Our Beloved Parents.......

Declaration

It is hereby decided that, except where specified references have been made to other investigation, the whole work embodied in this thesis is the result of study carried by authors under the supervision of Dr. Syed Fakrul Ameen, Professor, Department of Civil Engineering, Buet.

Neither the thesis nor any part of this has been being concurrently submitted for any degree at any other institution.

14 September, 2015

Md Riyadul Islam
&
Arnab Datta

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Abstract

Bored pile construction deals with drilling fluids during the construction to stabilize the shaft by forming filter cake on the wall of excavation. An overview of bored pile construction methods and function and properties of slurries is discussed. Bentonite slurry, commonly used as drilling fluids, is addressed with its properties and functions involving standard laboratory investigation. A distinguish between the determined properties of collected Bentonite sample from local market and properties determined by previous scholars is demonstrated which leads to a decision that local bentonite clay doesn't meet desired qualities of drilling fluids physically and economically. However, properties of local soil known as Dhaka Clay were investigated in the laboratory to compare with normal bentonite sample. The results provide some supports to introduce the use of local soil as drilling fluids. A special test was conducted to separate finer particles from Dhaka Clay and further investigations on this improved clay show more better results which is illustrated. On the basis of the results, it can be concluded that separation of finer particles increases the value of liquid limit of soil as well as improves the slurry properties which recommends using Dhaka clay as drilling fluids in bored pile construction.

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Introduction

1.1. General:

Geotechnical engineers recommend deep foundation in case of very large design loads and soil condition where shallow foundation would be encountered stability problems. There are different kinds of deep foundation available to the engineers or contractors and their choices are based on soil condition, equipment availability, cost etc. Drilled shaft foundation, mostly used in bridge, flyovers and waterways constructions, has become popular option of deep foundation now-a-days. They are usually put in place using excavation and drilling. Drilled shafts require rigorous inspection. The most important concern during construction of drilled shafts is the stability of borehole and thus it introduces a new topic named 'Slurry' which is also a prime topic of this paper. Slurry is being used in the construction to provide some functions like ensuring stability of borehole, preventing detritus materials to enter to the hole, cleaning the bottom of the hole and so on. Availability of slurry is also a concern to the contractors and engineers. In the present decades, 'Bentonite' clay is being used to make slurry or drilling mud. Polymer slurry is also available to use but requires the economic concern as well. Local clay soil might be a solution where both bentonite and polymer isn't available or economically not sustainable. But local soil should have the ability to protect the hole. And so, before using it, proper laboratory tests should be performed based on other known slurry.

Quality control of slurries is an important part of drilled shaft construction. Slurry performs its function at some specified properties. Otherwise it would be meaningless. In Bangladesh many construction projects are using drilled shaft or drilled pier foundation as selected and contactors are importing slurry from outside the country or using local manufactured slurry. Both slurries need to be satisfied the desirable properties to perform their functions.

In this thesis paper, according to Bangladesh site conditions, required properties of bentonite slurry and local slurry is highlighted broadly as engineers or contractors can use slurry in their construction ensuring the provided specification. A general idea of drilled shaft construction is also described here.

1.2. Objective of Our Study:

To find out best quality of drilling slurries for drilled shaft construction, scholars and scientists worked on this topic a lot. Review of their work leads us to make progress and find better solution of our problems. In the context of Bangladesh, as many constructions have introduced the technology of using drilling fluids in the borehole, it focuses researchers to work on it. Because not only use of slurry will provide the solution of drilling shafts but also quality control of drilling slurries is a great concern. In the market mainly three kinds of bentonite slurry and polymer slurry is available all of which are imported. But local soil can also meet the desired properties of slurry and it can be a source of research work. In Bangladesh, as economy plays always vital part, we could use local clay soil if they satisfy the functions of slurry properly. That is the scope of our thesis. We want to introduce Dhaka clay as an alternative of bentonite slurry for drilled shaft constructions.

Considering the problem mentioned above, the scope of the study is intended to fulfill some objectives. The main objective is to find better qualities of slurry in the context of Bangladesh for the construction of drilled shafts. Our focus was also on using Dhaka clay as slurry as mentioned earlier. The intended objectives of this study are as follows:

i. To review the construction methods of drilled shafts.
ii. To review previous research works on drilling slurries.
iii. To demonstrate the idea about drilling slurries.
iv. Introducing functions and properties of slurries for drilled shaft construction.
v. A clear description of laboratory and field test of slurry to be performed.
vi. Providing ways to control the quality of slurry at the site.
vii. To introduce local soil named 'Dhaka Clay' as drilling slurry.

viii. To provide specification of both Bentonite and Dhaka clay slurries required for drilled shaft construction in Bangladesh.

1.3. Framework of This Paper:

- Chapter 2 contains 'literature review' where a general idea of drilled shaft and its construction methods have been described. Also, slurry, its functions and properties, mixing and handling are discussed. It also defines bentonite, Dhaka clay and their properties.
- Chapter 3 includes discussion about the tests such as specific gravity, Atterberg limit tests, grain size analysis, density, viscosity and pH test for Bentonite and Dhaka clay.
- Chapter 4 discusses the outcome of the tests that were performed in the laboratory and specification is also provided.
- Chapter 5 provides a comparison between bentonite and Dhaka clay slurries on the basis of the outcome of the test along with summarization of the whole thesis.

Chapter 2
Literature Review

Chapter 2

Literature Review

2.1. General:

Drilled shaft foundations are broadly described as cast-in-place deep foundation elements constructed in a drilled hole that is stabilized to allow controlled placement of reinforcing and concrete. In modern world this foundation method is used dominantly in many cases where normal pile or driven pile foundations are encountered so many problems like stability problems, dewatering etc. However, drilled shafts are distinguished from other types of piles in that drilled shafts are often substantially larger in size, frequently used as a single shaft support for a single column without a cap, and often installed into hard bearing strata to achieve very high load resistance in a single shaft. Although there has been a significant evolution of the drilled shaft industry over the past 40 years to the type of construction and design which is prevalent today (2009), machine drilled shafts became more widespread during the 1930's and became increasingly used during the building boom after World War II. The A.H. Beck Company began using drilled shafts in 1932 and, along with McKinney Drilling (founded 1937), were some of the pioneers of the drilled shaft industry in Texas. Augered uncased holes smaller than 30 inch diameter were common, and sometimes tools were employed to rapidly cut an under ream or bell. In California, "bucket-auger" machines were more common, using a bottom dumping digging bucket to dig and lift soils rather than an auger.

In drilled shafts, the most important part of its procedure is use of slurry to provide better stability to the hole. The greatest concern during the process is maintaining the stability of the excavation walls (formwork) and preventing the collapse or sloughing of material into the boring during excavation or the concreting process, and so slurry is introduced. Inspection of drilled shafts and quality control of slurry produce great concern during construction. In different countries different specified quality of slurries are maintained. In recent years, slurry is being used extravagantly in many flyovers, bridge construction in Bangladesh.

In this part of this research paper, some important terms are defined which are used latter in this document and a theoretical framework of drilled shafts and slurry is described with some existing research on slurry used in foundation.

2.2. Drilled Shaft Foundation:

2.2.1. General:

Drilled shaft foundations, a deep foundation, are formed by excavating a hole, typically 3 to 12 feet in diameter, inspecting the soil or rock into which the foundation is formed, and constructing a cast-in-place reinforced concrete foundation within the hole. Drilled shafts are typically designed and constructed to support axial forces through a combination of side shearing and end bearing resistance as illustrated in figure 1. Drilled shafts are an economic solution to accommodate large axial, lateral and overturning forces on a small footprint. The large diameter reinforced concrete member is also capable of providing substantial resistance to lateral and overturning forces. Drilled shafts for transportation structures are fairly commonly used to depths of up to 200 ft in the U.S., but can extend to depths of as much as 300 ft or more. Drilled shafts are also referred to by other names, including drilled piers, caissons, cast-in-drilled-hole piles (CIDH - Caltrans terminology), and bored piles (Europe). The common reference to these foundations as "caissons" reflects the history of development of drilled shaft foundations.

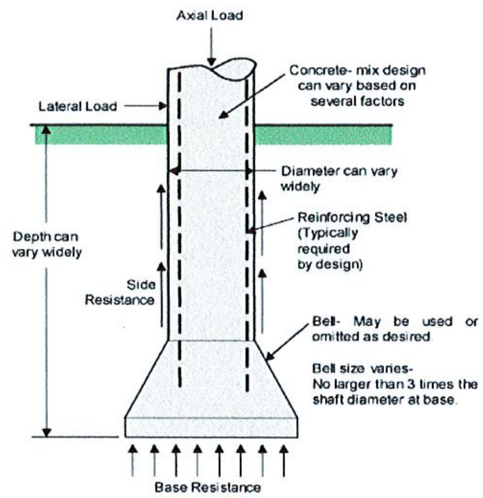

Figure 2. 1: Schematic of Axial and Lateral Resistance of a Drilled Shaft (Source: DRILLED SHAFT FOUNDATION CONSTRUCTION INSPECTION MANUAL)

2.2.2. Selection of Drilled Shafts:

- Drilled shaft are most efficient where a strong bearing layer is present.
- Foundation over water can be selected as drilled shafts, avoiding the need for cofferdams.
- Drilled shafts can also be installed into hard, scour-resistant soil and rock formations to found below scour able soil in conditions where installation of driven piles might be impractical or impossible.
- Drilled shafts have enjoyed increased use for highway bridges in seismically active areas because of the flexural strength of a large diameter column of reinforced concrete.
- Drilled shafts may be used as foundations for other applications such as retaining walls, sound walls, signs, or high mast lighting where a simple support for overturning loads is the primary function of the foundation.

2.2.3. Advantages and Limitations of Drilled Shafts:

Generally, drilled shafts offer the opportunity to directly inspect the bearing material so that the nature of the bearing stratum can be confirmed. However, there is no direct measurement that can be related to axial resistance as in the case of pile driving resistance. The most significant of the limitations are related to the sensitivity of the construction to ground conditions and the influence of ground conditions on drilled shaft performance. A summary of advantages and limitations of drilled shafts compared to other types of deep foundations is provided in Table 2-1:

Table 2. 1: Advantages and limitations of drilled shafts (source: AASTHO LRFD bridge design specification, 4th edition)

Advantage	Limitation
• Easy construction in cohesive materials, even rock	• Construction is sensitive to groundwater or difficult drilling condition
• Suitable to a wide range of ground conditions	• Performance of the drilled shaft may be influenced by the method of construction
• Visual inspection of bearing stratum	• No direct measurement of axial resistance during installation as with pile driving
• Possible to have extremely high axial resistance	• Load testing of high axial resistance may be challenging and expensive
• Excellent strength in flexure	• Structural integrity of cast-in-place reinforced concrete member requires careful construction, QA/QC
• Small footprint for single shaft foundation without the need for a pile cap	• Single shaft foundation lacks redundancy and must therefore have a high degree of reliability
• Low noise and vibration and therefore well suited to use in urban areas and near existing structures	• Requires an experienced, capable contractor, usually performed as specialty work by a subcontractor
• Can penetrate below scour zone into stable, scour-resistant formation	• May not be efficient in deep soft soils without suitable bearing formation
• Can be easily adjusted to accommodate variable conditions encountered in production	• Requires thorough site investigation with evaluation of conditions affecting construction; potential for differing site conditions to impact costs, schedule

2.2.4. Construction Methods:

For general discussion of construction methods, the approach to construction can be classified in three broad categories.

These are:

1. Dry construction method.

2. The casing method.

3. Wet Construction method.

In many cases, the installation will incorporate combinations of these three methods to appropriately address existing subsurface conditions. Because elements of the drilled shaft design can depend on the method of construction, consideration of the construction method is a part of the design process.

- ***Dry construction method:*** Dry hole construction represents the most favorable conditions for economical use of drilled shafts. The dry method is applicable to soil and rock that is above the water table and that will not cave or slump when the hole is drilled to its full depth during the period required for installation of the drilled shaft. Construction of a shaft using the dry method and open holes should generally be completed in one continuous operation without stopping. The length of time necessary to complete the excavation will depend on the soil conditions, the presence of obstructions, and the geometry of the hole. . Construction steps are illustrated in following figure 2-2.
- ***The casing method:*** The casing method is applicable to sites where soil conditions are such that caving or excessive soil or rock deformation can occur when a shaft is excavated. Casing can also be used to extend the shaft excavation through water or permeable strata to reach a dry, stable formation. Unless the bearing formation into which the casing is sealed is stable and dry, it will not be possible to use the casing method alone without the addition of drilling fluid or water.

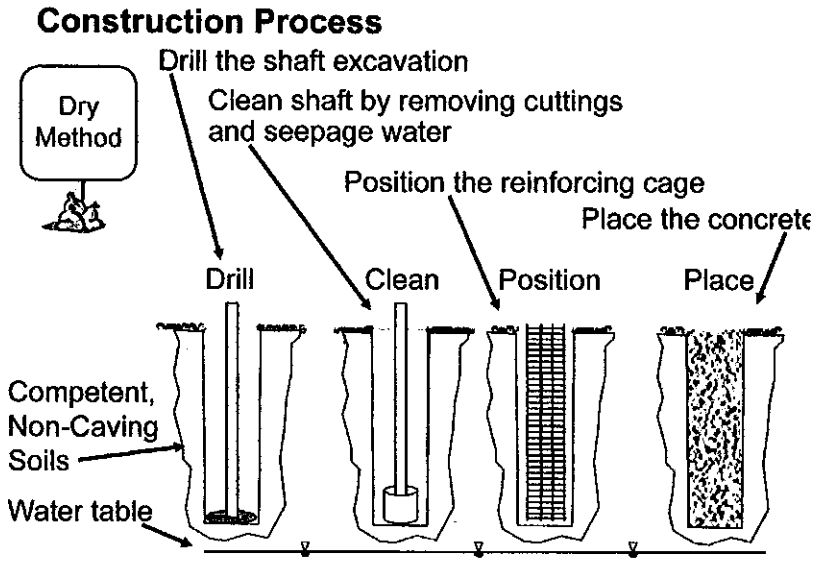

Figure 2. 2: Construction Steps of Dry Construction Method (Source: Inspector Quality Assurance Program)

- ***Wet Construction method:*** When soil conditions do not permit dewatering of the shaft excavation, the excavation and concrete placement operations must be completed "in the wet". With this method, the hole is kept filled with a fluid during the entire operation of drilling the hole and placing the reinforcing and concrete. The drilling fluid may consist of water if the hole is stable against collapse, or prepared slurry designed to maintain the stability of the bored or excavated hole.
  - Several circumstances in which construction in the wet would be used are described below:
    - The shaft is founded in a sand or permeable stratum which will collapse or become unstable during excavation. Drilling slurry is required to maintain the stability of the hole and prevent inflow of groundwater.
    - The shaft is founded in a stable formation, but extends through caving or water-bearing soils of such depth and thickness that the required casing would be very long and difficult to handle. Drilling slurry is required to maintain the stability of the hole and prevent inflow of groundwater.

- A full length casing is driven in advance of the excavation but the soil or rock conditions at the base are permeable and do not permit dewatering. Because the full length casing provides a stable hole, plain water can often be used instead of slurry.
- The hole is cased to a stratum of rock which is stable, but groundwater inflow is greater than 12 inches per hour. In this case, the hole is kept filled with water to prevent inflow during concrete placement.

➢ Construction Steps of Wet Construction Method:

- An excavation hole is formed by drilling up to desired depth and size and shape is uniformly managed during drilling.
- Then the hole is filled with slurry and the elevation of slurry is maintained as it remains in higher elevation than groundwater table position.
- After the excavation completion and cleaning of base by slurry, a reinforcing cage is placed and then concrete placement is performed using a tremie.

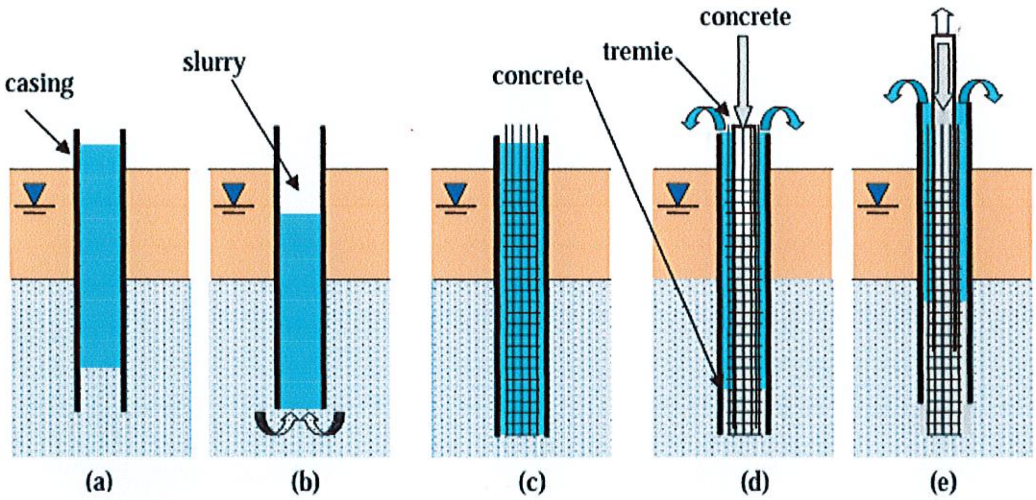

Figure 2. 3: Wet Hole Construction Using Full Length Casing: (a) advance casing and excavating, while maintaining soil plug within casing through caving soils; (b) bottom instability due to inadequate slurry level and/or soil plug at base in caving soils; (c) complete and clean excavation, set reinforcing; (d) place concrete through tremie; (e) pull tremie, casing while adding concrete (Source: *AASHTO LRFD Bridge Design Specifications, 4th Edition*)

2.2.5. Stability of Drilled hole/ Borehole:

The most important aspect of the construction process is maintaining the integrity of the excavation walls. The stability of the excavation is dependent upon the nature of the soils and stratigraphy. Heavily fissured or slicken sided clays, or predominantly clay soil profiles containing silt or sand layers having thickness of more than an inch or two may result in sloughing, excessive seepage or both. In such conditions, the contractor should immediately employ casing or slurry methods. If the site investigation identifies the potential for wet conditions to be encountered, the engineer may preclude the use of the dry method of construction. Otherwise, the contractor must have the necessary equipment available on-site to adopt alternate methods when necessary. Note also that even if long term deep groundwater conditions are identified during the site investigation, shallow permeable layers can result in perched water conditions, particularly during or after rainy weather.

- **Surface Casing:** The surface casing may be temporary or permanent. Surface casings are recommended practice in all soils, and should be left protruding above the ground surface to serve as drilling tool guides, as safety barriers for personnel (although other barriers can be used), and as means of preventing deleterious material from falling into the borehole after it has been cleaned.
- **Mechanical Stabilization:** Mechanical stabilization is achieved by inserting a steel casing and drilling inside the casing. The steel casing can either be permanent or temporary.
- **Hydrostatic Stabilization by Slurry:** Hydrostatic stabilization (wet construction) involves introducing slurry into the excavation that provides a net outward pressure against the in-situ ground water. Therein, the slurry inside the excavation is typically maintained 4 to 8-feet above the water table depending on the type of slurry. Of these methods, slurry type construction tends to be more cost effective; however, it requires more quality control. When using slurry, a temporary surface casing is often required for the upper portion of the shaft in order to raise the slurry level and increase the hydrostatic pressure on the walls of the excavation (Figure 2-4).

Figure 2. 4: Temporary Surface Casing Providing Containment for Slurry

2.3. Drilled Slurries:

2.3.1. General:

Drilling fluid is employed in the wet method of construction and may also be used with the casing method of construction. Drilling fluid therefore plays an important role in drilled shaft construction and its proper use must be understood by both contractors and engineers. When a drilled shaft is to be installed through potentially caving soils or below groundwater, filling of the excavation with properly-mixed drilling fluid allows the excavation to be made without caving.

Water alone is sometimes used as a drilling fluid and may be quite effective where the formations being penetrated are permeable but will not slough or erode when exposed to water in the borehole. During the 1950's and 1960's it was common practice for drilled shaft contractors to create a slurry by mixing water with on-site clayey soils, primarily for use with the casing method (*AASHTO LRFD Bridge Design Specifications, 4th Edition, 2007*).

2.3.2. Applications and Limitations of Slurry in Drilled Shaft Construction:

In case of all drilled shaft construction methods and materials, success depends upon proper execution by the contractor and on the suitability of the methods and materials for the ground conditions. There are numerous examples of circumstances where drilling slurry has been used with outstanding success. A few are given here:

- A site was encountered where the soil consisted of very silty clay, which was not sufficiently stable to permit the construction of drilled shafts by the dry method. Bentonite slurry was used, and shafts up to 4 ft in diameter and 90 ft long were installed successfully.
- Mineral slurry was used to penetrate a soil profile that consisted of interbedded silts, sands, and clays to a depth of about 105 ft, where soft rock was encountered. A loading test was performed, and the test shaft sustained a load of over 1,000 tons, with little permanent settlement.
- Three test shafts were constructed with bentonite drilling slurry in a soil profile containing alternating layers of stiff clay, clayey silt, and fine sand below the water table. The test shafts were later exhumed, and it was found that the geometry of the constructed shafts was excellent.
- Two instrumented test shafts, 30 inches in diameter, were installed with PAM polymer slurry in a mixed profile of stiff, silty clay, clayey silt, lignite, and dense sand to depths of up to 51 ft at a freeway interchange site. The contractor allowed the sand in the slurry columns to settle out of suspension for 30 minutes after completing the excavations before cleaning the bases with a clean-out bucket and concreting.

While much is known about the properties of drilling slurries and their effects, success in maintaining borehole stability with given slurry depends on many factors that are understood qualitatively but not all of which are readily quantified. Some of these are:

- Soils of higher relative density are retained more easily than soils of lower relative density (loose).
- Well-graded soils are retained more easily than poorly graded soils.

- Silt or clay within the matrix of sand or gravel assists in maintaining stability, especially with polymer slurries, but fines can become mixed with the slurry, causing its properties to deteriorate.
- Maintenance of positive fluid pressure in the slurry column at all times.
- Stability is more difficult to maintain in large-diameter boreholes than in small-diameter boreholes because of a reduction in arching action in the soil, and because more passes of the drilling tool often must be made to excavate a given depth of soil or rock compared with excavation of a smaller-diameter borehole.
- For various reasons, the deeper the borehole, the more difficult it is to assure stability.
- Boreholes in granular soil have been kept open and stable for weeks with the newer polymer slurries as compared to days with bentonite and PAM polymer slurries. However, in general, stability decreases with time.

2.3.3. Slurry Performance for Drilled Shafts:

Bentonite and other clay minerals, when mixed with water in a proper manner, form suspensions of microscopic, plate-like solids within the water. When introduced into a drilled shaft excavation, this solid-water suspension, or slurry, contributes to borehole stability through two mechanisms:

- **Formation of a filter cake:**

There are three mechanisms by which a seal is formed at the soil surface, causing filter-cake development.

➢ **Surface Filtration**- the most efficient mechanism by which a filter cake is formed. In surface filtration, very little bentonite penetrates the soil. The bentonite particles remain in the pore spaces as the water from the slurry passes into the soil. As the pore spaces are filled with bentonite particles, a filter cake is formed on the soil surface (Fig. 2.5-a). The process continues with time, so that the filter cake thickens and the amount of water passing into the soil decreases.

- **Deep Filtration-** a more complex mechanism of filter-cake development than is surface filtration. During deep filtration, the slurry penetrates the soil several millimeters before a seal is formed (Fig. 2.5-b). As a result, a seal is not formed as quickly as in surface filtration, and, thus, filter-cake development is slower.
- **Rheological blocking-** the least efficient of the three mechanisms. In rheological blocking, a seal is formed as a result of the shear stresses between the slurry and the soil particles. The slurry penetrates the soil until the shear stresses are such that the slurry can go no further. In some instances, the slurry will penetrate several meters into the soil.

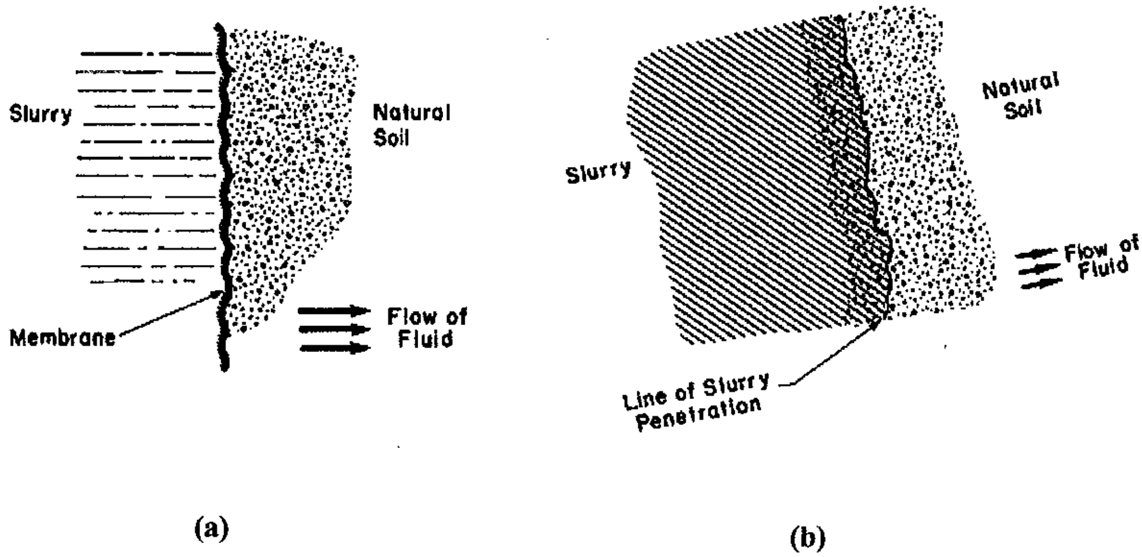

Figure 2. 5: (a) Surface Filtration; (b) Deep Filtration (Source- *The Effect of Bentonite Slurry in Drilled Shafts by Karen L. Tuck.er Lymon C. Reese*)

- **Maintaining of Positive Fluid Pressure:**

  The action of clay particle transport and deposition is termed "filtration" and once the filter cake is formed filtration gradually stops. At this point, a positive fluid pressure must be maintained to provide continued stability. As shown in the figure 2-6, it is necessary to maintain a slurry head inside the borehole so that the fluid pressure on the inside surface of the filter cake exceeds the fluid pressure in the pores of the soil in the formation. This

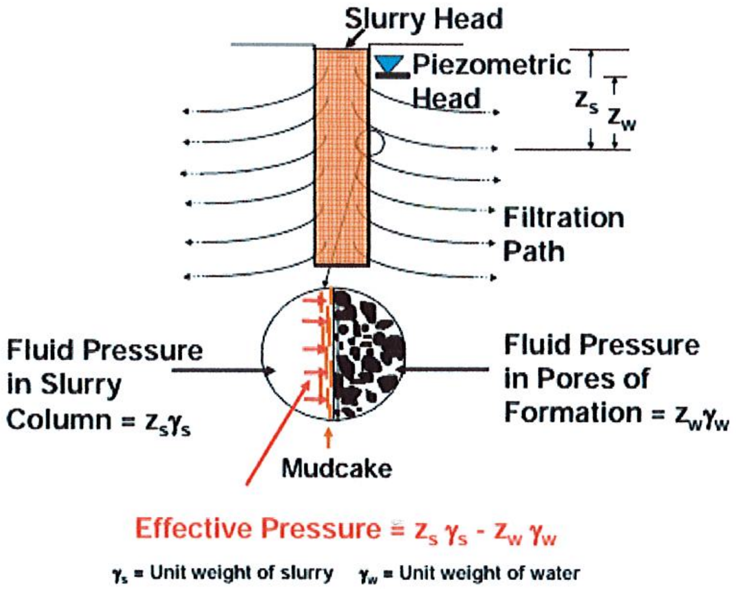

Figure 2. 6: Formation of Filter Cake and Positive Pressure (Source- AASTHO Manual)

differential pressure and the resulting seepage into the formation cause a positive effective stress against the walls of the borehole, which acts to hold the membrane in place. It is the combination of membrane formation and positive fluid pressure against the borehole wall that enables mineral slurry to stabilize a drilled shaft excavation.

However several important factors can impact the ability of slurry to function as intended. The most important of these are:

(1) Proper hydration,

(2) Pore size distribution of the permeable formation, and

(3) Suspension of solids derived from the excavated materials.

2.3.4. Common types of Slurry:

Drilling fluids are made from several types of materials which when mixed with water can be controlled in a manner that makes them highly effective for the support of boreholes. Suitable materials include several naturally occurring clay minerals, and polymers. Bentonite is the most common name for a type of processed powdered clay consisting predominately of the mineral montmorillonite, a member of the smectite group. Technologies pertaining to the use of mineral slurries as drilling fluids have been developed extensively by the petroleum industry, and many references on bentonite slurries are available; for example, Chilingarian and Vorabutr (1981) and Gray et al. (1980). While these references are useful, this information must be balanced by knowledge gained through field experience pertaining specifically to drilled shaft construction. Other processed, powdered clay minerals, notably attapulgite and sepiolite, are occasionally used in place of bentonite, typically in saline groundwater conditions. Any drilling fluid that is made from one of these clay minerals is referred to as mineral slurry.

A second group of materials used to make drilling slurry is polymers [from Greek polymeres, having many parts: poly + merous]. The term polymer refers to any of numerous natural and synthetic compounds, usually of high molecular weight, consisting of individual units (monomers) linked in a chain-like structure. Synthetic polymer slurries made from acrylamide and acrylic acid, specifically termed anionic polyacrylamide or PAM, entered the drilled shaft market beginning in the 1980's. More recently, advanced polymers made by combining polyacrylamides with other chemicals have been introduced in an effort to improve performance while minimizing the need for additives.

2.3.5. Bentonite Slurry:

Bentonite clay, the largest and most active deposits come from Wyoming and Montana is sedimentary clay composed of weathered and aged volcanic ash. Bentonite is a type of material with smectite as its main composition and also having its physical properties to be dictated by the smectite minerals [R. Grim, and N. Guven, 1978]. It is a montmorillonite and hygroscopic clay which is characterized by an octahedral sheet of aluminum atoms being infixed between two tetrahedral layers of silicon atoms [A.Safa Özcan and A. Özcan, 2004].

Some defined properties, for which, bentonite has become so popular not only to geotechnical society but also to others are mentioned here:

- **Water absorption and swelling:** A fundamental property of bentonite is to absorb water and expand. It has net negative electric charge due to the isomorphic substitution of Al^{3+} with Fe^{2+} and Mg^{2+} in the octahedral sites and Si^{4+} with Al^{3+} in the tetrahedral sites and is balanced by the cations such as Na^{+} and Ca^{2+} located between the layers and surrounding the edges [M. Önal, and Y. Sarıkaya, 2007]. Natural bentonite, when hydrated with water, is alkaline with pH of 8 to 10 [25]. It is hydrophilic in nature as it is strongly hydrated by water. This explains why bentonite has great water absorption capability. Water absorption of bentonite occurs by means of diffusion and capillary suction [L. Börgesson, 1985]. In addition, it also able to retain water or rather moisture content for a considerable period of time at atmospheric pressure. Once water is absorbed, it can expand up to several times of its original volume. However, this water retention and swelling capacity of bentonite is dependent on temperature and pressure [M.V Villar and A Lloret, 2004].
- **Viscosity and thixotropy of aqueous suspensions:** When bentonite is dispersed in water, highly stable colloidal suspensions are formed with high viscosity and thixotropy. At high enough concentrations, these suspensions begin to take on the characteristics of a gel. Suspensions are formed when water molecules penetrate into platelet interlayers. Here, hydrogen bridge bonds are formed by the hydrogen atoms contained in the water molecules. Platelets become isolated from each other, while bonded through interposition water. When left still, a mesh is formed which, by incorporating water, jellifies. Conversely, under mechanical stress, these bonds partially break, thus allowing platelets to move more freely. Viscosity under these conditions is lower than at rest. This reversible sol-gel-sol process is known as thixotropy. These properties shown by bentonite aqueous suspensions are mainly exploited in drilling slurries.

- ❖ **Colloidal and waterproofing properties:** When water is absorbed by bentonite, a semisolid gel is formed with strong hydrostatic pressure resistance. A montmorillonite platelet can be figured out as a thin packet of negatively charged layers. Due to their negative charge, they repel each other while letting water through. In this way, while the packet swells, a stable shell is formed around the platelet. When saturated, this shell will repel water, even under pressure. For all these properties, bentonite is employed in ponds and docks, to seal off soil infiltrations, and line the base of landfills.
- ❖ **Binding property:** This bentonite property is mainly exploited to produce green molding sand. In this application, bentonite with suitable moisture content covers quartz sand grains and acts as a connective tissue to the entire mass. Under this homogenous coating, even at maximum compression, water will remain in a highly "rigid" state, binding the sand grains and lending maximum resistance to the sand mould. Bentonite vitrification temperature is higher than other clays. Therefore, when used as an additive, it makes green sand more durable, and, in particular, more resistant to heat stress.
- ❖ **Surface properties (coagulation– absorption – adsorption):** Bentonite absorption – adsorption properties are determined by the high specific surface and free charges present on each micelle. Coagulation occurs through the adsorption of ions of opposite charge to that of colloidal particles.

Due to all of the mentioned properties, bentonite finds many applications in various fields which include pelletization of iron ore, feedstock, oil drilling, cosmetics, pharmaceuticals, sealants, farming and hydraulic containment [P.W. Harben, J. G Marks Jr., J.F Fowler Jr., E. F Sherertz, and R. L Rietschel, 1995]. When treated with acid, bentonite powder has great ionic adsorption capacity and thus can be used as adsorbent in catalyst, bleaching earth, and also in the preparations of organoclay, and nanocomposites [A.Safa Özcan and A. Özcan, 2004], [C. Breen, and R. Watson, 1998]. Another field which has been increasingly using natural bentonite is waste water treatment whereby it is used to remove heavy metallic ions such as cadmium, plumbum , copper and zinc [A. Mellah, and S. Chegrouche, 1997]. It should be noted also that all of the aforementioned properties varies with the type of bentonite namely Sodium bentonite and Calcium bentonite.

2.3.6. Physical Properties of Bentonite Clay:

Physical properties of bentonite clay refer to specific gravity, gradation curve properties, atterberg limits. Commonly three types of bentonite clay is used widely- Indian, China & pakistan. Many scholars have studied on these properties of bentonite clay. Bentonite contains montmorillonite minerals which has a high range of liquid limit and plastic limit. A recent study by Md Abdullah Asad (2013) on these properties of three bentonite sample gives a general idea about it. Following table represents his research:

Table 2. 2: Physical Properties of three different bentonite samples by Md Asadulla Azad, (2004)

Properties	China Bentonite	Pakistan Bentonite	Indian Bentonite
Specific gravity	2.87	2.75	2.76
Liquid limit	140%	84.5%	82.5
Plastic limit	75.17%	46.41%	51.39%
Plasticity Index	75.33%	38.08%	31.11%
Sand	5%	9%	12%
Clay	75%	63%	65%
Silt	20%	28%	20%

2.3.7. Engineering Properties of Bentonite Slurry:

The engineering properties of bentonite slurry include shear strength, viscosity, and density. Sand content and pH are also of interest. Measurement of these characteristics aids in the determination of the slurry's ability to build up a filter cake and to hold detritus in suspension. These properties are influenced by the amount of bentonite present, the method of mixing, the duration of mixing, the amount of time without agitation, and the amount of contamination (*Karen L. Tuck.er Lymon C. Reese.*)

- **Density:** The density of the slurry is determined by the amount of bentonite and the amount of contamination. Ideally, proper mixing will result in the bentonite being distributed uniformly through the slurry. However, the degree of contamination will most likely vary over the length of the shaft, with the highest percentage at the base. The density of the slurry is of concern for a number of reasons. First, a relatively high density aids in preventing sloughing of the soil surrounding the excavation because as the density increases the pressure of the slurry increases. Second, very dense slurry can be difficult to circulate if reverse circulation is used, and third, very dense slurry may be difficult for concrete to displace, possibly resulting in slurry inclusions. With these considerations in mind, the density of slurry should be such that it aids in supporting the shaft walls and in keeping the shaft free of water,.while at the same time it allows for circulation and concrete placement.
- **Viscosity:** Viscosity is determined primarily by the amount of bentonite that is present and by the thoroughness of mixing. Contamination of the slurry will also influence viscosity. The viscosity, like shear strength, is a measure of the thixotropic properties of the slurry. As the viscosity increases, the ability of the slurry to hold detritus in suspension increases. However, if the viscosity is too great, the slurry will not flow easily. This would hinder circulation as well as hinder displacement by the concrete. In addition, the slurry might collect on the reinforcement rather than flow around it.
- **pH:** The pH of the slurry can be influenced by minerals present in the water and in the soil. The pH should be kept in a range such that it would have no adverse effects on the shaft reinforcement, casing, or concrete.

- ❖ **Sand Content:** The sand content is a means of estimating the amount of slurry contamination. As mentioned above, the presence of detritus will increase the density of the slurry and can cause the slurry to be difficult to circulate and to be displaced. In addition, a high sand content may cause a thick filter cake to build up due to the added particles in the slurry. Also, as the slurry is displaced, sand may collect on the reinforcement if the slurry is highly contaminated and proper bonding between the concrete and reinforcement would be hindered. When slurry is to be circulated and/or reused, it is possible to remove most of the contamination through the use of slurry shakers and desanders.
- ❖ **Shear Strength:** The shear strength of the slurry is determined by the amount of bentonite present, the thoroughness of mixing, and the amount of time since agitation. Without agitation, the slurry will gel, resulting in increased shear strength. As the shear strength of the slurry increases, the ability of the slurry to hold detritus in suspension increases. It is possible for the slurry to be satisfactory regarding density, pH, sand content and even viscosity, and have very little shear strength. Hence, determination of shear strength is instrumental in evaluating slurry performance.

2.3.8. Bentonite Slurry in Drilled Shaft Construction:

Bentonite has been used extensively for making drilling fluid used in drilled shaft construction and continues to be used widely in some parts of the Bangladesh. Because bentonite is a naturally-occurring material which is mined and then subjected to varying degrees of processing before being supplied commercially, its properties can vary. It becomes important to consider the source of the bentonite and to conduct screening tests to establish the proper mix of bentonite, water, and additives for a given project. For the interested reader, several excellent references are available in which the chemistry of bentonite and slurries made from bentonite are covered thoroughly (e.g., Darley and Gray, 1988). The focus here is on the practical aspects of bentonite slurry used for drilled shaft construction. The following general observations pertaining to bentonite will prove to be useful:

- The materials to be selected for a particular job will depend on the requirements of the drilling operation. Different types of drilling fluids are required to drill through different types of formations. Some of the factors that influence the selection of drilling fluid are economics, contamination, available make-up water, pressure, temperature, hole depth, and the materials being penetrated, especially pore sizes and the chemistry of the soil or rock and the groundwater.
- An economic consideration for the contractor is the "yield" of the mineral used to make the slurry. The yield is the number of barrels (42 gallons) of liquid slurry that can be made per ton of the dry mineral added to achieve slurry with a viscosity of 15 cP (AASTHO).
- The best yield comes from sodium smectite ("Wyoming bentonite"). Other natural clays give very low yield and, for reasons discussed previously, are typically not used in drilled shaft construction. Calcium smectite yields a lesser amount of slurry per unit of weight than Wyoming bentonite because it is hydrated by only about one fourth as much water as Wyoming bentonite.
- The yield of Wyoming bentonite has been dropping due to the depletion of high-quality deposits in the areas where it is mined. The yield of some pure bentonite products is now as low as 50 barrels of slurry per ton of dry bentonite. High-quality Wyoming bentonite that will produce a yield of 100 bbl. /ton is still available, but at a premium price. In recent years, suppliers have been producing Wyoming bentonite mixed with polymer "extenders" to increase the yield. In fact, most bentonite products available today are actually mixes of bentonite and some type of polymer, ranging from natural polymers such as cellulose derived as a waste product of paper and pulp processing, to synthetic polymers. Some suppliers are also chemically modifying calcium smectite to give it essentially the same properties as Wyoming bentonite, but the resulting products are relatively expensive.
- The quality of the water that is used to make drilling slurry is important. For bentonite slurries potable water should be used. Saline water can be used for slurry if attapulgite or sepiolite clay is used instead of bentonite. These clays derive their viscosity from being vigorously sheared by specialized mixing equipment designed to accelerate the suspension

of such clays. As described previously, bentonite, with proper preparation, can be used for limited periods of time while drilling in salt water if the makeup water is fresh and if additives are applied to inhibit migration of salt. They key is that makeup water should be uncontaminated.

2.4. Local Soil as Drilling Fluids:

Unless special measures are taken, any dispersible clay encountered during the course of drilling with a fresh-water mud is generally taken up by the mud and becomes part of its dispersed solids. Where a relatively small amount of dispersible clays is encountered, the over-all effect may be beneficial, as it may reduce or eliminate the necessity for purchasing clays and weighting materials. However, when long intervals of such clays must be drilled through, incorporation of the clay into the mud can give serious trouble, particularly if the mud has been weighted with a commercial weighting material such as ground barite. Prior to about six or eight years ago, one had a choice only of diluting the mud with water, thereby increasing its total volume and wasting a portion of any weighting agents present, or of adding dispersing agents to the mud so that even though the clays were incorporated in the mud, gel strength reduction would be brought about by the addition of such chemical agents. In more recent years, however, techniques have been developed which make it possible to drill through colloidal, normally dispersible shale's and either avoid the incorporation of very much of the shale into the mud or, with some types of treatment, reduce the normally gelatinous character of the shale so that they make scarcely any contribution to the viscosity and shear strength of the mud. It has been universal practice for many years in rotary drilling to make use of nearby clay deposits as a source of drilling mud. The use of such local clays is probably as highly developed in California as anywhere else in the world (DELMAR H. LARSEN).

Probably the majority of surface clays used for drilling mud purposes in the United States are of the so-called low-yield type. That is, they require 25 to 40 percent clay by weight of mud to give a workable viscosity, corresponding to a density in the range of about 1.2 to 1.2 or a yield, as defined above, of from about 10 to 20 barrels of 15 centipoises mud per ton of clay. (DELMAR H. LARSEN).

A number of clay deposits have been worked for drilling mud purposes which give drilling mud at a moderate yield, of perhaps 20 to 40 barrels per ton. Representative of such deposits are Wilmington Slough clay taken from a slough just north of Wilmington, California; Frazier Mountain clay. (DELMAR H. LARSEN).

2.5. Sampling and Testing of Slurry:

2.5.1 Sampling:

Freshly mixed slurry is sampled from the slurry tanks immediately prior to its introduction into the drilled hole. For this purpose, satisfactory samples may be taken from almost anywhere in the storage tank. The important point is to obtain a sample that is representative of the mixture. During drilling, it is highly recommended (and should be required by appropriate specifications) that slurry has to be sampled from the borehole and tested at least every two hours after its introduction. Typically, samples are taken from mid-height and near the bottom of the borehole. Several types of sampling tools are available to obtain a representative sample from the desired location in the slurry column. A device used for this purpose is shown in Figure 2.7. When the sampler is brought to the surface, its contents are usually poured into a plastic slurry cup for subsequent testing.

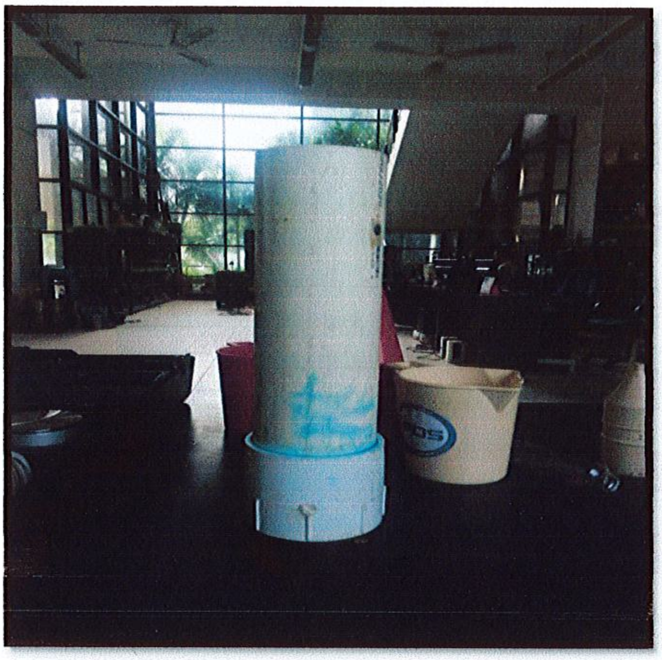

Figure 2. 7: Sampling Tube (LGED laboratory, Bangladesh)

2.5.2 Laboratory Testing of Slurry:

- **Specific Gravity:**

The specific gravity of a soil is defined as the ratio of the weight in air of a given volume of soil particles to the weight in air of an equal volume of distilled water at a temperature of 4°C. It is used for determination of void ratio and particle size. The specific gravity of the bentonite, GB can be obtained from

$$GB=W_s*G_T/W_s-W_1+W_2$$

Where,

GB=Specific gravity of bentonite sample

G_T=Specific gravity of distilled water at temperature T

W_S= Dry weight of bentonite

W_1= Weight of pycnometer, bentonite and water

W_2= Weight of pycnometer and water

The specific gravity was determined in the laboratory by pycnometer method. Then it was compared with the standard values. Standard values of specific gravity are presented here:

Table 2. 3: Standard values of specific gravity

Soil Type	Specific Gravity
Gravel	2.65
Sand	2.65-2.68
Silty Sands	2.66-2.70
Inorganic Clays	2.68-2.80
Organic Clays	Below 2.00

➢ Grain Size Distribution- Hydrometer Test:

Grain sizes in soil samples are found by means of two tests. The sieve analysis is used for coarser materials and hydrometer test is used for finer soils. If significant quantities of both coarse and fine grained soils are in the sample, the results of both the test will have to combine to get the grain sizes in the sample. In this research we have performed some tests on Bentonite and Dhaka clay samples. Both samples were finer material. Even bentonite was totally manufactured on industry and passed through #200 sieves. So we conducted only Hydrometer test on these samples.

The rate at which particles settle in a fluid media is used as an indicator of their size, in a hydrometer analysis. This is given by Stoke's law which states that particles in a suspension settle out at a rate that varies with their size. A hydrometer is used to measure the density of the water soil suspension at times intervals as the grains settle. The size of particle that has settled along the centre of the hydrometer bulb can be calculated and the density indicated the percentage of sample still in the suspension. The depth of centre of hydrometer changes as particles settle out over a period of time. In the test procedure a known amount of powdered soil sample of finer soils (usually passing no. 200 sieve) is mixed with water at known temperature to form suspension. A figure of hydrometer is shown above here.

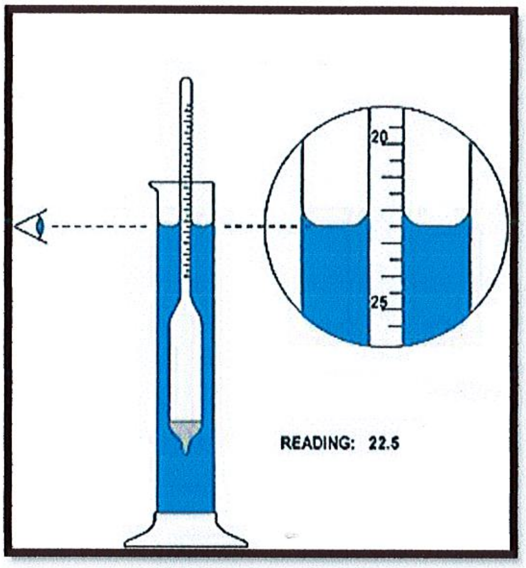

Figure 2. 8: Hydrometer

Grain size analysis usually is used in soil classification. From the gradation curve we can determine the soil properties. A soil composed of mainly of one size particles is called '*uniform or poorly graded soil'*. When a sample contains all sizes of grains and spread over a wide range in the curve is known as '*well graded soil*'. The third type of soil is a mixture of only large and small size particles with some with some of the intermediate sizes missing is gap graded.

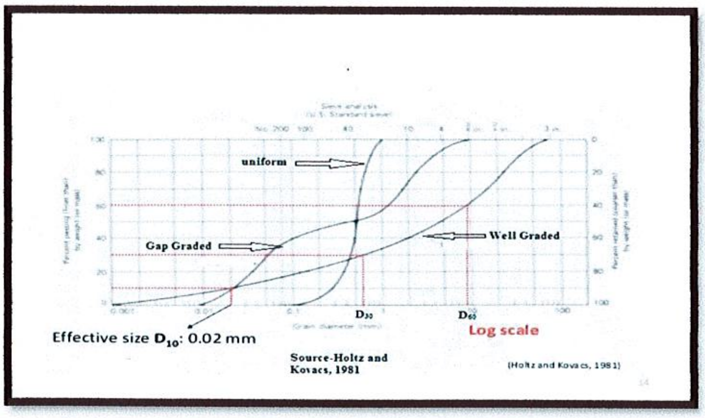

Figure 2. 9: Standard gradation curve for grain size analysis

From the gradation curve three parameters are derived – D_{10}, D_{30}, D_{60} which are used to derive the properties of soil. D_{10} is known as the 'effective size'. A coefficient named 'coefficient of curvature, C_z' is used to express the spread of distribution curve, where

$$C_z = (D_{30})^2 / (D_{10} * D_{60})$$

And another co-efficient known as 'Uniformity co-efficient, C_u' which is used to determine the gradation of curve, where

$$C_u = D_{60} / D_{10}$$

The standard values for CU is given in table 2.4.

Table 2. 4: Standard values of C_u

Type of Soil	Uniformity Coefficient
Uniform	<2
Well Graded	≥4
Gap Graded	≥6

➢ Atterberg limits Test:

The behavior of fine grained cohesive soil depends on its mineral composition, water content, degree of saturation and structure. In particular, water content has always been considered as an important and reliable indication of the behavior of cohesive soils since the beginning of soil mechanics (Lancellotta, 1995). Swedish scientist Atterberg, in the early 1990's first identified that a gradual decrease in water content of clay soil slurry causes the soil to pass through four states; liquid, plastic, semi-solid and solid.

- **Liquid Limit:** The liquid limit (w_L or LL), is the water content at the transition of liquid state to plastic state, whereby it gains a certain small shearing strength. A study by Youseef et. al. (1965) on clays over the range of 30-200% indicates that the range of undrained shear strength at liquid limit is from 1.3 to 2.4 kPa with an average value of 1.7 kPa. Two methods are used to determine liquid limit;

(1) Cassagrande's Method

(2) Cone Penetration Method.

Cassagrande's method is popularly used. Cassagrande's (1932) developed a standard device (figure) for the determination of liquid limit suggesting that at the water content of liquid limit a clay soil has a shearing strength of approximately 2.5 kPa. Dried and broken soil, passed through no. 40 sieve is taken for limit test. The soil, mixed with water, forms a paste which is leveled off in the device to form a depth of 8mm. A grooving tool is used to form a groove at mid section of the cup. Then using the handle blow is started and no of blow is counted until the soil come in contact. From the cup sample is taken and water content is determined from it. The liquid limit according to this method is defined as the moisture content at which 25 blows are required.

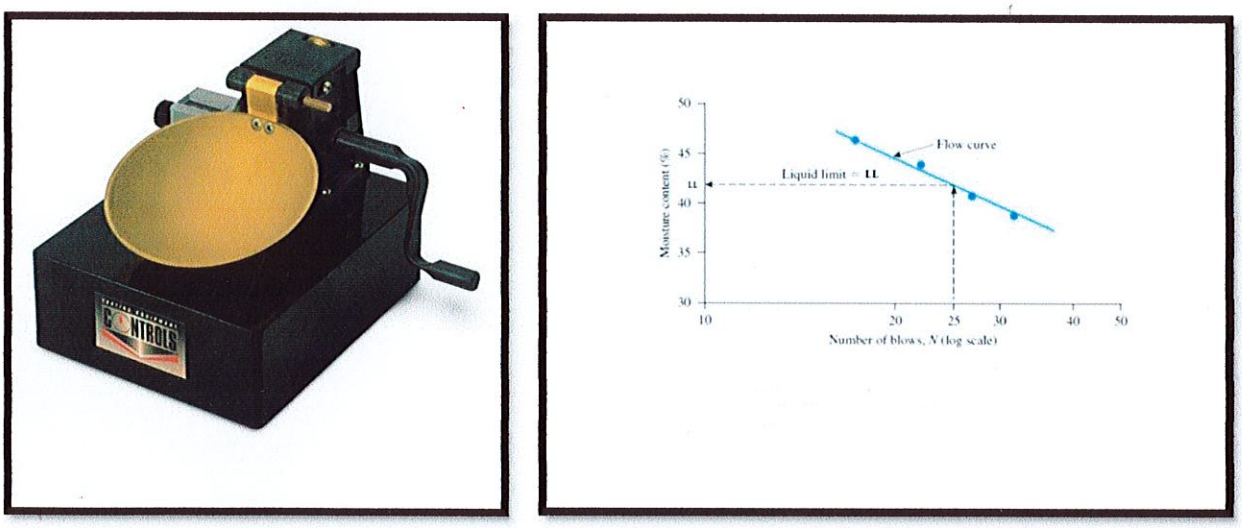

Figure 2. 10: (a) Cassagrande's device; (b) Flow curve of liquid limit

The slope of the curve is termed as flow index, I_f and may be expressed as

$$I_f = (w_1 - w_2) / \log (n_2/n_1)$$

Where, w_1 = moisture content at n_1 blows

w_2 = moisture content at n_2 blows

- **Plastic limit:** Plastic Limit (PL) is the minimum moisture content at which the soil can be deformed plastically. As standardized, it can be taken as the smallest water content at which the soil begins to crumble when rolled out into thin threads, approximately 3 mm in diameter. That is at plastic limit the soil must gain some minimum stiffness or strength. According to Skempton and Northey (1953) the shear strength at plastic limit is about 100 times that at liquid limit.

Plasticity Index, PI is the range of water contents over which the soil remains plastic. As such, plasticity index is the numerical difference between liquid and plastic limits.

$$PI = LL - PL$$

The plasticity of soil gives a good direction of the types of soil grains present in the soil sample. Low values of limits are indicative of silty soils, with higher values in clay soils. Very high limits are found in extremely fine grained clays such as bentonite and montmorillonite.

Table 2. 5: Typical values of liquid limit and plastic limit (after Atkins, 1977)

Soil	Liquid Limit	Plastic Limit
Silt clay mixture	25-40	20-30
Kaolinite clay	40-70	20-40
Montmorillonite clay/bentonite	300-600	100-200

Table 2. 6: Plasticity of soils (after Atkins, 1977)

Plasticity Index	Term used for the soil	Dry strength	Field test
0-3	Non-plastic	Very low	Grains fall apart easily
4-6	Slightly Plastic	Low	Easily crushed by fingers
7-15	Moderately Plastic	Low to medium	Slight pressure required to crush
16-35	Plastic	Medium to high	Difficult to crush
Over 35	Highly Plastic	High	Impossible to crush with fingers

➢ Density Test:

The density of slurry prior to introduction to the bore hole, as well as prior to the placement of concrete is verified with a mud balance (Figure). Prior to introduction, the slurry must have sufficient density such that the net pressure across the soil/slurry interface maintains wall stability. Prior to concreting, the density should not be too high, whereby the slurry will not be easily displaced by the heavier concrete. There have been no studies to show at what level the slurry may be too heavy, but high density is more commonly attributed to high solids content.

A mud balance (lever-arm scale) is typically used to measure the density, or unit weight, of the slurry. A metal cup that will hold a small quantity of slurry is carefully filled out of the slurry cup and cleaned of excess slurry on its exterior. It is then balanced by moving a sliding weight on a balance beam. The density of the slurry is read directly from a scale on the beam in several forms [unit weight (lb/cubic foot, lb/gallon), specific gravity]. The scale should be properly calibrated with water in the cup before making slurry density readings. This device is accurate, and readings can be taken rapidly. The only problem is to obtain a representative sample because the quantity of the slurry that is tested is small in relation to the quantity in a borehole. Therefore, multiple tests are recommended.

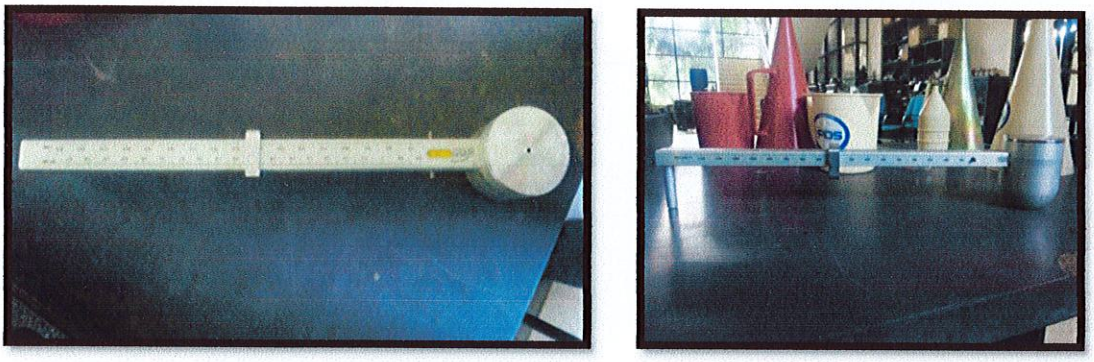

Figure 2. 11: Mud balance (LGED laboratory, Bangladesh)

➢ Viscosity Test:

The viscosity of a fluid is its ability to resist flow under shear stress. Viscosity that is verified with a viscometer is the ratio of shear stress to strain rate. When determining the viscosity in the field a Marsh funnel is used (Figure). This determines the time required for one quart of material to pass through a standard funnel (qt/sec). The material tested is passed first through a No. 12 sieve when introduced to the funnel. The Marsh funnel is based on the principles of the falling head flow; therein, fluid flows faster with higher pressure (when the 13 funnel is full) and progressively slows as the pressure decreases (funnel empties) As a result, longer emptying times indicate higher viscosity, but the Marsh funnel test is not a true viscosity test (shear stress/strain rate). The test is simply an indicator of gel strength and/or the presence of clay mineral content. However, the flow times can be affected by the presence of suspended solids.

Figure 2. 12: Marsh Funnel for viscosity test

➢ pH Test:

The pH of the slurry is an indicator of the degree of acidity or alkalinity of the slurry. Maintenance of a proper range of pH is important to the proper functioning of the slurry and is an indicator of the effectiveness of anti-hardness additives. For example, neutral-to-acid pH (7.0 or lower) can reflect conditions in a borehole that is being drilled through an acidic fill and that a bentonite-based slurry may be in danger of flocculating, or it could indicate that a polymer slurry is mixing with acidic groundwater and is in danger of agglomerating. The pH can be determined readily by the use of pH paper or by a pocket pH meter. The pocket pH meter, which is the size of a large pencil, is more accurate and is easy to use, but it must be calibrated often against a standard buffer solution.

➢ Sand Content:

The material retained on a No. 200 screen (74 microns) is defined as sand. Prior to concrete placement, sand content of mineral slurry should not exceed 4 percent by volume. Sand content is measured using a standard API (American Petroleum Institute) sand content kit by taking a slurry sample of 100 ml. A photograph of an API sand content test kit is shown in Figure. The sample is usually taken from the slurry cup after stirring vigorously to make sure all of the sand in the original sample in the cup is uniformly distributed in the suspension from which the 100 ml sample is taken. The slurry sample is diluted with water and then passed through a No. 200 stainless steel screen. The sand from the slurry is retained on the screen. That sand is then backwashed from the screen into a burette with a graduated, conical base, and the sand content in percent by volume is obtained by reading the scale on the burette.

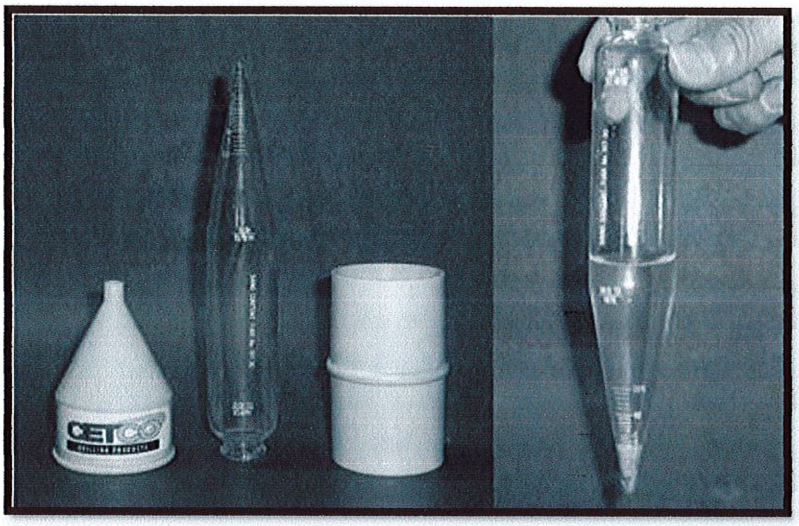

Figure 2. 13: Sand Content Testing Tool

2.6. Mixing & Handling of Slurry:

A variety of procedures are employed for the mixing and handling of mineral slurry. The principal concern is that the slurry characteristics are appropriate during the excavation of the borehole and during concrete placement. The mixing equipment and procedures must satisfy two general requirements: (1) adequate mixing of the mineral with the makeup water, and (2) adequate hydration to form a dispersed, lump-free suspension. A schematic diagram of a complete, appropriate system for mixing and handling bentonite slurry for drilled shafts is shown in Figure 2-7 and described below:

- The mixer identified by b_1 consists of a funnel into which dry bentonite is fed into a jet of water directed at right angles to the flow of the bentonite (a "venturi"). The mixture is then pumped to a holding tank. The mixer identified by b_2 consists of an electric motor, with or without speed controls, that drives a vertical shaft.

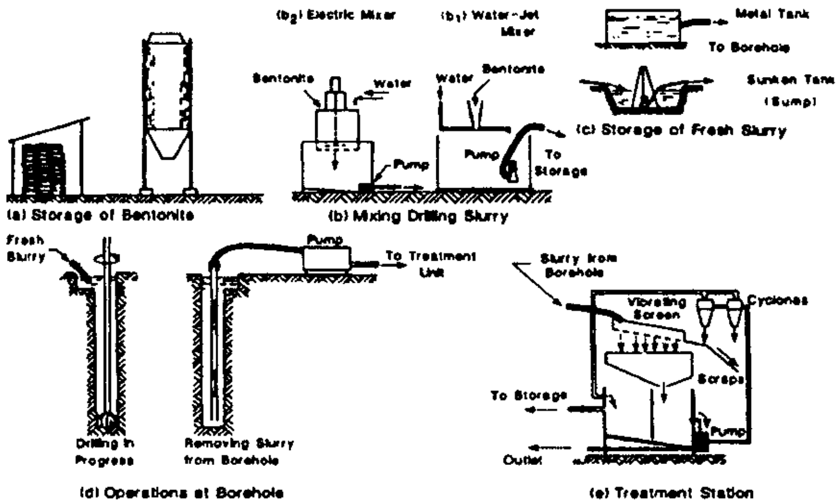

Figure 2. 14: Mixing and Handling of Slurry

- Freshly-mixed slurry should be held in storage for a period of time to allow complete hydration. The stored slurry can be re-mixed, if necessary, by pumps, mechanical agitation, or compressed air. It is recommended that bentonite be hydrated for 24 hours prior to its introduction to a drilled shaft excavation.
- The slurry stored in the storage tank (Figure 2-7c) is carried to the borehole by pump or by gravity with the slurry level in the borehole kept continuously above the level of the piezometric surface in the formation during drilling.

- Slurry with excessive sand or viscosity must be pumped from the bottom of the borehole to a treatment unit located on the surface for removal of the particulate matter. Simultaneously, fresh slurry meeting all of the sand content, density, and viscosity requirements is pumped from a holding tank on the surface and introduced at the top of the borehole, keeping the level of slurry in the borehole constant.
- The contaminated mineral slurry is moved to a treatment unit, Figure 2-7e, consisting of screens and hydro cyclones. The slurry first passes through the screens (usually No. 4 size), where the large-sized sediments are removed, and then is pumped through the cyclone unit where the small-sized material is removed by vigorously spinning the slurry.
- The cleaned ("desanded") slurry is pumped back to a holding tank where it should be tested. Since slurry drilling ordinarily involves some loss of slurry to the formation, some amount of fresh slurry is usually mixed with the desanded slurry at this point. If the used slurry is to be discarded without treatment, it is essential that approved methods be used for disposing of the slurry.

2.7. Slurry Used in Bangladesh:

In past few years too many projects are being conducted in Bangladesh where drilling fluids are used to stable the borehole. And construction companies are importing Bentonite slurry as powder from India, China. Following are the big projects where slurries are being used in Bangladesh:

i. Mayor Mohammad Hanif Flyover, Dhaka
ii. Mohakhali Flyover, Dhaka
iii. Banani-mirpur Flyover, Dhaka
iv. 3rd Karnaphuli Bridge, Chittagong
v. 2nd Mahananda bridge, Chapainababganj
vi. Kadamtali Flyover, Chittagong.
vii. Padma Bridge, Narayangonj.

2.8. Specification for Drilling Slurry:

The use of slurry in construction has increased over the years. However, its use has not always been under ideal conditions. Many times the slurry has been mixed in the excavation using an auger. If any testing is done, it consists solely of density and viscosity measurements. As a result of the relaxed conditions associated with bentonite slurry at times, concern has arisen as to the integrity of the slurry and the finished product. This concern has lead to the development in the last ten years of various specifications.

Sliwinski and Fleming (1975) suggested general ranges for the various properties of bentonite slurry. The properties were associated with the function of the slurry. Table 3.5 shows these relationships. As can be seen, the desired values of the properties range from low to high depending on the function. Thus, slurry which would function ideally at all times must change properties with functions. Ideal slurry, therefore, is impossible. However, effective slurry is possible with controls. Hutchinson, Daw, Shotton, and James (1975) suggested a more detailed set of specifications as did P. T. Hodgeson (1977). Tables 3.7 and 3.6, respectively, show the suggested specifications. Neither set regards the Marsh Cone as more than a qualitative measurement. However, its use has continued due to its simplicity and the expense of alternate methods.

Table 2. 7: Slurry specifications from Fleming and Sliwinski (1975)

Function of Suspension	Parameter				
	Viscosity	Shear Strength	Density	Fluid loss	pH
Form filter cake and stabilize bore by hydrostatic pressure application	Moderate to high	Moderate to high	High	Moderate to low	
Reduce cavitations caused by tool disturbance	High	High	-	Moderate	Low
Minimize los of fluid in previous strata	High	High	-	-	Low
Minimize loss of fluid in excavation spoil	Low	Low	-	-	-
Prevent accumulation of dense particles at base of excavation prior to concreting	High	High	High	-	-
Ensure free flow of concrete from tremie and easy displacement of bentonite	Low	Low	low	-	Low

from excavation and reinforcement					
Allow easy pumping of bentonite fluid	Low	Low	Low	-	-
Prevent sedimentation in pipes and tanks	Moderate	High	High	-	-

The Federation of Piling Specialists (1977) suggested a set of specifications which not only include slurry properties, but also material requirements and construction procedures. Table 6.4 is a summary of the FPS slurry specifications. The FPS specifications are not as extensive as are some others. Holden (1983) found the FPS specifications to be inadequate for a project in Australia. He suggests a much more extensive set of specifications (Table 3.8). He also suggests that the specifications be modified, after further study, to suit the particular equipment, methods, and conditions of a project. Modification of any specification is necessary for optimal compatibility for a particular project due to the different soil conditions that may be encountered. As the development of specifications is in the early stages, more studies are needed to broaden the scope of specifications. The FPS specifications are a good base on which to build, although they may not always be adequate.

Table 2. 8: Slurry specification from Hodgeson (1977)

Property	**Method**	**Supplied to trench**		**Prior to Concreting**	
		3-5%	5-8%	3-5%	5-8%
Plastic viscosity	Fann viscometer	3-10	7-20	20	20
10 min gel strength, N/m²	Fann viscometer	2-20	10-40	20	40
Density, g/ml	Mud balance	1.02-1.07	1.03-1.10	1.02-1.20	1.03-1.15
API sand content, % vol	API test	5	5	14	9
Fluid loss, ml in 30 min	API test	40	40	60	60
pH	API test	10.8	10.8	11.7	11.7

Table 2. 9: Slurry specification from Hutchinson, Daw, Shotton and James (1975)

<table>
<tr><th></th><th>Bentonite concentration</th><th>Density g/cm^3</th><th>Plastic viscosity</th><th>Apparent viscosity</th><th>Marsh cone viscosity</th><th>Yield strength</th><th>10 min gel strength dyne/cm^2</th><th>pH</th><th>Fluid loss</th><th>Sand content</th></tr>
<tr><td>Excavation support</td><td>>4.5%</td><td>>1.034</td><td></td><td rowspan="7">Not a primary parameter</td><td rowspan="7">Regarded only as a qualitative test</td><td rowspan="7">Regarded as less important than 10 min gel strength</td><td>>36</td><td></td><td rowspan="7">Results can be deceptive with present type of test</td><td>>1%</td></tr>
<tr><td>Excavation sealing</td><td>>4.5%</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Detritus suspension</td><td>>4%</td><td></td><td></td><td>>25</td><td></td><td></td></tr>
<tr><td>Displacement by</td><td><15%</td><td><1.3 (requires further verification)</td><td><20 cp (requires further verification)</td><td></td><td><11.7</td><td><35%</td></tr>
<tr><td>Physical cleaning</td><td></td><td><1.21</td><td></td><td></td><td></td><td><25%</td></tr>
<tr><td>Pumping</td><td></td><td></td><td></td><td>>25
<200</td><td></td><td></td></tr>
<tr><td>Limits</td><td>>4.5%
<15%</td><td>1.034
1.21</td><td><20 cp</td><td>>36
<200</td><td><11.7</td><td>>1%
<25%</td></tr>
</table>

Table 2. 10: Slurry specification from F.P.S

Items to be measured	Range of results at 20^0 C	Test method
Density	<1.10 g/ml	Mud balance
Viscosity	30-90 sec	Marsh cone method
	<20 cp	Fann viscometer
Shear strength	1.4-10 N/m^2	Shearometer
	4-40 N/m^2	Fann viscometer
pH	9.5-12	pH indicator paper strips or electrical pH meter

AASTHO recently introduced a specification of drilling slurry for drilled shaft construction and they brought the attention of engineers to adjust their values with site conditions. Table 3.9 shows the standard specification which is now followed all over the world with necessary modification.

Table 2. 11: Slurry specification recommended by AASTHO (2008)

Property of Slurry (units)	Requirement	Test methods (API standard method)
Density (lb/ft^3)	64.3 to 72	Mud Weight Density Balance (API 13B-1)
Viscosity (sec/qt)	28 to 50	Marsh Funnel and Cup (API 13B-1)
pH	8 to 11	Glass electrode pH meter or pH paper strips
Sand Content immediately prior to concrete placement (percent by volume)	≤ 4.0	Sand Content (API 13B-1)

2.9. Conclusion:

To conclude it can be said that, the introduction of using drilling fluid has set a benchmark in drilled shaft foundation as drilling fluids are responsible for the increment of strength in the borehole as well as in the piles. Advancement of technology in the field of production and use of drilling fluids are significant in recent years. In Bangladesh there are several options regarding drilling fluids or slurries of which bentonite slurry can be considered as the most preferable considering its availability, price and effectiveness in comparison with other types of slurries. Slurries produced from local clays can be another good option as it's the most available one. In this thesis, a comparative analysis of quality between slurry made from bentonite sample (bought from market) and a slurry of locally available clay (madhupur clay)has been performed on the basis of marsh funnel viscosity test, density test, Atterberg test from liquid and plastic limit and pH test.

Chapter 3
Laboratory Testing of Drilling Fluids

Chapter 3

Laboratory Testing of Drilling Fluids

3.1. General:

Drilling fluids or slurries will have certain desirable properties which should be inspected by the contractors to maintain properly so that the purpose of using slurries will be fulfilled. For the purpose of this research lab experiments on slurry samples had been conducted to determine specified properties. Properties of slurry were divided into two categories (1) physical characteristics of soil sample (2) engineering properties of slurry. Physical properties of sample contains grain size analysis, Atterberg limit test, specific gravity whereas engineering properties were density, viscosity, shear strength, pH, sand content etc. In this chapter, the tests of Bentonite clay and Dhaka clay and the slurry made by those two samples is discussed.

3.2. Collection of Bentonite & Dhaka Clay:

We had experimented on two soil sample, one was Bentonite clay and other was tha local soil-Dhaka Clay. Bentonite clay is not so available in Bangladesh. And contractors mainly import this chemicals from abroad. Even in local market there are some sample which is also used in drilled shaft construction in Bangladesh. We have bought bentonite clay as powder manufactured in indusrty from Sabbir Enterprise, 250 Nawabpur Road, Dhaka.

One of the most promising part of our project was introducing local soil sample as slurry in drilled shaft construction as it is said earlier that bentonite clay is not so available. So we had run some tests on local soil. Our local soil sample was dhaka clay, commonly known as Madhupur Clay. We had collected this sample from 15 feet depth of a hole excavated due to the government work purpose for utility at Polashi Bazar, Dhaka.

3.3. Laboratory Test of Bentonite:

3.3.1. Determination of Specific Gravity:

Following the ASTM D854-14 specific gravity of Bentonite slurry had been determined.

Table 3. 1: Lab data of specific graviity test for Bentonite

Determination No.	
Wt. of Bottle + water + soil (W_1) in gm	371.5
Temperature T in ^{0}C	27.5
Wt of Bottle + Water W_2 in gm	341.7
Wt of Dish in gm	25.8
Wt of dish + Dry soil in gm	75.8
Wt of Bottle + Dry soil in gm	143
Wt of Bottle in gm	93
Wt of soil W_s in gm	50
Specific Gravity of Water G_T at T^{0}C	0.9958

3.3.2. Grain Size Analysis:

According to ASTM D422 , hydrometer test was proceed and following graph was plotted.

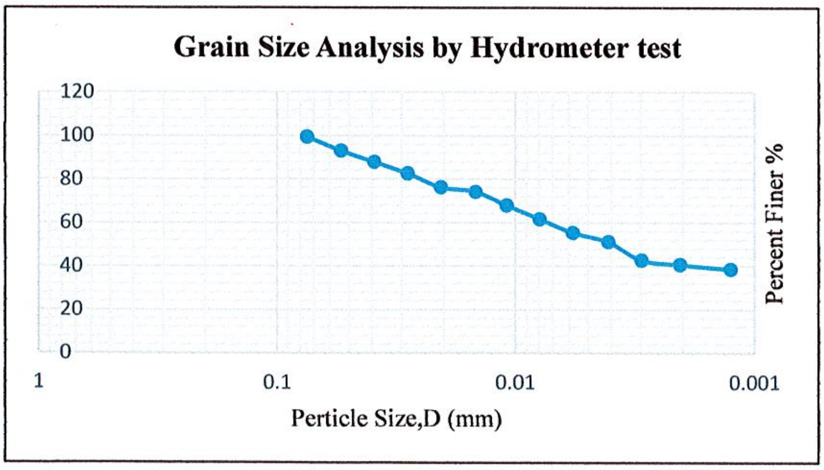

Figure 3. 1: Grain size analysis of bentonite clay

3.3.3. Atterberg Limit Test :

Table 3. 2: Lab data of liquid limit

No of Blows	38	28	22	19
Wt of Container, gm	9.9	10	7.2	10.4
Wt Container + Wet Soil, gm	22.5	20.1	18.6	22.3
Wt Container + Dry Soil, gm	18.9	17.1	15.2	18.9
Wt Water, W_w in gm	3.6	3	3.4	3.4
Wt. Dry Soil W_s in gm	9	7.1	8	8.5
Water Content, W, in %	40	42	43	45

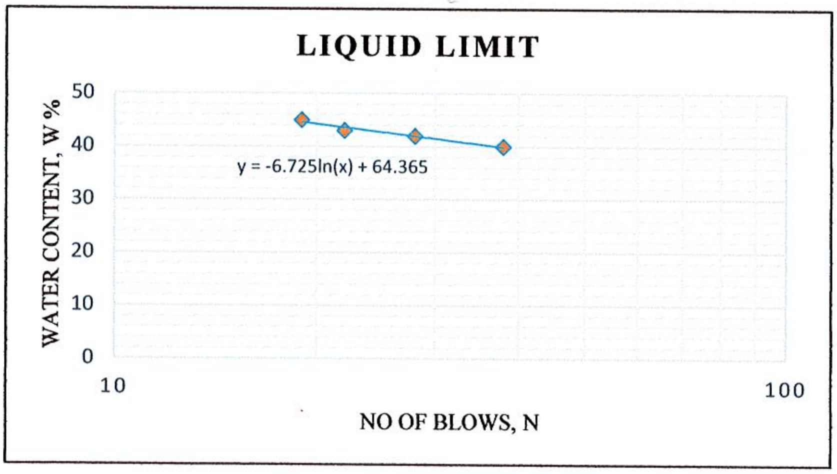

Figure 3. 2: Flow curve of Bentonite clay

Table 3. 3: Lab data of plastic limit

Wt. Container, gm	7	7.	10.9
Wt. Container + Wet Soil, in gm	10.4	10	15.1
Wt. Container + Dry Soil in gm	9.9	9.5	14.2
Wt. Water, W_w in gm	0.5	0.5	0.9
Wt. Dry Soil, W_s in gm	2.9	2.5	3.3
Water Content W in %	17.24	20	27.27

3.3.4. Marsh Funnel Viscosity:

According to ASTM D4380 viscosity of bentonite was determined. Five different amounts of bentonite clay was mixed with certain amount of water to conduct the test.

Table 3. 4: Viscosity of Bentonite slurry for different amount of Bentonite added in a given volume of water

Amount of Clay (gm)	Amount of Water (CC)	Weight/Volume (%)	Viscosity (s/qt)
200		13.33	24
700		46.67	25
1000	1500	66.67	26
1500		100	29
1700		113.33	37

3.3.5. pH Test:

We have followed ASTM D4972 standard procedure to determine pH of bentonite clay.

3.4. Laboratory Test for Dhaka Clay :

3.4.1. Specific Gravity:

According to ASTM standard procedure this test was conducted and the data is given in appendix.

Table 3. 5: Data for specific gravity test for Dhaka clay

Determination No.	
Wt. of Bottle + water + soil (W_1) in gm	371.5
Temperature T in ^{0}C	27.5
Wt of Bottle + Water W_2 in gm	341.7
Wt of Dish in gm	25.8
Wt of dish + Dry soil in gm	75.8
Wt of Bottle + Dry soil in gm	143.3
Wt of Bottle in gm	93.3
Wt of soil W_s in gm	50
Specific Gravity of Water G_T at T^{0}C	0.9958

3.4.2. Grain Size Analysis:

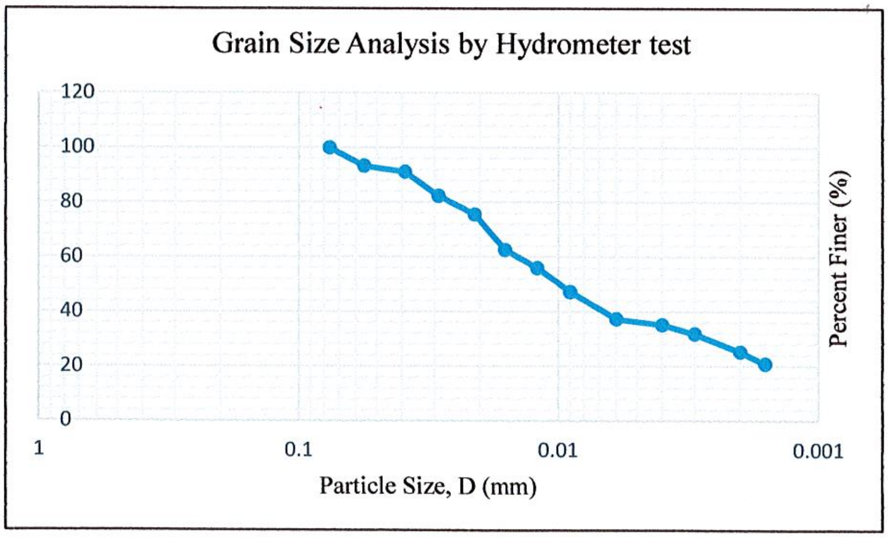

Figure 3. 3: Grain size analysis of Dhaka Clay

3.4.3. Atterberg Limit Test:

According to ASTM Standard we had determined liquid limit and plastic limit. The data sheet is given in the Appendix.

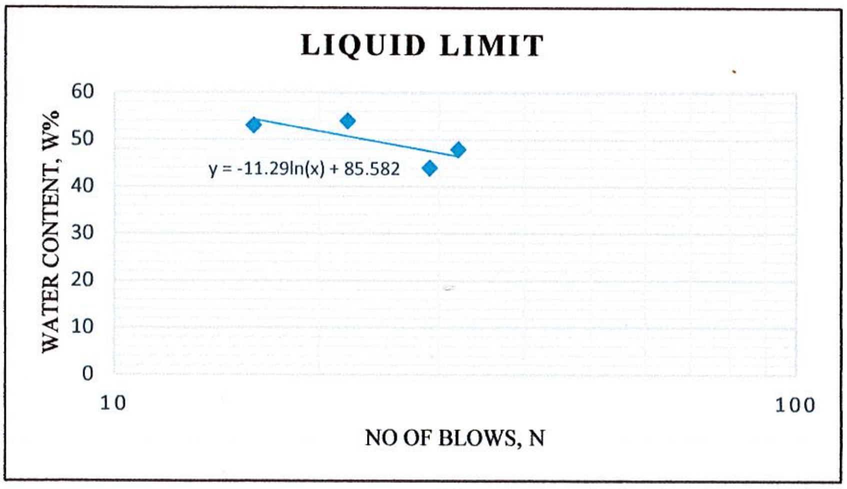

Figure 3. 4: Flow curve of Dhaka clay

3.4.4. Marsh Funnel Viscosity Test:

According to ASTM D4380 viscosity of Dhaka clay was determined. Five different amounts of clay was mixed with certain amount of water to conduct the test.

Table 3. 6: Viscosity of Dhaka clay slurry for different amount of Dhaka clay added in a given volume of water

Amount of Clay (gm)	Amount of Water (CC)	Weight/Volume (%)	Viscosity (s/qt)
100	1500	6.67	23
200		13.33	24
350		23.33	25
1300		86.67	29
1400		93.33	31
1500		100	34

3.4.5. Slurry Preparation with Finer Particles of Clay:

In our local soil sample previous results show that it has low clay particles than silts and liquid limit was 49. As percentage of clay particles and liquid limit increased, slurry made by this sample would be desirable. For this specific purpose, a test had been conducted with same local soil sample. Sample had been mixed with water in a bucket and kept it about 10 mins for settling some part of its which normally contains silty particles. After 10 mins upper layer of solution was collected and that solution was then oven dried for 24 hours. Then same liquid limit and plastic limit tests were conducted on that dries sample, which gives us satisfactory results and the values of atterberg limits are:

Liquid limit = 57

Plastic Limit = 28

Plasticity Index = 29

This new sample provides a better result as slurry. Viscosity is increased with lower densified slurry. So it can be said that soil with with more clay particles and higher liquid limit will be satisfactory as slurry for drilled shaft construction.

Chapter 4
Results & Discussion

Chapter 4

Results And Discussion

4.1. General:

For the purpose of this thesis project, some laboratory experiment had been investigated as discussed earlier to our collected soil sample and demonstrated the idea of bentonite slurry and local soil (Dhaka Clay) slurry for drilled shaft construction in Bangladesh. For some the limitation on laboratory, some of the tests which were enough to provide desired result and for equipment unavailability, some conventional method had been followed rather than standard ASTM methods regards to slurry tests. In this chapter, the results of the experiments tested in laboratory has been illustrated and a brief analysis about the results has been provided with discussions. And that gives us a conclusion of this project.

4.2. Results of Laboratory Testing:

The results found in laboratory testing on both samples are represented here in a tabular form in two separate tables.

Table 4. 1: Laboratory testing result of Bentonite clay

Name	Value
Specific Gravity	2.456
Liquid Limit	43
Plastic Limit	22
Plasticity Index	21
Flow Index	6.73
pH	6.00

Table 4. 2: Laboratory testing results of Dhaka clay

Name	Value
Specific Gravity	2.52
Liquid Limit	49
Plastic Limit	25
Plasticity Index	24
Flow Index	11.3
pH	7.00

4.3. Analysis of Results:

4.3.1. Bentonity Clay and Slurry:

- From hydrometer analysis, it is found that the gradation curve lies between 0.1~.001mm of particle size, the sample of bentonite was silty clay. And clay was 52.5% (from graph) and percentage of silt was 47.5 (as per AASTHO).
- Bentonite clay can be classified in "Kaolinite clay" as per its liquid value.
- Plasticity index shows that the sample is plastic in behaviour.
- Dry strength of the soil medium to high. And it is difficult to crush.
- As per USCS the sample can be classified as CL.
- Marsh funnel viscosity as per standard value, for bentonite slurry it was satisfied when mixing ratio of bentonite to water was 1.1 and 1.13.
- From viscosity test result a relation between mixing ratio and viscosity can be shown as a graphical relation and from a linear regression analysis a equation is derived which is helpful to check the density of slurry as density is defined by mass of sample per volume which is the mixing ratio.

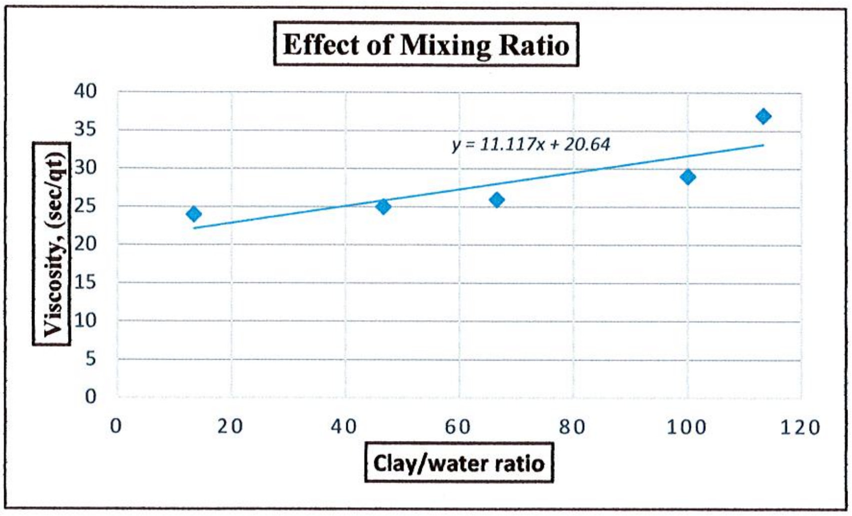

Figure 4. 1: Effect of mixing ratio

$$y = 11.117 * x + 20.64$$

Where y = Viscosity (sec/qt)

x = mixing ratio or density (kg/L)

From this equation, desired value of viscosity of density can be derived for this slurry for drilled shaft construction.

4.5.1. Dhaka Clay And Slurry:

- According to gradation curve, percentage of clay and silt in Dhaka clay were 37.5 and 62.5 respectively. Percentage of sand was totally zero (as per AASTHO).
- As per liquid value obtained in the test this soil sample is under 'Kaolinite Clay'.
- Plasticity index shows that the sample is plastic in behavior.
- Dry strength of the soil medium to high. And it is difficult to crush.
- As per USCS the sample can be classified as CL.

- From the marsh funnel viscosity test the desired value was obtained at mixing ratio 0.86, 0.93 and 1.0.

- As stated earlier for bentonite sample, a graphical relation can be demonstrated to determine density from viscosity results.

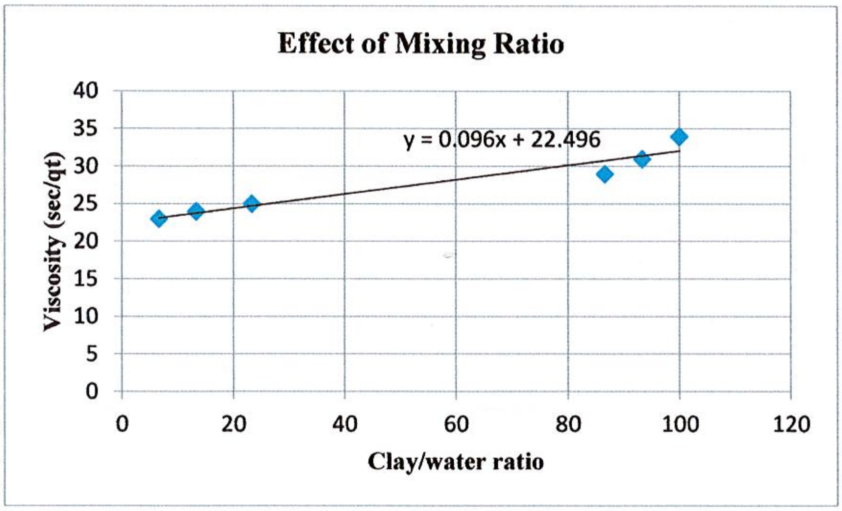

Figure 4. 2: Effect of mixing ratio

$$y = 0.096 * x + 22.496$$

Where y = Viscosity (sec/qt)

x = mixing ratio or density (kg/L)

4.4. Comparative Analysis Between Bentonite Slurry and previous studies:

Satndard values of physical and engineering properties of Bentonite has been provided in chapter 2 which demonstrates a comparative analysis and illustrates that how much the sample used in this research is appropriate for bored pile construction. Some graphical comparative analysis is represented here where the bentonite sample used here, is marked as Bangladesh. It is compared with the values of three bantonite sample derived in previous case study.

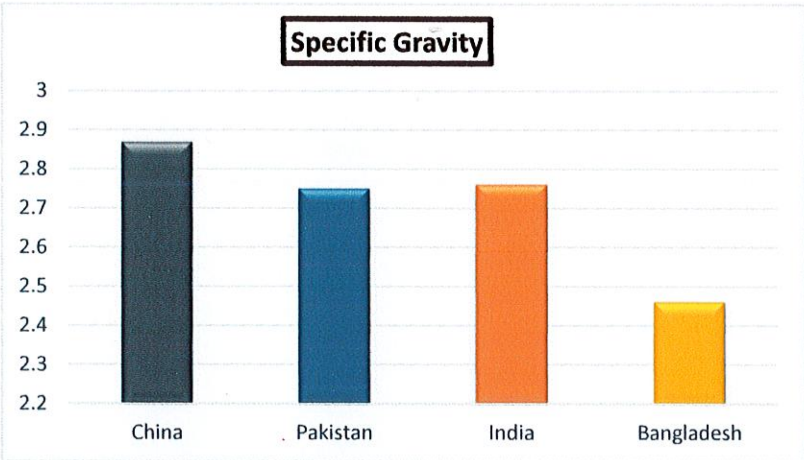

Figure 4. 3: Comparative analysis of specific gravity

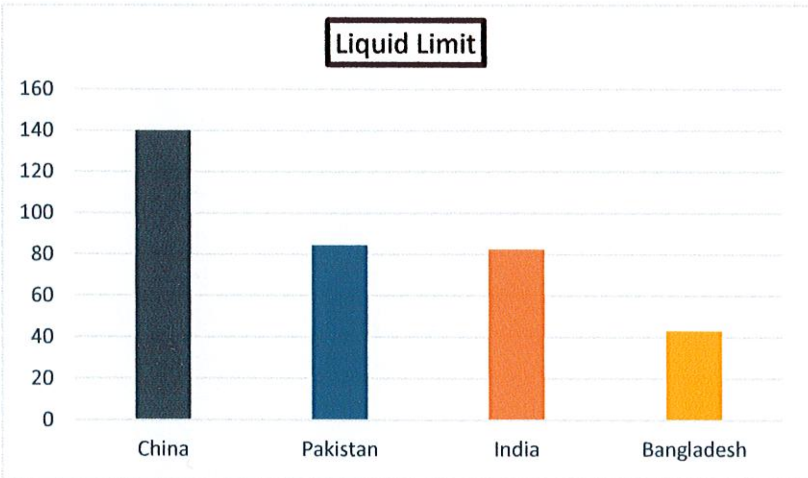

Figure 4. 4: Comparative analysis of liquid limit

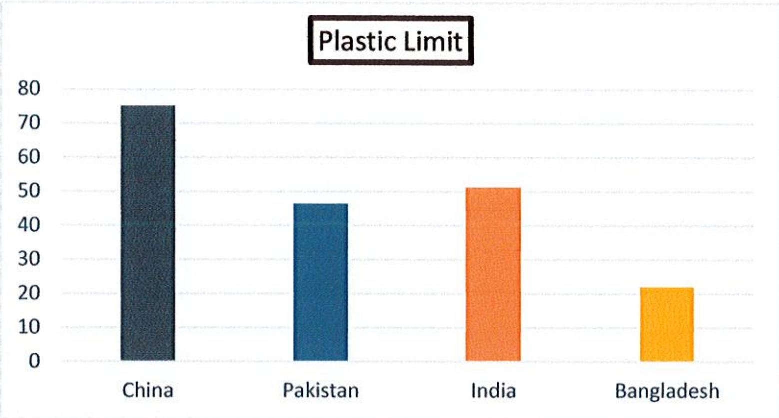

Figure 4. 5: Comparative analysis of plastic limit

Graphical analysis shows that bentonite sample of Bangladesh has low values of specific gravity, liquid limit and plastic limit compared to other standard samples which concludes to a decision that quality of bentonite sample of Bangladesh is poor.

Grain size analysis also provides a lower percentage (52.5%) of clay particles present in this typical sample compared to others (table 2.2). Higher percentage of clay particles ensures better slurry qualities with higher liquid limits. So the results found in this sample is not satisfactory.

4.5. Comparative Analysis Between Bentonite and Dhaka Clay Slurry:

- From the analysis report it is shown that our soil samples were almost identical in behavior. Both are CL soil and contains Kaolinite minerals. Liquid limit was also between same ranges.
- Bentonite sample was comparatively acidic than dhaka clay sample.
- Desired viscosity was obtained in dhaka clay slurry earlier than bentonite slurry. It results in less densified slurry compared to bentonite slurry provides satisfied results.
- As weight/volume ratio is reduced, soil sample required to make slurry is less required than bentonite slurry which results in economical solution.
- Improved Dhaka clay (separation of finer particles) provides more better results than normal Dhaka clay and bentonite sample.

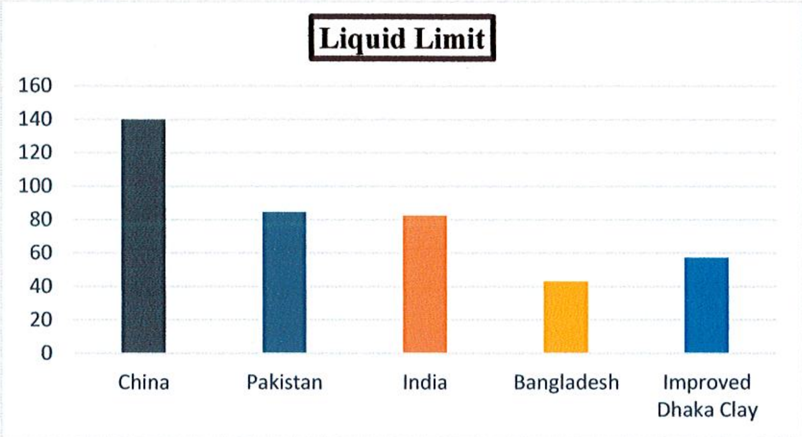

Figure 4. 6: Comparative analysis of Improved Dhaka clay with others

4.6. Findings of Analysis:

- Compared with standard data, stated in chapter 2, it can be said firmly that the slurries which are being used in drilled shaft construction in Bangladesh is not good if contractors collect them from local market as our sample of bentonite was. Normally a bentonite sample should contain montmorillonite minerals whereas our sample contains kaolinite minerals in which value of liquid limit is low in large scale compared to montmorillonite. So required value of viscosity and desnity to control the quality of slurry is obtaind at higher mixing ratio which results in higher cost compared to pure bentonite slurry or simply standard slurry.
- Local soil can be used as an alternative of bentonite slurry in drilled shaft construction. The sample which was used here, had showed better results than the bentonite slurry which had promoted us to a challenge to introduce it as an alternative.
- With the increase of clay contents and liquid limit, the desired behavior of slurry is achieved quite earlier. Higher values of liquid limit is always better for slurry.
- A graphical relation can be plotted between viscosity and mixing ratio (density) which will provide a relation for a particular soil sample. This relation will help a contractor or engineer to design the required mixture of the slurry sample. The relation is shown here:

$$M = aV + b$$

where M = mixing ratio (clay/water)

V= Viscosity (sec/qt), measured by mursh funnel.

a, b are parameters, constant for particular sample.

As for our Bentonite sample a = 11.117 and b = 20.64. And for dhaka clay a & b values are 9.5954 and 22.496 respectively.

4.7. Conclusion:

From the above lab analysis and discussion, it can be stated that, the slurry samples bought from local market may be results in vulnerable effects in drilled shaft which may not be shown during construction. And economically this samples are not satisfactory if desired results is achieved. Local clay can be manufactured for slurry using in drilled shafts.

Chapter 5
Conclusion

Chapter 5

Conclusion

5.1. Summary of The Project:

At the beginning of this project, target was to accomplish a better quality control system for drilling slurry used in drilled shaft construction for Bangladesh. According to this goal some experiments on two slurry samples; one was Bentonite slurry collected from local market and another one was local clay soil named as 'Dhaka Clay'or 'Madhupur Clay', were conducted. The total work done within this research project is summarized here:

- Clay soil with high liquid limit provides better results as drilling slurry, that's why some identification tests was conducted from where we had got a better idea about our sample. Normally slurry soil should contain montmorillonite minerals which has a range of liquid limit between 300-600 whereas both slurry sample contains a liquid limit within 40-50. From this, it was cleared that our samples won't perform well in the drilled shaft.

- Slurry has some particular engineering properties like density, viscosity etc which is required to control the better quality. We had conducted ASTM standard procedure to determine these properties for our sample. From the results, a comparative analysis between both samples was done and represented in earlier chapter. According to that Dhaka clay shows better results than Bentonite Clay.

- Developing local soil as an alternative option of bentonite was another goal of this research. And fortunately our local soil was better than normal bentonite soil but not as much satisfactory as liquid limit was low. That's why we had done another test on local soil to improve its liquid limit and clay contents which is discussed in previous chapter.

After conducting the processes described above, it can be concluded that Bentonite slurry from local market was not as much as satisfactory and local soil- Dhaka clay can be used as an alternative of bentonite slurry in bored pile construction with some improvement by separation of finer particles from collected sample.

5.2 Scope of Further Study on Drilling Fluids:

This research paper gives its focus to drilled fluids used in bored pile construction. For that bentonite and local soil is used to investigate the goals of this research which leads to find more scopes of further studies on drilling fluids. Following topics can be investigated later:

- Bentonite slurry can provide better results by using additives. So a research can be conducted to introduce proper additives to make Bangladeshi Bentonite as more reliable drilling fluids for bored pile construction.
- Development of local soil has a promising future in this sector of geotechnical engineering. Already this paper has introduced this topic. Better way of separation of finer particles can be a part of research, as finer particles ensure higher values of Atterberg's limits and thus provides better slurry qualities.
- As viscosity of slurry is related to liquid limit of clay, further investigation on different types of drilling fluids can illustrate a co-relation between liquid limit and viscosity of slurry which will provide a idea of soil properties that should be contained in the sample of drilling fluids.

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