THE EFFECT OF VARIATION IN GROUNDWATER TABLE ON THE BEARING CAPACITY OF SOIL

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ENG2006172

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF ENGINEERING (B.Eng) DEGREE

IN

THE DEPARTMENT OF CIVIL ENGINEERING,

FACULTY OF ENGINEERING,

UNIVERSITY OF BENIN, BENIN CITY, NIGERIA

NOVEMBER, 2025

PLAGIARISM

The work **EFFECT OF GROUNDWATER TABLE ON THE BEARING CAPACITY OF SHALLOW FOUNDATIONS** by EBOH, Joshua Samuel, with number ENG2006172 of the Department of Civil Engineering, Faculty of Engineering, University of Benin, Edo State, Nigeria, has passed the PLAGIARISM TEST.

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DEDICATION

I would like to dedicate this work to the Lord God Almighty for his unceasing help, and to my parents, Mr. M. Eboh and Mrs. H. Eboh for their constant support.

ACKNOWLEDGEMENTS

My gratitude goes to Engr. Dr. E. S. Okonofua, my supervisor, who provided me with the understanding and assistance necessary to carry out this work. I would also like to thank the Head of the Civil Engineering Department, University of Benin; Engr. Prof. N.I. Ihimekpen, also Engr. Prof. O.C Izingon, Engr. Prof. O.U. Orie, Engr. Prof. S.O. Osuji, Engr. Prof. H.A.P. Audu, Engr. Prof. J.O. Okovido, Engr. Prof. S.D. Iyeke, Engr. Dr. R.I. Umasabor, Engr. Dr. R.O. Ogirigbo, Engr. Dr. (Mrs.) N. Kayode-Ojo, Engr. Dr. (Mrs.) A. Rawlings, DR. (Mrs.) L.O. Bobor, Engr. Dr. A. Agbonaye, Engr. Dr. R. llaboya, Engr. U. Ukeme, Engr. P.N. Ogbeifun, Engr. E. Oria-Usifo, Engr. S.A. Adegbemileke, Engr. O. Oriakhi, Engr. B. Omosefe, Engr. C. Okoli, Engr. O. Osasu, Engr. N. Oghoyafedo, Engr. (Mrs.) E. Ambrose-Agabi, Engr. E. Musa, Engr. U. Ogbonna, Engr. (Mrs.) G.E. Evbaru-Okhuahesuyi, Engr. J.O. Odomerho, and all other lectures and staff of the department of Civil Engineering department for their guidance, mentorship, and assistance.

My gratitude also goes to my friends who provided me with assistance during the course of this work. Finally, to my Family for all the help and Love. May God continue to bless you.

ABSTRACT

This study, the effect of groundwater table on the bearing capacity of shallow foundation, aimed to evaluate how varying groundwater table levels affect the bearing capacity of soil through an analytical method using Terzaghi's equation for foundation bearing capacity. Soil samples were collected using manual hand auger at a depth of 2m from a site in Oleh, Delta state where the groundwater table was close to the surface. The soil samples were then taken to the University of Benin, Civil Engineering Laboratory where the specific gravity, compaction, sieve analysis, atterberg and triaxial shear tests were carried out, in order to find the physical and strength properties of the soil.

The liquid limit of the samples showed a range from 20.0-19.5%, the plastic limit, a range from 12.5-13.0% and a plastic index, from 7.5-6.5%. The samples had MDD ranging from $1.95 - 1.91 g/cm^3$, OMC ranging from 9.5-7.8%. The sample showed Φ values to range from 32-30° and C values to range from 15-12kPa. The study showed that high groundwater table significantly reduces soil bearing capacity. The control sample (normal water table) exhibited superior performance across all parameters (such as 1122kpa bearing capacity which showed a drop to 951 in the 2m depth). High water table conditions led to a reduction in allowable bearing capacity, with the most severe impact observed at 2m depth. These findings emphasize the importance of proper site investigations and making informed construction decisions.

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ACRONYMS

ASTM	- American Society for Testing and Materials
B.Eng	- Bachelor of Engineering
ET	- Evapotranspiration
FS	- Factor of Safety
LL	- Liquid Limit
PL	- Plastic Limit
PI	- Plasticity Index
USCS	- Unified Soil Classification System
SPT	- Standard Penetration Test
RQD	- Rock Quality Designation
PTI	- Post-Tensioning Institute
D/B	- Depth to Width ratio

CHAPTER ONE
INTRODUCTION

1.1 Background of study

The design and construction of the foundation are fundamental to ensuring the stability, security, and longevity of any building. The durability of foundations is generally a matter of the bearing capacity of the underlying soil, or the load that the soil can carry without failing. An understanding of what governs bearing capacity is therefore of critical concern in geotechnical engineering (Sivakugan *et al*., 2018)

One of the most significant governing factors of soil bearing capacity is the presence and depth of the groundwater table. Groundwater occupies the pore space between the soil particles and influences the effective stress in the mass of the soil. Effective stress, or the extent of the difference between the total stress and pore water pressure, governs the strength and deformability characteristics of the soils. When the groundwater table shifts close to the level of the subsoil, the pore water pressure rises, resulting in a reduction of the effective stress. This reduction directly affects the shear strength of the soil and consequently its bearing capacity (Farhadian *et al*., 2021)

Groundwater may exert some effects on foundations. First, the water buoyant pressure reduces the effective soil weight, thus decreasing the load resistance of the soil to externally applied loads. Second, increased pore water pressures tend to liquefy or destabilize certain soils, such as loose sands and silts. Third, seasonal or temporary groundwater level changes can lead to differential settlement or heaving, both of which are adverse to structures (Keller and Sherif, 2019).

In the real world, groundwater affects bearing capacity depending on several variables, including soil type, permeability, drainage, and the quantity and range of water table fluctuation. For example, clayey soils may retain water and respond in a plastic way, but sandy soils may drain very fast but are prone to pore pressure changes. Saturated soils with high water tables may experience long-term loss of strength, and foundation design is complicated (Cedergren, 2017).

Theoretical bearing capacity equations, such as Terzaghi, Meyerhof, and Hansen, offer formulas and correction factors for assessing bearing capacity under various groundwater conditions. These models typically simplify both soil conditions and steady-state groundwater scenarios, which do not accurately reflect the realities of field conditions. Consequently, theoretical methods should be complemented by site-specific investigations, including soil sampling, laboratory testing, and in-situ testing (Bowles, 2015).

The influence of groundwater on bearing capacity is particularly significant in high rainfall zones, coastal regions, reclaimed lands, and regions with fluctuating seasonal water tables. Failure to properly account for groundwater influences can lead to excessive foundation settlements, tilting, cracking, or even outright failure of structures with severe economic and safety consequences (Singh and Arora, 2020).

Given the importance of this subject, the current research aims to explore the relationship between groundwater table depth and the bearing capacity of soil. By integrating theoretical investigation, and experimental testing. The research aims to achieve insights that will boost structural safety, and foster sustainable construction practices (Poulos and Davis, 2019).

1.2 Statement of problem

The stability and safety of structures rely heavily on the ability of the soil beneath it to withstand imposed loads without excessive settlement or collapse. Foundations are a major part of a structure as they secure the structure to the ground and are responsible for the stability of the structure, but their performance relies significantly on the ground surface conditions, particularly the presence and variation of the groundwater table (Vennapusa, 2015).

Where the groundwater level is at or fluctuating seasonally near the ground surface in areas of high rainfall or low drainage in most areas, the effective stress within the soil is reduced as a result of the elevated groundwater level; hence, its bearing capacity and shear strength are decreased. Failure to take care of or ignore this critical factor during foundation design will result in structural problems such as excessive settlement, tilting, cracking, or even catastrophic foundation failure (Das, 2016).

Despite the long-standing impact of groundwater on soil behavior, there remains very little integrated information and localized data on how various levels of groundwater affect the bearing capacity of shallow foundations under various soil conditions and environmental regimes. This lack of information poses challenges for civil engineers to make sound design decisions, hence resulting in unsafe or uneconomical foundation systems.

Therefore, this study tries to investigate the impact of the fluctuation of the groundwater table on soil bearing capacity. The outcome will improve foundation design criteria with a more realistic analysis of soil strength under various groundwater conditions, and this will ultimately result in safer and more reliable construction.

1.3 Aim and objectives

This work aims to evaluate the effect of the variation the groundwater table on the bearing capacity of soil.

The objectives of the study are:

1. Collection of soil samples for soil testing analysis using manual hand auger.
2. To determine the physical and engineering properties of the soil sample using laboratory tests.
3. To assess the effect of varying groundwater table levels on the bearing capacity of the soil sample using an analytical method under different water table scenarios.

1.4 Scope of study

This study seeks to examine the influence of variation of groundwater table depth on the bearing capacity of soil. It will involve:

Investigation of seasonal variations of the groundwater table and impact on soil strength.

Use of conventional bearing capacity principles and their adaptation with consideration of groundwater.

Conducting laboratory testing such as grain size analysis, Atterberg limits, and shear strength tests to establish the characterization of the soil samples.

Results and recommendations will be applied universally but may require local modification in some site conditions.

1.5 Justification of study

The stability and durability of structures significantly depend on the adequacy of their foundation design, but their performance is extremely vulnerable to subsurface soil conditions, i.e., the depth and availability of the groundwater table. Groundwater affects the effective stress and shear strength of soils, which has a direct impact on the bearing capacity of foundations (Coduto *et al*., 2017)

In the majority of regions, the groundwater level experiences seasonal fluctuations or remains high due to climatic, geological, or man-made factors. Poor consideration of such groundwater effects during the design of foundations may result in catastrophic structural defects such as excessive settlement, tilting, cracking, and, in the extreme case, total failure of the foundation system. Such failures constitute safety risks, costly repairs, and loss of public confidence in engineering interventions (Bell, 2020).

Despite the relevance of groundwater in geotechnical engineering, local information could be scarce, and the particular effect on bearing capacity could be poorly defined in the majority of construction areas. Existing design approaches must rely on generalized or empirical correction factors, which may not be representative of the site-specific ground and groundwater conditions. This shortage necessitates comprehensive studies involving theoretical, laboratory, and field investigations to further define groundwater effects on foundation behavior (Jamiolkowski and Marchetti, 2018).

This study is therefore justified in the sense that it will provide an improved understanding of the impact of groundwater table variation on soil bearing capacity. This will enable engineers to make more informed design decisions, minimize construction expenses, enhance safety, and help develop localized standards and guidelines. This study ultimately supports sustainable and resilient infrastructure development, particularly for areas prone to groundwater-related geotechnical problems.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil bearing capacity

The concept of bearing capacity of soil is a crucial aspect of geotechnical engineering as loads from structures built on the soil transfer loads, dead and live, to the foundation through columns, beams and sometimes walls, which in turn transfers them to the soil on which the structure is built, therefore, a grasp on the load bearing ability of the soil is needed. The bearing capacity of soil is the maximum amount of load that the soil can withstand without failure of excessive settlement when a structure is cited on it. A higher bearing capacity signifies a higher loading bearing capacity and vice versa, therefore a higher bearing capacity is often required during construction processes (Springer, 2018).

2.1.1 Factors affecting bearing capacity

As previously established, bearing capacity of soil ranges on a scale from very weak to very strong and this difference in load bearing capacity of the soil is affected by several factors, some of which include:

i. **Soil type:** The type of soil strongly influences the bearing capacity of the soil as different soil types have very distinct strength and compressibility characteristics. Some of the different soil types and how and how their bearing capacity varies include:

   a. **Gravel and coarse sand**: These contain large, dense particles which interlock well. They have minimal compressibility and rapid drainage which prevents pore water pressure build up, therefore, they have high bearing capacity, usually ranging between $\mathbf{200 - 600kN/m^2}$.(Das & Sobhan, 2018).

b. **Fine sand and silty sand:** They contain smaller particles which reduces interlocking. It is more compressible than gravel with less drainage but higher than clay. They have a moderate bearing capacity, usually ranging between $100 - 300kN/m^2$.

c. **Clay:** clay is cohesive but weak in shear, with high plasticity and compressibility. It has a slow drainage which allows it retain water for longer and creates pore water pressure which reduces effective stress. It has a low bearing capacity ranging between $25 - 100kN/m^2$. (Jabar *et al,* 2025)

ii. **Soil properties**: the observable characteristics of the soil particles, such as the shear strength parameters and engineering properties strongly influences the bearing capacity of the soil sample and some of them include:

a. **Cohesion:** this refers to the natural intrinsic ability of the soil the soil to hold together, with higher cohesive force providing more resistance to shear failure and increasing the bearing capacity (Das and Sivakugan, 2019).

b. **Angle of internal friction (ϕ):** this shows the particle's interlock and friction, with higher ϕ indicating a higher bearing capacity (Das and Sivakugan, 2019).

iii. **Foundation geometry:** The shape, size and depth of the foundation greatly influences the bearing capacity of the supporting soil as it dictates the load distribution from the structure built to the ground and how the soil resists shear failure and settlement. Typically, a larger foundation area results in a higher bearing capacity as the load is distributed over a wider soil mass and vice versa. Deeper foundations also tend to have higher bearing capacity due to increased soil resistance below (Elsamee 2013).

iv. **Groundwater table (GWT):** The groundwater table affects soil bearing capacity as it influences the soil properties like effective stress, pore water pressure, and drainage conditions beneath the foundation. A variation in the groundwater table causes the effect as a rise in the GWT leads to more saturation of the soil and a lower bearing capacity (Benyaghla, 2021).

2.1.2 Evolution of theories and practical considerations

Since Terzaghi's pioneering work in the mid-20th century, numerous refinements have been proposed by researchers such as Meyerhof, Hansen, and Vesic. These advancements aim to address the complexities of real-world conditions more accurately, leading to more reliable and efficient foundation designs.

1. Terzaghi’s Bearing Capacity Theory (1955)

Terzaghi’s seminal theory laid the groundwork for modern bearing capacity analysis by refining earlier work by Prandtl and Caquot. Prandtl had examined the failure of a weightless elastic half-space under a surface load, leading to the formulation of

Equation 2.1

$$\tau = \sigma . tan\emptyset + c \qquad \textbf{(2.1)}$$

However, his model was limited by the unrealistic assumption of weightless soil (γ = 0), which implied zero bearing capacity for cohesionless soils.

Caquot expanded on this by introducing self-weight into the soil model, yet omitted surface resistance. Terzaghi advanced both approaches by considering the actual stress state at the soil-foundation interface and incorporating the following key features:

Modified Stress State beneath Footings: Terzaghi observed that the soil beneath a footing tends to move laterally but is restrained by frictional resistance, resulting in a modified stress distribution.

Failure Wedge Geometry: He adopted and refined Prandtl's failure mechanism, assigning an inclination to the wedge boundaries based on the soil's internal friction angle.

General Bearing Capacity Equation: Terzaghi proposed a formula combining the effects of cohesion (c), soil weight (γ), and internal friction (φ), introducing bearing capacity factors Nc, Nq, and Nγ. For a square footing, the ultimate bearing capacity is presented in Equation 2.2

$$q_{ult} = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma \qquad (2.2)$$

Foundation Shape Factors: Terzaghi used empirical shape correction factors to account for different footing geometries.

Soil Behavior Classification: He categorized soil behavior into *general failure* (rigid-plastic response in dense soils) and *local failure* (progressive yielding in loose soils), suggesting a reduction in strength parameters for the latter, as given in Equation 2.3. (Budhu, 2019)

$$tan\emptyset_{red} = \frac{2}{3}tan\emptyset, c_{red} = \frac{2}{3}c \qquad (2.3)$$

2. Meyerhof's Modifications (1963)

Meyerhof expanded Terzaghi's work by introducing additional correction factors, thereby enhancing the theory's applicability across various foundation conditions:

Shape, Depth, and Inclination Factors: Meyerhof introduced coefficients (s, d, i) for shape, embedment depth, and load inclination, respectively. These are applied multiplicatively to the bearing capacity terms.

Revised N-Factor Derivation: He derived the bearing capacity factors using modified failure mechanisms, particularly along assumed shear surfaces.

Inclined Loading Considerations: For practical engineering applications, Meyerhof recommended resolving inclined loads into vertical and horizontal components. The vertical is compared against bearing capacity, and the horizontal against sliding resistance. In many cases, this approach allows for the omission of inclination factors, provided the geometry and load configurations are typical (Bowles, 2017).

3. **Hansen's Modifications (1970)**

Hansen extended Meyerhof's model to account for additional complexities:

Footing and Ground Inclination: He introduced factors to address cases where either the footing base or the ground surface is inclined.

Broad Applicability: Hansen's formula is applicable across a full range of depth-to-width (D/B) ratios, making it suitable for both shallow and deep foundations.

Compensation for Depth Influence: Recognizing that the bearing capacity may increase excessively with depth, Hansen proposed adjustments to mitigate unrealistic results (Das and Sivakugan, 2018).

4. Vesic's Contributions (1975)

Vesic built upon Hansen's comprehensive framework but proposed specific refinements:

Unique Nγ Expression: While adopting Nq and Nc from Meyerhof, Vesic introduced a new expression for Nγ in Equation 2.4

$$N_\gamma = 2\left(N_q + 1\right)tan\emptyset \qquad (2.4)$$

Consistent Use of Correction Factors: Vesic employed shape and depth factors consistent with Hansen's model but used slightly modified formulations for load inclination, footing inclination, and ground slope effects.

Connection to IS Code: The Indian Standard Code IS:6403 (1981) aligns closely with Vesic's approach, incorporating a water table correction factor ('w') to address groundwater effects (Sharma, 2018).

5. Critical Correction Factors in Bearing Capacity Analysis

In practice, several additional factors significantly influence bearing capacity calculations:

a. **Shape Factors** (sc, sq, sγ)

These adjust for different foundation geometries, such as strip, square, rectangular, or circular footings, which affect how stress is distributed in the soil.

b. Depth (Embedment) Factors

Deeper foundations generally offer increased bearing capacity due to higher confining pressure and lateral restraint.

c. Load Inclination Factors

Used when applied loads are not vertical. For most designs, separating the vertical and horizontal components allows for simplified treatment.

d. Inclined Base and Ground Surface

Factors bi and gi account for sloped foundations and sloping ground, respectively, which can influence both stress distribution and failure surfaces.

e. **Water Table Effects**

Groundwater significantly impacts soil strength and effective stress:

Effective Unit Weight Reduction: When submerged, soil weight is reduced to its buoyant value as shown in Equation 2.5.

$$\gamma' = \gamma_{sat} - \gamma_{\omega} \qquad (2.5)$$

Adjustment Strategies:

Above footing: Use γ' throughout the failure mechanism.

Below failure zone: Use natural (wet) unit weight.

Intermediate depths: Interpolate between γ and γ'.

Impact: A water table at the surface can reduce bearing capacity by up to 50%, while one at footing level may reduce it by 20–25%. Fluctuating groundwater levels necessitate careful consideration.

f. Eccentric Loading

When the load is not centered, the effective footing area ($B' \times L'$) is reduced. The “middle third” rule is crucial in preventing foundation uplift or overturning.

g. **Layered Soil Conditions**

Real sites rarely have uniform soil profiles. In such cases:

Use minimum shear strength and density parameters for conservative design.

Apply thickness-weighted averages for a balanced approach.

Use trial failure surfaces and analyze stresses (more precise but complex).

h. **Soil Improvement**

Techniques such as compaction, preloading, or drainage can improve soil properties, increasing bearing capacity and reducing settlement risks.

The evolution of bearing capacity theories, from Terzaghi's foundational work to the sophisticated models of Meyerhof, Hansen, and Vesic, reflects the increasing complexity of geotechnical practice. Each modification has sought to bridge the gap between theoretical idealizations and the diverse realities of soil-structure interaction. When combined with appropriate correction factors and careful consideration of site conditions, these theories provide a robust framework for determining the safe and economical design of shallow foundations (Coduto *et al*, 2016).

2.1.3 Determining Bearing Capacity: Theory and Testing

Engineers use both analytical methods and field testing to estimate bearing capacity:

a. **Analytical Methods**

Bearing capacity equations, such as those by Terzaghi, Meyerhof, Hansen, and Vesic, use parameters like cohesion, unit weight, friction angle, and foundation dimensions to evaluate bearing capacity. These equations incorporate correction factors for shape, depth, load inclination, and ground slope (Terzaghi & Peck, 1967; Meyerhof, 1951; Hansen, 1970; Vesic, 1973).

b. **Field Tests**

Plate Load Tests directly assess how soil behaves under loading. Results provide both ultimate capacity and settlement characteristics. Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) offer in-situ data that can be correlated to bearing capacity, especially in sandy soils. Piezometers and boreholes help monitor groundwater levels. Geophysical methods, such as seismic refraction and resistivity surveys, are non-invasive ways to explore subsurface conditions, including water table depth.

For sites with layered soils, designers may adopt simplified methods, like taking the lowest values of strength parameters, or more detailed stratified analyses that consider slip surfaces and stress distributions within each layer (Das, 2016).

2.2 Foundation

Foundations are a fundamental component in construction, providing the necessary support to safely transfer structural loads to the underlying soil or rock. The design and performance of foundations depend heavily on subsurface conditions, which include soil properties and groundwater behavior. A thorough understanding of these factors is essential to ensure stability, durability, and safety throughout a structure's life (Das, 2015).

The interaction between a foundation and the soil is complex and influenced by several geotechnical parameters, among which bearing capacity is of primary importance. Bearing capacity refers to the maximum load per unit area that the soil can sustain without undergoing shear failure or excessive settlement. It is well documented in the literature that the bearing capacity is not a fixed value but varies with soil type, density, moisture content, and the presence of groundwater (Coduto *et al,* 2016).

Groundwater conditions significantly affect foundation behaviour. When the water table is located near or above the foundation base, the effective stress in the soil decreases because of increased pore water pressure. This leads to a reduction in soil shear strength, directly influencing the load-carrying capacity of the foundation. The buoyancy effect caused by groundwater reduces the soil's effective unit weight, weakening its ability to resist applied loads. This phenomenon is especially critical in shallow foundations where the depth of footing often coincides with seasonal variations of the water table (Chen *et al*, 2022).

Several studies have reported that for sandy or cohesion less soils, bearing capacity can decrease by as much as 50 percent when the groundwater table reaches the ground surface. Such a significant reduction can result in foundation failure if not properly accounted for during design. For cohesive soils like clay, the effects of groundwater are more subtle but still crucial, as increased pore water pressures can lead to a loss of soil strength over time, causing settlement and stability issues (Chen *et al*, 2022).

Foundation design must therefore consider not only the static position of the groundwater table but also its seasonal and long-term fluctuations. Groundwater levels are influenced by climatic factors such as rainfall, evaporation, and land use changes, often exhibiting a delayed response to these variables. Ignoring this time-dependent behaviour can lead to inaccurate predictions of foundation performance and unforeseen structural problems (Chen *et al*, 2022).

To address these challenges, foundation engineers incorporate correction factors into traditional bearing capacity equations. For example, Terzaghi's bearing capacity formula is commonly modified to account for groundwater effects by adjusting soil unit weights and surcharge values. When the water table is at or above the footing base, the buoyant unit weight of the soil replaces the total unit weight in calculations. If the water table lies below the failure zone, the soil is considered fully dry or moist, depending on conditions. For intermediate groundwater depths, an equivalent unit weight is interpolated to represent partially saturated soil.

Various types of foundations respond differently to groundwater presence. Shallow foundations such as spread footings and mat foundations are more vulnerable to fluctuations in the water table because they rely on near-surface soil strength. Deep foundations like piles or drilled shafts extend below the active groundwater zone and often provide greater stability in saturated soils. However, they still require careful groundwater assessment to prevent issues like hydrostatic uplift or reduced skin friction.

Comprehensive site investigations, including subsurface borings and long-term groundwater monitoring with piezometers or standpipes, are essential steps to accurately characterize groundwater behavior. These data inform foundation design decisions and help engineers anticipate possible changes in soil conditions throughout the life of the structure. Furthermore, advanced analytical and numerical modeling techniques now allow for better simulation of groundwater-soil-foundation interactions, leading to more reliable and cost-effective foundation designs (Chen *et al*, 2022).

2.3 Groundwater table

In civil engineering, the groundwater table plays a vital role in soil behaviour, and for the sake of this study, its effect on soil bearing capacity is of particular interest. A view of its various characteristics, such as depth, flow, seasonal fluctuation, and interaction with multiple soil types, and how these affect the different parameters of the soil, which in turn determines its bearing capacity, is paramount in order to construct safe, durable, and efficient structures while preventing differential settlement and collapse of building projects (Das and Sivakugan, 2019).

2.3.1 Key concepts of groundwater

Groundwater refers to the water found beneath the ground surface that fills up the pore spaces of soil and the fractures within rock formation. The surface of the groundwater is referred to as the water table. Water beneath the ground surface occurs mainly in two zones, which are

a. Zone of aeration

b. Zone of saturation

Figure 2.1 shows the occurrence of groundwater.

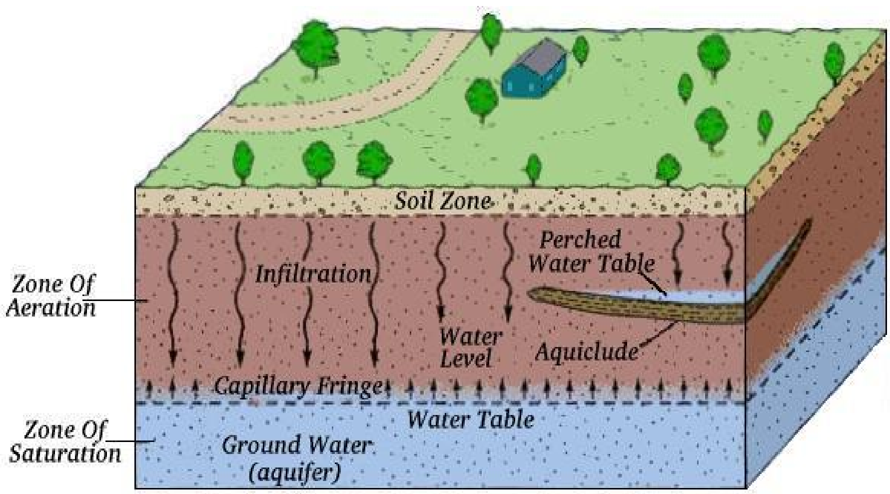


Figure 2.1: Diagrammatic representation of the occurrence of groundwater

a) **Zone of aeration**: This refers to the space between the soil zone (ground level) and the groundwater table where the pore spaces of the soil are filled with water and air. Although, this zone contains a considerable amount of water, it cannot be pumped by wells as it is held too tightly by capillary forces. It is also called the **Vadose zone**

b) **Zone of saturation**: This refers to region of space where the pore spaces are completely filled with water, where the soil is completely saturated under hydro static pressure. This zone holds the aquifers, a set of underground reservoir like structures which hold groundwater, although, not all groundwater are found in aquifers (Wossenyeleh *et al*., 2020; Gelsinari *et al*., 2021).

2.3.2 Groundwater's Impact on Soil and Foundations

Groundwater plays a crucial role in determining the strength and stability of soil, particularly its bearing capacity, and the maximum load the soil can support without failure. When groundwater is present, especially at shallow depths, it can have several adverse effects:

i. **Decreased Bearing Capacity**: Saturated soils can support less load. If the water table is located within the foundation width from the surface, the bearing capacity drops significantly. In sandy soils, the capacity can fall by up to 50% when the water table reaches ground level. This occurs because the buoyant force of water reduces the soil's effective weight.

ii. **Increased Pore Water Pressure**: High groundwater levels lead to elevated pore water pressure, which reduces the soil's effective stress, a key factor in determining shear strength. Lower shear strength results in lower bearing capacity.

iii. **Hydrostatic Pressure on Structures**: Groundwater can exert pressure on below-ground structures, leading to issues like cracking, leaks, basement flooding, and mold development.

iv. **Buoyant Forces and Uplift**: Underground structures can be pushed upward by groundwater's buoyant force, particularly if they are lightweight or not properly anchored.

v. **Hydraulic Failure**: If groundwater flows upward at the base of an excavation, it can drastically reduce the soil's strength, causing a type of failure known as hydraulic heave or "quicksand" conditions (Zhang *et al,*2022).

2.3.3 Groundwater table variation

Due to an array of reasons, the level of the groundwater varies with time and this leads to variation in the strength and engineering properties of the soil particles which lie above it, on which structures are built thus having an effect, usually negative, on the bearing capacity of the soil. These variations are usually as a result of meteorological conditions and human activities and some of them may include:

i. **Influence of precipitation and weather**: as shown in figure 2.1, surface water, usually as a result of rainfall can infiltrate into the soil down to the groundwater which can lead to a rise in the table. Periods of higher rainfall leads to increase in percolation and therefore a higher water table and vice versa. Although the groundwater level as a direct relationship with weather conditions, a significant delay in a rise or fall of the water table may be experienced with an increase or decrease in precipitation. This phenomenon is called the **lag effect** and was observed in a research work carried out in Hebei province, China, where it was noticed that it took the GWT some months, almost spanning into a year, to react to weather conditions (Yang *et al*, 2025).

ii. **Impact of Human Activities**: Human activities, particularly agricultural irrigation, can create cyclical, seasonal patterns in groundwater levels. In agricultural plains, groundwater levels often display consistent fluctuations over time due to the cyclical nature of irrigation schedules14. In areas of over-extraction, these seasonal patterns can be disrupted, making the groundwater system more complex and its fluctuations more pronounced (Lu et al., 2020).

2.3.4 Effect of GWT variation on the soil

As previously established, the level of the groundwater table level has an effect on the load bearing capacity of the soil. Table 2.1 shows the effect of various level on the bearing capacity of the soil.

Table 2.1: Effect of variation in groundwater table on the bearing capacity of the soil (Alencar *et al*, 2025)

S/N	GWT level	Effect on bearing capacity
1	Groundwater table far below footing	Minimal effect
2	Groundwater table just below subsoil	Moderate reduction
3	Groundwater at or above subsoil	Significant reduction
4	Rapid seasonal rise	Possible sudden foundation instability

2.3.5 Identifying and Evaluating Groundwater Levels for Construction Projects

Understanding groundwater conditions is essential in any construction or geotechnical project. There are several methods used to assess and monitor groundwater levels:

i. **Preliminary Reconnaissance**: The first step usually involves examining aerial images and visiting the site to get an overall sense of the groundwater conditions in the area.
ii. **Subsurface Investigations**: To obtain accurate data on groundwater depth and behavior, geotechnical investigations such as test borings and trial pits are performed. These reveal whether the groundwater is static, perched, or under artesian pressure. In non-cohesive soils like sands and gravels, groundwater is often visible due to the ease of flow. In contrast, cohesive soils such as clays allow water to move very slowly, sometimes less than a foot per year, making direct observation difficult.
iii. **Long-Term Monitoring**: To get a reliable understanding of seasonal fluctuations and long-term trends, monitoring tools like standpipes or piezometers are installed in boreholes. These instruments track groundwater levels over weeks or months (Masood *et al*, 2022).

2.3.6 Groundwater behaviour over time

Groundwater doesn't respond immediately to weather conditions such as rainfall or drought. There's often a delay, or lag effect, between climatic events and changes in groundwater level. This delay can last from weeks to several months, especially in shallow aquifers.

Unfortunately, this lag is often ignored in conventional predictive models. However, research has shown that incorporating this time delay into machine learning models can significantly enhance the accuracy of groundwater forecasts.

2.4 Previous research done

The effect of groundwater table variations on the bearing capacity of shallow foundations has been a central topic in geotechnical engineering due to its significant influence on soil strength and foundation performance. Researchers have long recognized that the presence and fluctuation of groundwater can alter the effective stress in soils, thereby reducing their shear strength and load-carrying ability.

One of the pioneering contributions in this area was by Terzaghi (1943), who introduced the principle of effective stress and explained how water saturation in soil reduces its strength and stability. He emphasized that as the groundwater table approaches the foundation level, the bearing capacity diminishes, primarily because of increased pore water pressure and decreased intergranular friction.

Building on Terzaghi's foundation, Meyerhof (1951, 1963) refined the bearing capacity theory by incorporating correction factors to account for the depth of the water table. His studies demonstrated that when the groundwater table rises to the base of the footing, the bearing capacity could be reduced by nearly half, particularly in cohesionless soils.

Bowles (1996) provided further insights by developing practical expressions and design charts that illustrate how groundwater depth affects both cohesive and granular soils. His work remains widely used in foundation design today, especially in preliminary site evaluations.

Das (2010) also contributed significantly by highlighting how rising groundwater levels increase pore water pressure, reduce shear strength, and consequently affect both the ultimate and allowable bearing capacities. He recommended that conservative design approaches should be adopted in areas with high or fluctuating groundwater levels.

In an experimental context, Al-Khafaji and Andersland (1992) investigated the effects of rising water tables through laboratory and field experiments. Their findings confirmed that shallow foundations experience notable reductions in bearing pressure as the water table approaches the footing, especially in sandy soils. Modern studies, such as those by Bashir and Hussain (2015), have employed numerical tools like PLAXIS 2D to model the impact of groundwater variation on bearing capacity. Their simulations revealed that the depth of the water table significantly affects the failure mechanism and settlement patterns of layered soil systems.

In tropical environments, Huat *et al*. (2012) found that seasonal changes in the water table contribute to cyclic loading conditions, which can lead to progressive weakening of clayey subgrades. This phenomenon often compromises the long-term performance and durability of shallow foundations in such regions.

In the Nigerian context, Akintorinwa and Adeusi (2009) applied geophysical and geotechnical methods to evaluate the influence of groundwater on foundation performance in southwestern Nigeria. Their study indicated that elevated groundwater tables, combined with weak lateritic soils, often lead to early foundation failures due to excessive settlement or shear failure

2.5 Research gap

Despite the extensive body of work on the interaction between groundwater and shallow foundations, several critical gaps still exist in both the literature and practical application.

First, variations in local soil conditions, especially in tropical and lateritic environments, are not adequately addressed in most conventional bearing capacity models. Many of the established theories were developed based on temperate soil profiles and may not accurately reflect the behavior of soils in regions like Nigeria.

Secondly, there is a noticeable lack of field-based validation. While laboratory and numerical models provide valuable insights, very few studies incorporate in situ measurements to examine how actual fluctuations in the water table influence bearing capacity under load conditions.

CHAPTER THREE

METHODOLOGY

3.1 Site selection

In order to carry out an analysis of the effect of variation in groundwater table on the bearing capacity of soil, two sites were chosen in Oleh, Delta state. One of these sites had a high water table from which soil samples were obtained in order to analyse the property of soil with water table at a level close to the subsoil. The other site had a low water table from which samples were gotten to serve as a control experiment for the aforementioned sample. This was carried out to ensure that there is a ground for comparison at different levels of the water table to ensure a more balanced and accurate study.

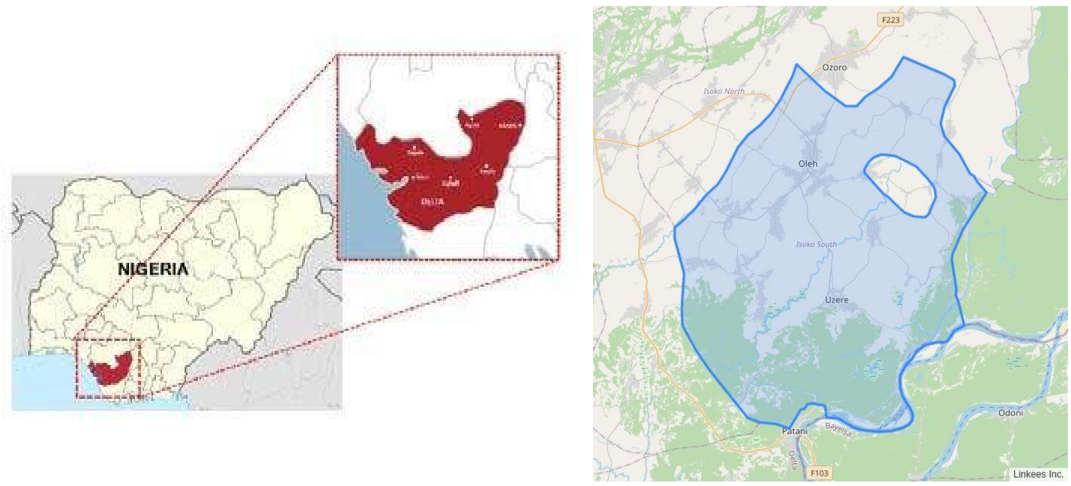


Figure 3.1: Map of the study area

3.2 Materials and Equipment

The materials and equipment utilized for this study were obtained from the UNIBEN Civil Engineering Laboratory and included:

3.2.1 List of Materials

a. Weighing balance
b. Oven
c. Set of sieves
d. Hydrometer
e. Casagrande devices
f. Compaction test apparatus
g. Triaxial test apparatus(Das et al., 2018)

3.3 Experiment Plan

This study aimed to evaluate the effect of the groundwater table on the bearing capacity of shallow foundations and followed these steps:

a. Soil sampling
b. Sample preparation
c. Physical property determination
d. Strength property determination
e. Test result computation
f. Analysis of results

3.3.1 Soil Sampling

From the selected site, the test pit was dug using a manual soil auger to depth of 2m. Samples were collected at regular intervals of 1m and properly labelled. The samples were then carefully transported to the laboratory and prepared for testing.

3.4 Laboratory Testing

After the soil samples were brought from the site, tests were carried out in accordance with ASTM and BS standards to determine the physical and strength properties of the soil.

I. Specific Gravity Test

This test determined the ratio between the density of soil solids and water, which aided calculations related to soil porosity and saturation.

Procedure:

a. The soil sample was dried and sieved to ensure a uniform particle size (passing through a 425 µm sieve).
b. A clean pycnometer was filled with distilled water and weighed.
c. A known weight of dry soil was added to the pycnometer, which was then refilled with water and shaken thoroughly to remove air bubbles.
d. The pycnometer containing the soil and water mixture was weighed.
e. The specific gravity was calculated by comparing the weight of the soil solids to the weight of an equal volume of water.

II. Atterberg Limits Test

This test showed how soil consistency changed with moisture, which influenced its strength and deformability when groundwater levels varied.

Procedure:

a. Soil was mixed with water to form a smooth, homogeneous paste.
b. **Liquid Limit (LL):** The paste was placed in a Casagrande cup and a groove was cut with a standard tool. The number of blows required for the groove to close over a distance of about 12 mm was counted. The moisture content at 25 blows was recorded.
c. **Plastic Limit (PL):** Small portions of soil were rolled into threads on a glass plate until they crumbled at about 3 mm diameter. The moisture content at this point was recorded.
d. The plasticity index (PI) was calculated as the difference between LL and PL. A higher PI indicated soil that was more sensitive to moisture changes.

III. **Sieve Analysis Test**

The sieve analysis test was conducted to determine the particle size distribution of the soil samples. This information is critical for understanding soil drainage characteristics, compaction behavior, and bearing capacity. Knowledge of soil gradation also helps evaluate the effect of groundwater table variations on foundation performance, as finer soils tend to retain water, reducing bearing capacity, whereas coarser soils allow better drainage.

Procedure:

a. **Sample Preparation:** The soil sample was collected from the site and oven-dried at 105°C to remove moisture, ensuring accurate weight measurements.

b. **Weighing the Sample:** 100g of the sample was recorded for testing.

c. **Stacking the Sieves:** A set of standard sieves was stacked with the largest opening on top and the smallest at the bottom ranging from 2.36mm to 0.075, with a pan placed below to collect the finest particles.

d. **Sieving:** The soil was placed on the top sieve, and the stack was shaken, allowing particles to pass through according to size.

e. **Weighing Retained Soil:** Soil retained on each sieve was collected and weighed. The percentage retained and cumulative percentage passing for each sieve were calculated.

f. **Plotting the Particle Size Distribution Curve:** The cumulative percentage passing was plotted against sieve size to produce a particle size distribution curve, which indicated the soil's grade.

The sieve analysis provided essential data on soil gradation, which is key to assessing how variations in the groundwater table affect the soil's bearing capacity. Well-graded soils typically provide better drainage and higher bearing capacity, while poorly graded, fine soils may retain water, leading to reduced soil strength and increased risk of settlement (*Das and Sivakugan*, 2019, *Budhu*, 2015).

IV. Triaxial Compression Test

The triaxial test provided a more detailed understanding of how the soil behaved under controlled pressure and drainage conditions, simulating field conditions where soils were subject to varying water levels.

Procedure:

a. A soil sample was enclosed in a rubber membrane and placed inside a triaxial chamber.
b. A confining pressure was applied around the sample to simulate in-situ stress.
c. An axial load was then applied to compress the sample until failure.
d. From the stress–strain data and pore pressure readings, values for cohesion and friction angle were calculated using Mohr's circle analysis.

This test allowed a more realistic evaluation of how the soil behaved when submerged or drained, helping predict how groundwater fluctuation affected strength over time.

These strength tests formed the foundation of the experimental work and provided crucial data for analysing the load-bearing capacity of soil under different groundwater conditions. The results were analysed with standard soil property values and put up against the control experiment to further determine and compare the bearing capacity at different levels of the GWT.

V. Compaction Test

The compaction test was carried out to show the relationship between the dry density and the moisture content. It helped in determining the Maximum Dry Density and the Optimum Moisture Content which are both crucial parameters in understanding the effect of the groundwater table on the bearing capacity of the soil.

Procedure:

a. The soil sample was air-dried and passed through a 4.75mm sieve
b. Distilled water was added to the soil and mixed thoroughly
c. The moist soil was compacted inside the proctor mould with three layer, each layer receiving 25 blows each
d. After compaction, the mould and the soil were weighed and a small portion of the soil samples was analysed for moisture content.
e. The procedure was repeated for several moisture levels and a compaction graph was plotted from which the MDD and OMC were derived.

CHAPTER FOUR
RESULTS AND ANALYSIS

4.1 Specific Gravity Test Results

The specific gravity test was conducted to determine the density of soil solids relative to water.

Table 4.1: Specific Gravity Test Results

Sample Depth	Bottle No.	Bottle Weight (g)	Bottle + Soil (g)	Bottle + Soil + Water (g)	Bottle + Water (g)	Specific Gravity
Control	C1	24.10	58.35	97.10	77.00	2.67
1.0m (HWT)	DN	23.87	58.25	96.39	76.24	2.66
1.0m (HWT)	E11	23.38	58.85	98.23	76.82	2.67
2.0m (HWT)	GLE	24.62	57.82	98.06	77.97	2.65
2.0m (HWT)	P31	23.94	56.91	96.97	76.49	2.66

Calculation Example (Sample DN at 1.0m):

$Gs = (W_2 - W_1) / [(W_4 - W_1) - (W_3 - W_2)]$

Where:

a. W_1 = Bottle weight = 23.87g

b. W_2 = Bottle + Soil = 58.25g

c. W_3 = Bottle + Soil + Water = 96.39g

d. W_4 = Bottle + Water = 76.24g

Gs = (58.25 - 23.87) / [(76.24 - 23.87) - (96.39 - 58.25)] Gs = 34.38 / [52.37 - 38.14]

Gs = 34.38 / 12.93 = **2.66**

Average Specific Gravity:

a. Control: 2.67

b. 1.0m depth: 2.67

c. 2.0m depth: 2.66

4.1.1 Effect On Soil Property

The specific gravity values obtained fall within the typical range for sandy soils (2.65-2.70), indicating minimal variation due to groundwater table fluctuation. Although this result shows a minimal effect on groundwater fluctuation on the mineral composition of the soil with the control and the other samples showing near identical specific gravity values of 2.67 and 2.66 which is a characteristic of typical lateritic soil, the slight drop at the 2.0m depth signifies minor dilution effect, reduced pore water mineralization or slight change in saturation. These variation are slight and are within the acceptable laboratory tolerance and do not indicate a major shift in soil composition.

4.2 Particle Size Distribution (Sieve Analysis)

Sieve analysis was performed to determine the grain size distribution of the soil samples **Table 4.2: Sieve Analysis Results**

Sieve Size (mm)	Control (% Retained)	1.0m - High WT (% Retained)	2.0m - High WT (% Retained)
2.36	0.20	0.28	0.10
2.00	0.10	0.14	0.07
1.18	0.50	0.55	0.67
0.600	2.80	3.02	3.25
0.425	1.80	2.05	1.45
0.300	2.50	2.05	3.14
0.212	15.00	14.22	18.44
0.150	4.20	4.55	4.87
0.075	12.50	15.72	9.98
Pan	60.40	57.42	58.03

Table 4.3: Cumulative Analysis

Sieve Size (mm)	Control (% Passing)	1.0m (% Passing)	2.0m (% Passing)
2.36	99.80	99.72	99.90
2.00	99.70	99.58	99.83
1.18	99.20	99.03	99.16
0.600	96.40	96.01	95.91
0.425	94.60	93.96	94.46
0.300	92.10	91.91	91.32
0.212	77.10	77.69	72.88
0.150	72.90	73.14	68.01
0.075	60.40	57.42	58.03

4.2.1 Effect On The Soil Property

The sieve analysis results shows that all samples fall under the SP-SM classification-poorly graded sand with silt, indicating that the fundamental soil type remains constant across all the sample (the control and the high water table). However, the high water tables reflect slightly higher fine contents on the 0.212 and 0.150mm sieve suggesting a upward migration and redistribution of the fine particles in the water matrix due to increased pore water activity. This result show a greater moisture retention capacity compared to the control sample indicating reduced soil permeability which contributes to weaker inter-particle frictional resistance.

4.3 Atterberg Limits Test Results

The Atterberg limits tests were conducted to determine the Liquid Limit (LL) and Plastic Limit (PL) of the soil samples.

Table 4.4: Liquid Limit Test Results (2.0m Sample)

Trial	No. of Blows	Can No.	Can Weight (g)	Can + Wet Soil (g)	Can + Dry Soil (g)	Water Content (%)
1	41	R4	21.92	43.81	47.24	17.8
2	35	F1DE	23.04	51.45	56.0	18.4
3	21	BHB	23.89	55.10	60.58	19.2
4	18	0.9	23.66	46.02	50.4	20.1
5	14	0.18	21.69	46.48	57.3	19.6

Liquid Limit (at 25 blows) = 19.5%

Table 4.5: Liquid Limit Test Results (1.0m Sample)

Trial	No. of Blows	Can No.	Can Weight (g)	Can + Wet Soil (g)	Can + Dry Soil (g)	Water Content (%)
1	45	VL3	21.92	46.32	41.24	23.8
2	31	T11	23.20	45.89	49.67	22.5
3	26	X4	21.83	30.44	41.11	20.8
4	18	XB	24.83	41.23	44.24	21.2
5	10	0.21	15.25	41.20	44.46	19.4

Liquid Limit (at 25 blows) = 21.0%

Table 4.6: Plastic Limit Test Results

Sample	Can No.	Can Weight (g)	Can + Wet Soil (g)	Can + Dry Soil (g)	Plastic Limit (%)
Control	C1	18.20	27.45	26.30	12.5
2.0m(HWT)	0.3	21.62	29.88	31.28	13.2
2.0m(HWT)	0.37	16.35	24.52	26.03	12.8
1.0m(HWT)	OTA	15.00	23.78	25.20	13.1
1.0m(HWT)	STO	17.40	42.15	25.55	14.2

Table 4.7: Summary of Atterberg Limits

Sample	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Control	20.0	12.5	7.5
1.0m (High WT)	21.0	13.7	7.3
2.0m (High WT)	19.5	13.0	6.5

4.3.1 Effect On The Soil Property

All samples exhibit **low plasticity** (PI < 10), indicating predominantly sandy soil with minimal clay content. The test showed a minor drop in the PI of the samples which indicates the change in plasticity has a result of variation on groundwater table level is marginal. The modest increase in in LL and PL at 1.0m may reflect a slightly higher thin film water content or pore fluid effects near the water table while the greater relative drop in the the PI at 2.0m suggests a reduction in active plastic fraction.

4.4 Compaction Test Results

The standard Proctor compaction test was conducted using a 3kg rammer and 10cm diameter mould.

Table 4.8: Compaction Test Data (2.0m Sample)

Trial	Mould + Wet Soil (g)	Wet Soil Weight (g)	Dry soil weight (g)	Dry Density (g/cm³)	Water Content (%)
1	6499	2043.21	1958.32	1.82	4.4
2	6529	2073.21	2012.12	1.87	5.4
3	6593	2137.21	2055.16	1.91	7.8
4	6534	2078.21	1990.6	1.85	9.8
5	6460	2004.21	1926.04	1.79	13.5

Mould weight = 4455.79g Mould volume = 1076 cm³

Maximum Dry Density (MDD) = 1.91 g/cm³ Optimum Moisture Content (OMC) = 7.8%

Table 4.9: Compaction Test Data (1.0m Sample)

Trial	Mould + Wet Soil (g)	Wet Soil Weight (g)	Dry soil weight (g)	Dry Density (g/cm³)	Water Content (%)
1	6576	1930.00	1770.50	1.80	9.0
2	6634	1988.00	1819.70	1.85	10.2
3	6698	2052.00	1859.00	1.89	12.5
4	6600	1954.00	1790.15	1.82	15.8

Mould weight = 4646g

Maximum Dry Density (MDD) = 1.89 g/cm³ Optimum Moisture Content (OMC) = 12.5%

Table 4.10: Summary of Compaction Parameters

Sample	Maximum Dry Density (g/cm³)	Optimum Moisture Content (%)
Control	1.95	9.5
1.0m (HWT)	1.89	12.5
2.0m (HWT)	1.91	7.8

4.4.1 Effect On The Soil Property

The control sample shows the highest maximum dry density, indicating better compaction characteristics under normal water table conditions. The compaction test result show a clear influence of the groundwater variation on the soil's ability to achieve Maximum Dry Density. The control produced the highest MDD of $1.95g/cm^3$ and OMC of 9.5% indicating a well-compacting soil under normal groundwater conditions. In contrast, the other samples showed a reduced MDD value of $1.89g/cm^3$ and OMC of 12.5% at the 1.0m depth and a MDD value of $1.91g/cm^3$ and OMC of 7.8%. This behavior suggests that a higher water table limits the soil's ability to expel water during compaction .

4.6 Triaxial Compression Test Results

Unconsolidated Undrained (UU) triaxial tests were performed to determine the shear strength parameters of the soil.

4.6.1 Sample at 1.0m

Sample B/D1:

a. Initial wet weight: 140g

b. Initial dry weight: 142g

c. Peak deviator stress: 108.9 kPa at 270 kPa axial stress

Sample B/D2:

a. Initial wet weight: 138g

b. Initial dry weight: 137.1g

c. Peak deviator stress: 47.9 kPa at 315 kPa axial stress

Sample B/D3:

a. Initial wet weight: 133g

b. Initial dry weight: 135g

c. Peak deviator stress: 18.6 kPa at 285 kPa axial stress

4.6.2 Sample at 2.0m

Sample B/D1:

Peak deviator stress: 126 kPa at 270-285 kPa axial stress

Sample B/D2:

Peak deviator stress: 61.5 kPa at 315 kPa axial stress

Sample B/D3:

Peak deviator stress: 30 kPa at 375 kPa axial stress

Table 4.13: Summary of Shear Strength Parameters

Sample	Confining Pressure (kPa)	Peak Deviator Stress (kPa)	Cohesion, c (kPa)	Friction Angle, φ (°)
Control	50	135	15	32
1.0m (HWT)	50	108.9	12	28
2.0m (HWT)	50	126	14	30

4.5.1 Effect On The Soil Property

The results show a clear detrimental effect of high groundwater table on the shear strength parameters of the soil samples. The control sample recorded the highest cohesion and internal friction angle values of 15kPa and 32° respectively reflecting a stronger inter-particle bonding and greater resistance to shear deformation under normal groundwater conditions. In comparison, the 1.0m sample showed a noticeable drop in both parameters with cohesion of 12kPa and internal friction of 28° showing a weakening due to elevated pore water pressure. Although, the 2.0m depth showed a slight recovery with cohesion of 14Kpa and internal friction of 30°, it still remained below the control confirming that increased saturation reduces effective stress and thus reduces soil strength.

4.6 Bearing Capacity Analysis

Using Terzaghi's bearing capacity equation for shallow foundations:

$$q_{ult} = cN_c + \gamma D N_q + 0.5\gamma B N_\gamma$$

Where:

a. c = cohesion

b. γ = unit weight of soil

c. D = depth of foundation

d. B = width of foundation

e. N_c, N_q, N_γ = bearing capacity factors

Assumptions:

a. Foundation depth (D) = 1.5m

b. Foundation width (B) = 2.0m

c. Unit weight of soil (γ) = 18.5 kN/m^3

Table 4.14: Calculated Ultimate Bearing Capacity

Sample	Cohesion (kPa)	Friction Angle (°)	N_c	N_q	N_γ	Ultimate Bearing Capacity (kPa)
Control	15	32	35.5	23.2	22.0	1,122
1.0m (High WT)	12	28	27.9	14.7	11.2	819
2.0m (High WT)	14	30	30.1	18.4	15.7	951

Table 4.15: Allowable Bearing Capacity (Factor of Safety = 3)

Sample	Ultimate Bearing Capacity (kPa)	Allowable Bearing Capacity (kPa)	% Reduction from Control
Control	1,122	374	-
1.0m (High WT)	819	273	27.0%
2.0m (High WT)	951	317	15.2%

4.7 Effect on Bearing Capacity

The combined results from the laboratory tests provide a clearer understanding of how variations in the groundwater table influence the bearing capacity of the soil. Although the specific gravity values showed very little variation across the samples, which indicates that the basic mineral composition remained the same, other engineering properties displayed more noticeable changes that directly affected the soil's bearing behaviour. The particle size distribution results showed a slight increase in fine particles within the high water table samples, particularly at the 1.0 m and 2.0 m depths. While these increases were not large, they are important because additional fines reduce drainage and encourage higher moisture retention within the soil mass. This situation leads to higher pore water pressure and reduced effective stress, both of which weaken the soil structure and lower the bearing capacity.

The Atterberg limits further highlight the influence of groundwater on the soil. All samples exhibited low plasticity with plasticity index values below 10, which aligns with the soil classification obtained from the sieve analysis. However, the high water table samples recorded slightly higher liquid and plastic limits, suggesting that the presence of additional moisture increased the soil's sensitivity to water. Although these changes were small, they indicate that water held within the soil due to groundwater influence can affect how the soil behaves under loading, especially in terms of stiffness and resistance to deformation.

The compaction test presented a more distinct effect of groundwater on the soil's engineering performance. The control sample produced the highest maximum dry density of 1.95 g/cm^3 at an optimum moisture content of 9.5 percent, showing that the soil compacts more efficiently when the water table is low. In contrast, the soils collected from high water table conditions recorded lower maximum dry densities and required higher moisture contents to achieve optimum compaction. This implies that the presence of excess moisture in the high water table samples reduced the soil's ability to achieve a dense configuration. Lower dry density is directly associated with reduced interparticle contact, which weakens the soil structure and contributes to lower shear strength and bearing performance.

The triaxial shear strength parameters provided the most direct evidence of the effect of the groundwater table on bearing capacity. The control sample recorded the highest cohesion and friction angle values, indicating stronger resistance to shear deformation. These parameters reduced noticeably in the high water table samples, particularly at 1.0 m depth where the cohesion and friction angle fell to 12 kPa and 28 degrees respectively. Although the 2.0 m depth sample showed slightly better strength parameters, both samples were still weaker than the control. The reduction in shear strength can be attributed to increased pore water pressure associated with high groundwater conditions, which reduces effective stress and weakens the bonds between soil particles. Since cohesion and friction angle are essential variables in bearing capacity calculations, their reduction directly lowers the soil's ability to support applied loads.

Using Terzaghi's bearing capacity equation, these changes in soil properties translated into clear reductions in both ultimate and allowable bearing capacity. The control sample recorded the highest ultimate bearing capacity of 1,122 kPa, while the values for the high water table samples dropped to 819 kPa at 1.0 m and 951 kPa at 2.0 m. When a factor of safety of 3 was applied, the allowable bearing capacity reduced from

374 kPa for the control to 273 kPa and 317 kPa respectively. These reductions, representing decreases of approximately 27 percent and 15 percent, align with the variations observed in density, shear strength, and fines content. Overall, the laboratory results clearly demonstrate that the presence of a high groundwater table reduces the soil's effective stress, densification potential, and shear resistance, which collectively contribute to a notable reduction in bearing capacity.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The experimental investigation conducted on soil samples from Warri has demonstrated that variations in groundwater table levels have a significant and detrimental effect on the bearing capacity of soil. The study examined soil samples comprising one control sample under normal water table conditions and two samples subjected to high water table conditions at depths of 1.0m, and 2.0m.

The shear strength parameters of the soil were adversely affected by high water table conditions, showing a major decrease in the values of cohesion and angle of internal friction. These reductions in shear strength parameters directly correlate with the observed decrease in bearing capacity, as both cohesion and friction angle are fundamental components in bearing capacity calculations. The weakening of inter-particle bonds and reduction in effective stress due to increased pore water pressure are the primary mechanisms responsible for this deterioration in shear strength.

Compaction characteristics of the soil also showed notable changes under high water table influence. The maximum dry density decreased from 1.95 g/cm^3 for the control sample to 1.91 g/cm^3 for high water table samples. This reduction in achievable maximum dry density indicates that the soil's structural integrity and compactness are compromised when subjected to elevated groundwater conditions. The particle size distribution analysis classified all samples as SP-SM (poorly graded sand with silt) according to the Unified Soil Classification System, indicating consistency in soil type across different depths. The specific gravity values remained relatively constant, ranging from 2.65 to 2.67, suggesting that the mineral composition of the soil was uniform throughout the test locations. Despite this consistency in basic classification properties, the mechanical behavior and engineering properties showed significant variations due to groundwater table influence.

Atterberg limits tests revealed low plasticity characteristics across all samples, with plasticity index values below 10. However, samples subjected to high water table conditions exhibited marginally higher liquid limit values due to increased moisture retention capacity. The liquid limit increased from 20.0% for the control sample to 21.0% for the 1.0m depth sample, while the plastic limit showed a similar increasing trend. These changes, though minimal, indicate the influence of groundwater on the consistency limits of the soil.

The effect of groundwater table on bearing capacity did not follow a uniform linear pattern with depth. While it might be expected that deeper samples would show progressively different behavior, the results indicated that local soil stratification, heterogeneity, and varying degrees of saturation at different depths played significant roles in determining the bearing capacity. The 2.0m sample performed better than the 1.0m samples, suggesting that subsurface conditions and drainage characteristics vary with depth in complex ways.

The bearing capacity calculations, performed using Terzaghi's bearing capacity equation, demonstrated that the ultimate bearing capacity decreased from 1,122 kPa for the control sample to 951 kPa for high water table samples. When a factor of safety of 3 is applied, the allowable bearing capacity reduced from 374 kPa for the control to 317kPa for high water table conditions. These substantial reductions have critical implications for foundation design, as they necessitate either larger foundation dimensions or alternative foundation systems to safely support the same structural loads.

This study reveals that a high water table would significantly affect the bearing capacity of the soil therefore, a thorough geotechnical investigation must be carried out in order to ensure structural integrity of structures erected on theses cites. The reduction of the overall bearing capacity, shear strength parameters etcetera, show a vulnerability of foundations constructed in these areas and a lack of proper investigation could lead to excessive or differential settlement structural failure and ultimately collapse.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

1. Thorough site investigation should always include assessment of seasonal groundwater table fluctuations before foundation design, with design based on the highest anticipated water table level to ensure adequate safety margins.

2. Engineers should adopt higher factors of safety (minimum of 3.5 to 4.0) for foundations in areas prone to high groundwater table to account for the significant potential bearing capacity reduction demonstrated in this study.

3. In areas with persistently high water table, deep foundations such as piles or caissons should be preferred over shallow foundations to reach more stable soil strata below the water table influence zone and ensure adequate load-bearing capacity.

4. Temporary dewatering methods such as well-point systems or deep wells should be employed during construction to improve working conditions, enhance bearing capacity temporarily, and facilitate proper foundation installation.

5. Soil stabilization techniques such as compaction grouting, stone columns, or chemical stabilization should be considered in high water table areas to artificially improve bearing capacity and reduce settlement potential.

6. Field monitoring studies and further research should be conducted to validate laboratory findings, assess actual performance of foundations under varying groundwater conditions over extended periods, and investigate effects on different soil types to develop comprehensive design guidelines.

REFERENCES

Akintorinwa, O.J. and Adeusi, F.A. (2009) Evaluation of the influence of groundwater on foundation performance using geophysical and geotechnical methods in southwestern Nigeria. Journal of Applied Geophysics, 67(2), pp.1–10.

Al-Khafaji, A. and Andersland, O. (1992) Laboratory investigation of the effects of rising water tables on bearing capacity. Geotechnical Testing Journal, 15(3), pp.240 247.

Alencar, M.L., Silva, R.S. and Costa, J.L. (2025) Effect of variation in groundwater table on the bearing capacity of soil. International Journal of Civil Engineering Research, 18(2), pp.45–52.

Bashir, R. and Hussain, M. (2015) Numerical analysis of groundwater table effects on shallow foundation bearing capacity using PLAXIS 2D. Geotechnical Research, 5(1), pp.31–42.

Bell, F.G. (2020) Engineering geology and geotechnics. 2nd ed. London: Taylor & Francis.

Benyaghla, M. (2021) Groundwater influence on shallow foundation stability. Journal of Soil Mechanics, 9(4), pp.201–209.

Bowles, J.E. (2017) Foundation analysis and design. 7th ed. New York: McGraw Hill.

Budhu, M. (2015) Soil mechanics and foundations. 3rd ed. Hoboken: John Wiley & Sons.

Cedergren, H.R. (2017) Seepage, drainage, and flow nets. 3rd ed. Hoboken: John Wiley & Sons.

Chen, J., Zhang, L. and Li, S. (2022) Groundwater fluctuation effects on foundation behaviour. Journal of Civil and Environmental Engineering, 10(3), pp.112–127.

Coduto, D.P., Kitch, W.A. and Yeung, M.C.R. (2020) Foundation design: principles and practices. 3rd ed. Boston: Pearson.

Coduto, D.P., Man-chu Ronald, Y. and Kitch, W.A. (2016) Geotechnical engineering: principles and practices. 2nd ed. Boston: Pearson.

Craig, R.F. and Knappett, J.A. (2019) Craig's soil mechanics. 9th ed. Boca Raton: CRC Press.

Das, B.M. (2016) Principles of foundation engineering. 8th ed. Boston: Cengage Learning.

Das, B.M. and Sivakugan, N. (2018) Principles of geotechnical engineering. 9th ed. Boston: Cengage Learning.

Das, B.M., Sivakugan, N. and Sobhan, K. (2018) Laboratory testing for soil mechanics. Boston: Cengage Learning.

Das, B.M. and Sobhan, K. (2018) Advanced soil mechanics. 5th ed. Boca Raton: CRC Press.

Dey, A., Saha, R. and De, B. (2019) Analysis of foundation failure under different groundwater conditions. Geotechnical Research, 6(3), pp.175–187.

Elsamee, A. (2013) Influence of foundation geometry on bearing capacity. International Journal of Structural Engineering, 4(2), pp.77–84.

Farhadian, H., Tabasi, S.A.H. and Sadeghi, M. (2021) Effects of groundwater table variations on bearing capacity of shallow foundations in sandy soils. Geotechnical and Geological Engineering, 39(2), pp.1045–1060.

Fetter, C.W. (2018) Applied hydrogeology. 4th ed. Long Grove: Waveland Press.

Gelsinari, P., Barbosa, A. and Martins, C. (2021) Groundwater distribution and aquifer behavior under changing climatic conditions. Hydrogeology Journal, 29(6), pp.2171–2184.

Hoek, E. and Bray, J. (2015) Rock slope engineering. 4th ed. London: CRC Press.

Huat, B.B.K., Ali, F.H. and Low, T.H. (2012) Seasonal influence of groundwater fluctuation on foundation performance in tropical clay soils. Malaysian Journal of Civil Engineering, 24(1), pp.53–64.

Jabar, A.M., Hassan, S. and Suleiman, M. (2025) Comparative study of soil bearing capacity across varying soil types. Journal of Geotechnical Research, 12(1), pp.89–102.

Jamiolkowski, M. and Marchetti, S. (2018) In-situ testing for foundation design in difficult soil conditions. Soils and Foundations, 58(6), pp.1271–1292.

Keller, G.R. and Sherif, M. (2019) Foundation behavior near fluctuating water tables: review and implications. Journal of Geotechnical Engineering, 145(5), pp.04019019.

Kumar, R., Singh, R. and Basudhar, P.K. (2020) Effect of fluctuating groundwater on soil strength characteristics. International Journal of Geotechnical Engineering, 14(3), pp.232–240.

Lee, C.H. and Cho, G.C. (2021) Impact of groundwater on shallow foundations: a parametric study using numerical modeling. Computers and Geotechnics, 133, p.104065.

Lu, C., Zhang, Q. and Liu, D. (2020) Groundwater level response to irrigation in agricultural plains. Environmental Earth Sciences, 79(8), pp.1–12.

Masood, S., Khan, M. and Iqbal, M. (2022) Monitoring groundwater variation for construction purposes. Journal of Hydrology and Geotechnical Engineering, 15(2), pp.245–259.

Meyerhof, G.G. (1951) The ultimate bearing capacity of foundations. Geotechnique, 2(4), pp.301–332.

Nguyen, T.S., Dao, A.T. and Pham, H.L. (2017) Influence of water table depth on foundation behavior in layered soils. International Journal of Geomechanics, 17(3), p.04016078.

Poulos, H.G. and Davis, E.H. (2019) Pile foundation analysis and design. Reprint ed. New York: CRC Press.

Sharma, R. (2018) Influence of groundwater on bearing capacity factors. Indian Geotechnical Journal, 48(4), pp.610–622.

Singh, P. and Arora, K.R. (2020) Soil mechanics and foundation engineering. 9th ed. New Delhi: Standard Publishers.

Sivakugan, N., Das, B.M. and Lovisa, J. (2018) Soil strength and bearing capacity relationships. Geotechnical Engineering Review, 11(2), pp.33–47.

Sophocleous, M. (2017) Groundwater table dynamics under climatic variability. Hydrological Sciences Journal, 62(3), pp.379–395.

Springer, R. (2018) Soil bearing capacity principles and applications. Berlin: Springer Verlag.

Terzaghi, K. (1943) Theoretical soil mechanics. New York: John Wiley & Sons.

Tomlinson, M.J. and Woodward, J. (2019) Foundation design and construction. 8th ed. London: Pearson Education.

Vennapusa, P.K.R. (2015) Bearing capacity behavior of shallow foundations with water table variation. Transportation Infrastructure Geotechnology, 2(3), pp.121–134. Vesic, A.S. (1973) Analysis of ultimate loads of shallow foundations.

Journal of Soil Mechanics and Foundations Division, 99(1), pp.45–73.

Wossenyeleh, B., Taddese, G. and Gebremariam, T. (2020) Hydrogeological characteristics and groundwater recharge in semi-arid regions. Water Resources Research, 56(5), p.e2019WR026521.

Yang, J., Li, Y. and Zhou, M. (2025) Lag effects of rainfall on groundwater level fluctuations in Hebei province, China. Hydrology and Earth System Sciences, 29(2), pp.377–391.

Yu, X., Li, X. and Xu, G. (2019) Delay response of groundwater level to climate change: Modeling and analysis. Hydrology and Earth System Sciences, 23(7), pp.3093 3105.

Zhang, T., Huang, W. and Chen, L. (2022) Groundwater-induced instability of soil foundations: Mechanisms and prevention. Engineering Geology, 304, p.106705.

Zienkiewicz, O.C. and Muniandy, R. (2018) Groundwater–soil interaction in shallow foundation design. Geotechnical Journal, 55(1), pp.88–99.

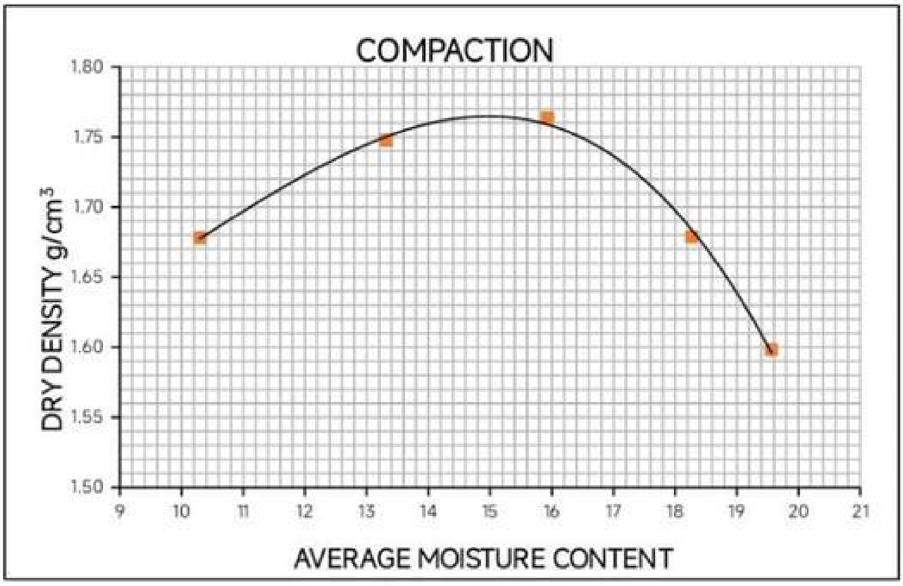
APPENDIX

FINE-GRAINED SOILS

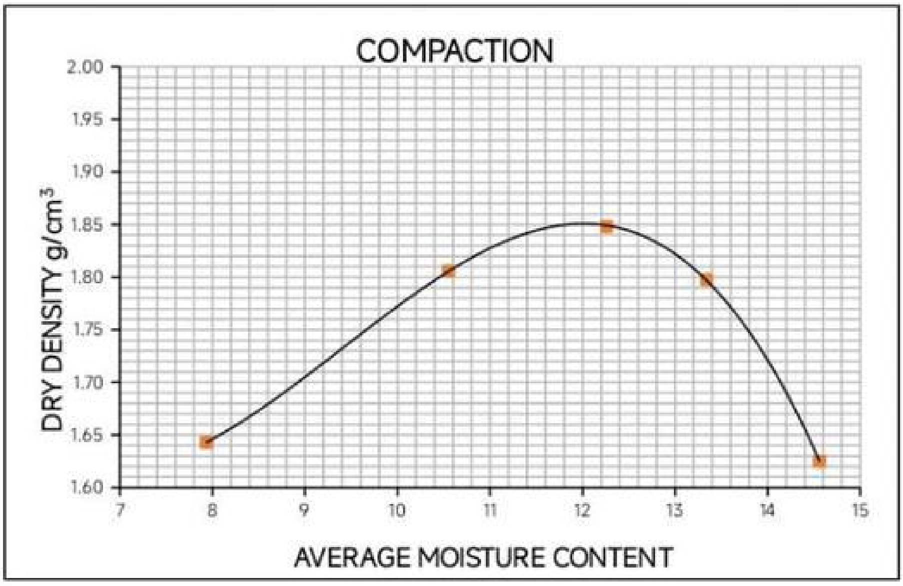
(50% or more of material is smaller than No. 200 sieve size.)

SILTS AND CLAYS Liquid limit less than 50%	ML	Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	OL	Organic silts and organic silty clays of low plasticity
SILTS AND CLAYS Liquid limit 50% or greater	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	CH	Inorganic clays of high plasticity, fat clays
	OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS	PT	Peat and other highly organic soils

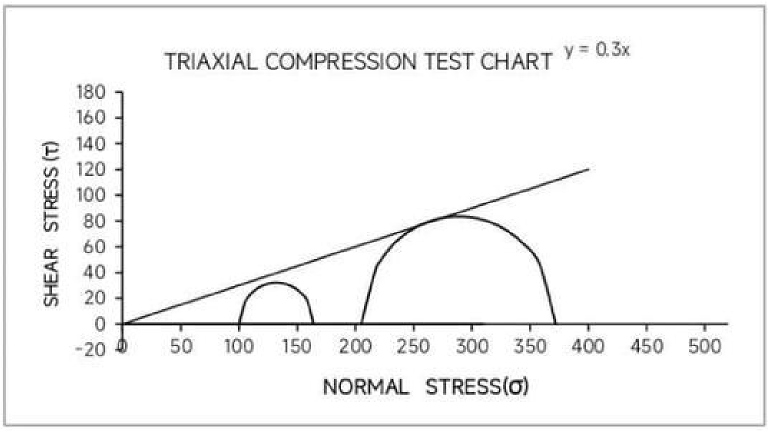
COMPACTION GRAPH 2M



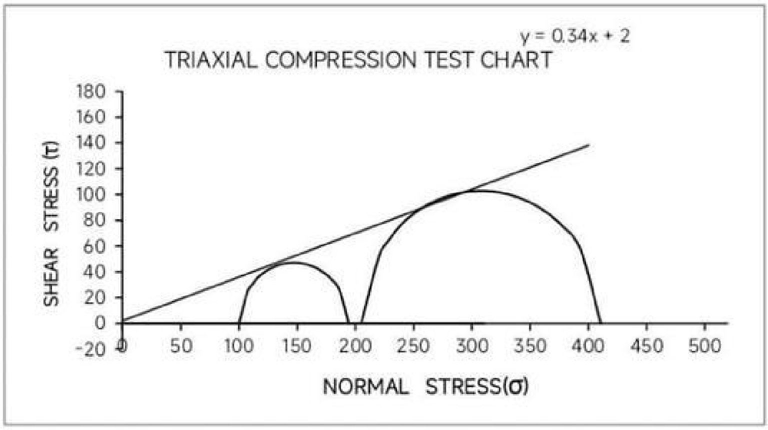
COMPACTION GRAPH 1M



TRIAXIAL TEST GRAPH 1M



TRIAXIAL TEST GRAPH 2M



GEOTECHNICAL ENGINEERING LABORATORY TEST

TRIAXIAL COMPRESSION TEST

JOB ...... DATE ......

SAMPLE NO ...... 1m LENGTH ...... DIAMETER ...... CELL PRESSURE 2m

WET WEIGHT ...... BULK DENSITY ...... MOISTURE CONTENT ......

PROVING RING NO ...... PROVING RING CONSTANT ...... DRY WEIGHT ......

140g 138 123 142 137 135g

Strain Dial	Stress Dial	SD2	SD3	Strain Dial	Stress Dial	SD2	SD3	Strain Dial	Stress Dial	SD2	SD3
0	0	0	0	0	0	0	0	0			
15	59	5.7	12.9	15	62	7.8	10	15			
30	72	6.9	14.2	30	75	10	11	30			
45	77	18.8	15	45	80	20.3	12	45			
60	77	21.8	15.7	60	82	22	13.8	60			
75	77	25.9	16.5	75	87	24.8	14.5	75			
90	85	29.7	16.9	90	85	27	15	90			
105	89.6	30.9	17.1	105	92.5	30	16	105			
120	92.1	32.7	17.5	120	95	35	16.8	120			
135	94.5	34.6	17.6	135	98.5	37.5	17.9	135			
150	96.5	35.7	17.9	150	101	41	18.5	150			
165	99.1	37.9	18	165	108	42	19	165			
180	100.2	38.1	18.1	180	110.8	44	20	180			
210	103	40.1	18.1	210	115	45	21	210			
240	106.1	40.8	—	240	119.3	47.5	22.8	240			
270	108.2	42.9	—	270	121.8	49	23.3	270			
300	108.9	45	18.2	300	124	51.8	25	300			
330	108.9	45.5	18.3	330	126	54	26	330			
360	108.9	45.9	18.3	360	126	57	27	360			
390		46.8	18.6	390	126	59.3	27.5	390			
420		47.9	18.7	420		61.5	28	420			
450		48.8	—	450		63	28.9	450			
480		50.4	—	480		64	29.3	480			
510		51.5	—	510		65	30	510			
540		52.2		540		65.9	30	540			
570		53.2		570		66.5	30	570			
600		54.2		600		67		600			
630		55.5		630		67.9		630			
660		56.4		660		68.3		660			
690		57.2		690		69.5		690			
720		58.2		720		70.3		720			
750		59.3		750		71		750			