TÜRKİYE
FIRAT UNİVERSİTY
GRADUATE SCHOOL OF NATURAL AND APPLİED SCİENCES

DETERMINING THE DIFFERENCES IN LOAD-SETTLEMENT BEHAVIOR OF OPEN-ENDED AND CLOSED-ENDED PILES

Awara Hussein IBRAHIM

Master's Thesis

DEPARTMENT OFCIVIL ENGINEERING

Division of Geotechnic

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THESİS APPROVAL

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DECLARATION

I hereby declare that I wrote this Master's Thesistitled " Determining the Differences in Load-Settlement Behavior of Open-Ended and Closed-Ended Piles " in consistent with the thesis writing guide of the Graduate School of Natural and Applied Sciences, Firat University. I also declare that all information in it is correct, that I acted according to scientific ethics in producing and presenting the findings, cited all the references I used, express all institutions or organizations or persons who supported the thesis financially. I have never used the data and information I provide here in order to get a degree in any way.

16 August 2021

Awara Hussein IBRAHIM

PREFACE

Foundation is the lowest part of the building or the civil structure that is in direct contact with the soil which transfers loads from the structure to the soil safely. In the earlier projects which had few floors and small apartments usually used shallow foundations because it's weight are not heavy, but after heavy structures and big towers appeared which shallow foundations are not enough to support them they need stronger foundations to contain the structure weights safely, in that case, deep foundations must be used. Pile foundation is the most common type of deep foundation which can take the whole large and complex structures like skyscrapers, offshore and onshore.

Pile foundation, is a type of deep foundation, is a thin column or long cylinder composed of materials such as concrete or steel that is used to support the structure and transfer the load at the desired depth by end bearing or skin friction. In this research open-ended and closed-ended steel pipe piles were used, and several experimental works were done to determining the differences in load-settlement behavior of two used piles.

Alhamdulillah, all praises to Allah for giving me the opportunity, determination, strengths, and his blessing in completing this research. His continuous grace and mercy were with me throughout my life and ever more during the tenure of my research. I would like to express my heartfelt gratitude to my boss, Assoc. Prof. Dr. H. Suha AKSOY, for the guidance, support, and advice he has given as his student during my study. I was incredibly grateful to have a supervisor who cared so much about my job and replied so quickly to my questions and queries. The purpose of this research would not have been realized without his continuous support. Finally, my profound and sincere gratitude to my parents for their affection, aid, and encouragement, constant and unparalleled. As a friend, I am thankful to my wife for always being there for me. Forgiving me the opportunities and experiences that have made me who I am, I am forever indebted to my parents. They kept me moving on and, without their input, this study would not have been possible.

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Piles are long, slender members that transfer load from shallow soil with a low bearing capacity to deeper soil or rock which have less compressibility and higher bearing capacity. There are two types of pipe piles: open-ended and closed-ended. It is well known that open-ended piles behave differently than closed-ended piles.

The aim of this study is to investigate the difference in load-settlement behavior of open-ended and closed-ended steel pipe piles in the sand under axial loading in four different relative densities including 10%, 40%, 65%, and 90%. It is also aimed to study the ultimate bearing capacity for the same piles. For this purpose, model experiments and numerical analyses were carried out. The finite element method was also used in this research to study the behavior of the single model piles under axial loading.

The obtained results show that the closed-ended piles have a higher ultimate bearing capacity than open-ended piles. For open-ended piles, the development of ultimate bearing capacity is due to the increased exterior shaft friction and soil plug inside the pile.

Also, the results from experimental pile model tests and finite element analyses indicated that the ultimate bearing capacity of the model piles increases with increasing relative density. There is a good agreement between experimental results and finite element programs results.

Keywords: Sand, Open-ended steel pile, Close-ended steel pile, Pile bearing capacity, Finite element method.

ÖZET

Determining the Differences in Load-Settlement Behavior of Open-Ended and Closed-Ended Piles

Awara Hussein IBRAHIM

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Kazıklar, yükleri düşük taşıma kapasiteli sığ zeminden, sıkışabilirliği daha düşük olan ve daha yüksek taşıma kapasitesine sahip derin zemin tabakalarına veya kayaya aktaran uzun, narin elemanlardır. Açık uçlu ve kapalı uçlu olmak üzere iki tip boru kazık vardır. Açık uçlu kazıkların kapalı uçlu kazıklardan farklı davrandığı bilinmektedir.

Bu çalışmanın amacı, %10, %40, %65 ve %90 olmak üzere dört farklı rölatif sıkılıkta hazırlanmış kum zemin içerisinde eksenel yükleme altındaki açık uçlu ve kapalı uçlu çelik boru kazıkların yük-oturma davranışlarındaki farkı araştırmaktır. Aynı kazıklar için nihai taşıma kapasitesinin de incelenmesi amaçlanmaktadır. Bu amaçla model deneyleri ve sayısal analizler yapılmıştır. Bu araştırmada, tekil model kazıkların eksenel yükleme altındaki davranışını incelemek için sonlu elemanlar yöntemi de kullanılmıştır.

Elde edilen sonuçlar, kapalı uçlu kazıkların, açık uçlu kazıklardan daha yüksek nihai taşıma kapasitesine sahip olduğunu göstermektedir. Açık uçlu kazıklar için, nihai taşıma kapasitesinin gelişimi, artan dış şaft sürtünmesinden ve kazık içindeki zemin tıkacından kaynaklanmaktadır.

Ayrıca, deneysel kazık model testleri ve sonlu elemanlar analizlerinden elde edilen sonuçlar, artan rölatif sıkılık ile model kazıkların nihai taşıma kapasitesinin arttığını göstermiştir. Deneysel sonuçlar ile sonlu elemanlar programı sonuçları arasında iyi bir uyum olduğu belirlenmiştir.

Anahtar Kelimeler: Kum, Açık uçlu çelik kazık, Kapalı uçlu çelik kazık, Kazık taşıma kapasitesi, Sonlu elemanlar yöntemi

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Symbols and Abbreviations

Symbols

δ : Pile-soil Interface Friction Angle

φ : Internal Friction Angle

p-y : Load-Displacement

D_r : Relative Density

Q_u : Ultimate Bearing Capacity of Pile

Q_p : Pile Point or End-Bearing Capacity of Pile

Q_f : Shaft Friction Resistance, or Skin Friction Resistance of Pile

A_p : Pile Point Area

q : Mean Overburden Pressure at the Pile Toe

N_q : Bearing Capacity Factor

γ : Soil Unit Weight

B : Least or Short Dimension of Pile (Pile Diameter)

N_γ : Bearing Capacity Factor

S_γ : Shape Factor

$K_{p\gamma}$: Terzaghi's Coefficient of Passive Earth Pressure

d_c : Depth Factor

N_c : Bearing Capacity Factor

S_q : Shape Factor

d_q : Depth Factor

d_γ : Depth Factor

L_b : Embedment Depth of Pile

D' : Pile Diameter

L : Pile Length

K_p : Coefficient of Passive Earth Pressure

D'' : Embedment Depth of Pile

B'' : Short Dimension of Pile

L'' : Long Dimension of Pile

Nq^* : Bearing Capacity Factor

Pa : Atmospheric Pressure (100 kN/m2)

η : Surface Angle in Radian at Pile Toe

σ_0^{-1} : Mean Effective Soil stress at the Pile Toe

N^*_σ : Vesic's Bearing Capacity Factor

Ko : Coefficient of Lateral Earth Pressure at Rest

B' : Least Dimension of Pile (Pile Diameter)

$N^`_q$: Bearing Capacity Factor

f : Unit Skin Friction Resistance

K : Coefficient of Lateral Earth Pressure

σ'_0 : Mean Effective Vertical Pressure at the Desired Depth

p : Pile Circumference or Pile Perimeter

L' : Critical Pile Embedment Length ≤ 15D

D : Pile Diameter

D_{tank} : Diameter or Short Dimension of Model Tank

D_{pile} : Diameter of Pile

γ_d : Dry Unit Weight

e : Void Ratio

G_s : Specific Gravity

$\gamma_{d\ min}$: Minimum Dry Unit Weight

$\gamma_{d\ max}$: Maximum Dry Unit Weight

e_{min} : Minimum Void Ratio

e_{max} : Maximum Void Ratio

D_{max} : Maximum Grain Size

D_{min} : Minimum Grain Size

D_{10} : 10% of the Sand Particles are Finer than this Size

D_{30} : 30% of the Sand Particles are Finer than this Size

D_{60} : 60% of the Sand Particles are Finer than this Size

Cu : Uniformity Coefficient

Cc : Coefficient of Curvature

$\sigma'\upsilon$: Effective overburden pressure at any depth

δ' : Effective skin friction angle between soil and pile material

f_s : Skin friction

Qf : Pile shaft friction

ψ : Angle of dilatancy of model sand

R_a : Arithmetical mean roughness

R_p : Maximum peak height

R_v : Maximum valley depth

R_z : Linear distance between the top of peak and base of the valley

Abbreviations

pH : Degree of acidity or alkalinity

FRP : Fiber Reinforced Polymer

SRP : Structurally Reinforced Plastic

FHWA : Federal Highway Administration

HDPE : High-Density Polyethylene

PVC : Polyvinyl Chloride

C: Cohesion

MDPE : Medium-Density Polyethylene

D_{50} : Soil Particle Mean Size

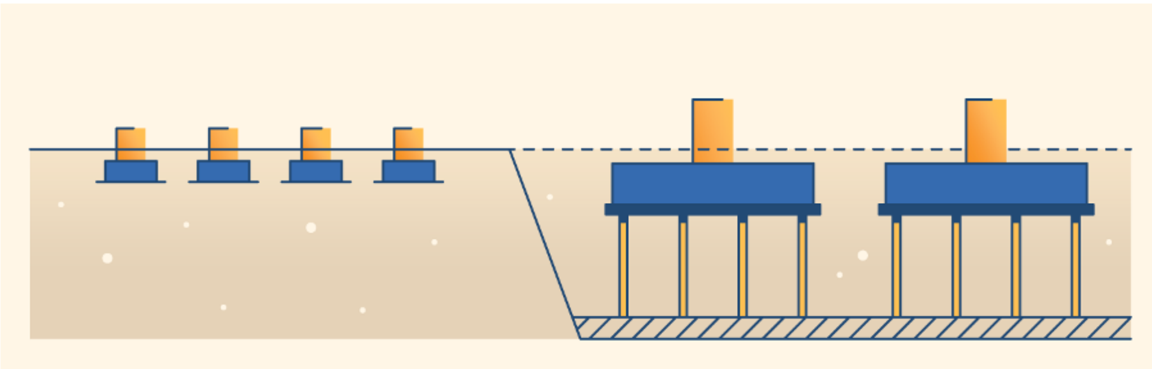
GFRP : Glass Fiber Reinforced Polymer
UV : Ultraviolet
SPT : Standard Penetration Test
CPT : Cone Penetration Test
RPP_s : Recycled Plastic Piles
SED : Strain Energy Density
UPVC : Unplasticized Polyvinyl Chloride
LVDT : Linear Variable Displacement Transducer
ASTM : American Society for Testing and Materials
DSB : Direct Shear Box
IFR : Incremental Filling Ratio
USCS : Unified Soil Classification System
API : American Petroleum Institute

1. INTRODUCTION

Foundations provide structural support and load transfer to the soil from the structure. However, the layer through that the load is transported from the foundation must have sufficient settlement characteristics and bearing capacity. Generally, foundations have several types, choosing any of them depending on many considerations such as:

- Total load from the superstructure.
- Soil conditions.
- Water level.
- Noise and vibration sensitivity.
- Available resources.
- Time-frame of the project.
- Cost.

Generally, foundations are classified into two main parts shallow foundations and deep foundations. When the surface soil bearing capacity is adequate to carry the loads enforced by a structure usually used shallow footings. On the other hand, when the bearing capacity of the surface soil is insufficient to carry the loads that a structure imposes deep foundations are used. As a result, where the bearing capacity of the soil layer is greater, the loads must be shifted to a deeper level, as cleared in (Figure 1.1.).



(a) (b)

Figure 1.1. Types of foundation, (a) shallow foundation, and (b) deep foundation

The earlier projects which had few floors and small apartments usually used shallow foundations because it's weight are not heavy and they were constructed as a horizontal building, but after heavy structures and big towers which constructed vertically (multi-storage buildings) appeared which shallow foundations are not enough to support them. They need stronger foundations to contain the structure weights safely, in that case, the researchers and engineers looked for a new type of foundation, they suggest deep foundations. The two most typical reasons for using a deep foundation are very large design loads (such as those associated with a skyscraper) or poor shallow soils which are unsuitable for construction. Some deep foundations are drilled into the ground while others are excavated and drilled into position. For thousands of years, engineers have understood the need of constructing on a stable foundation. More than two thousand years ago timber piles (deep foundation) were used by Romans in bridge construction. The massive majority of structures are made up of two main parts: a superstructure that is above ground level and a foundation that is below ground level, (Figure 1.2.) shows the foundation classification.

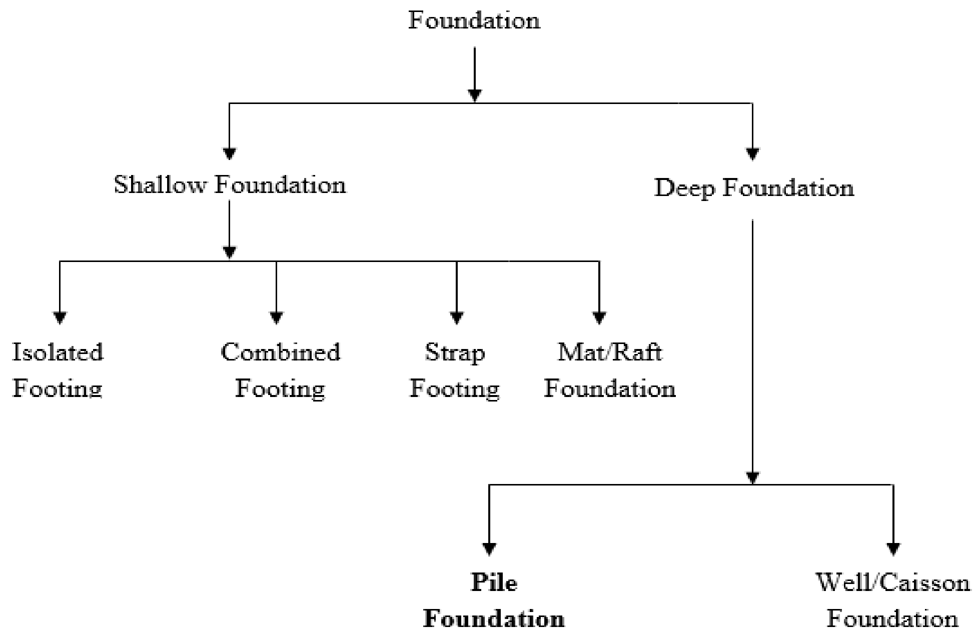


Figure 1.2. Foundation classification

The foundation is built at the base of any structure to carry out and satisfy the following significant purposes.

- The most basic function is to carry the entire structure's weight.
- While nature's forces inflict damage, a solid and strong foundation holds the building standing. During natural disasters like floods, earthquakes, and strong winds, well-built foundations keep the building's residents safe.
- The base must be constructed in such a way that ground moisture does not seep in and weaken the structure.

A deep foundation is one in which the width of the footing is smaller than or equal to the depth of the footing in any structure. A deep foundation is used, when the soil's bearing capacity is very low. The load is transferred vertically from the superstructure to the soil. Deep foundations can be divided into three categories, which is pile foundations, caisson foundations, and well foundations.

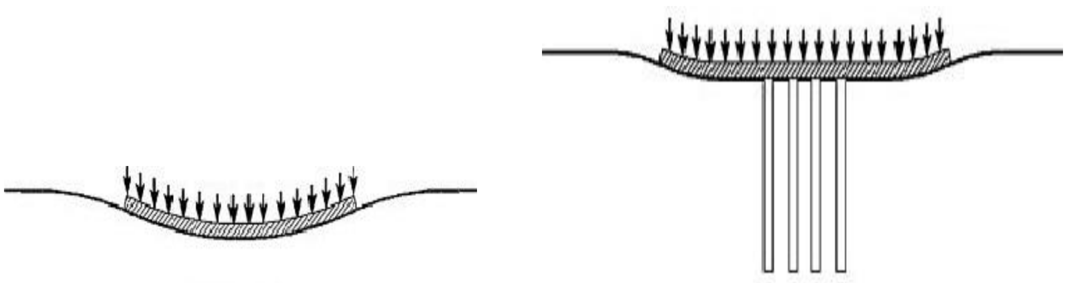
1.1. General Explanation of Piles

Piles are slender columns or long cylinders made of materials such as Steel, Timber, Plastic, Concrete, and Composite piles as shown in (Figure 1.3.), that are used in deep foundations to care the structure and move the load at the desired depth through end-bearing or skin friction. With raft foundations, piles can be used to provide suitable bearing capacity or to decrease settlements to an acceptable level. The most popular piled raft design assumes that the entire load of the superstructure will carry by the piles, ignoring the raft's bearing contribution.

Figure 1.3. Types of piles based on shape and composition

Pile foundations are principally used to transport loads from superstructures to deeper layers of soil or rock that are heavier, stiffer, less compressible, and more compact, thereby increasing the effective size of a foundation and attacking horizontal loads.

The basic idea behind this method is that the foundation consists of only a few piles that are required to keep settlements to a minimum, and the loads from the structure are transmitted through the piles, part to the piles, part to the foundation soil through a raft (load shared between the raft and piles). This method allows for the optimization of the piled raft configuration and a major reduction in the number of piles. (Figure 1.4.) Shows graphically the principles behind the design of piles to decrease differential settlement.



(a) (b)

Figure 1.4. The principles behind the design of piles and rafts, (a) unpiled raft, and (b) raft with settlement reducing piles

Until the early 1900s, a pile was a straight log of timber approximately its diameters were 300mm and 10m or so long that was hammered into the ground. Pile foundations have become much more communal than any other type of deep foundation in recent years. The pile foundations must be used in a location that meets the following requirements:

- The soil layers beneath the foundations are weak and compressible.
- The structure loads are very high and the load distribution on the soil is irregular.
- The water table beneath the soils under the structure is very high and may affect the foundations easily.
- Due to the heavy inflow of capillary water or seepage, keeping foundation trenches dry by pumping is extremely difficult.
- When the structures located on or near the river bed or the sea-shore and foundations are responsible to be scoured due to the water action.
- In inclined places and places where soils are erosions.
- Where expansive soils and horizontal forces are present.
- In piers, docks, and other marine structures construction.
- Using other types of foundations is impossible and it has a high cost.

Pile foundations are made up of two parts: a pile cap and single or group piles. Depending on the specifications, piles may be made of concrete, wood, or steel. The piles are then driven, bored, or jacked into the ground, and the pile caps are attached. The material used to construct the piles, the soil types, and the load-transmitting characteristics of the piles can all be used to classify pile foundations. (Figure1.5.) Shows pile parts. The most common reasons for employing piles are large constructions and conditions where the soil is unsuitable for preventing excessive settling.

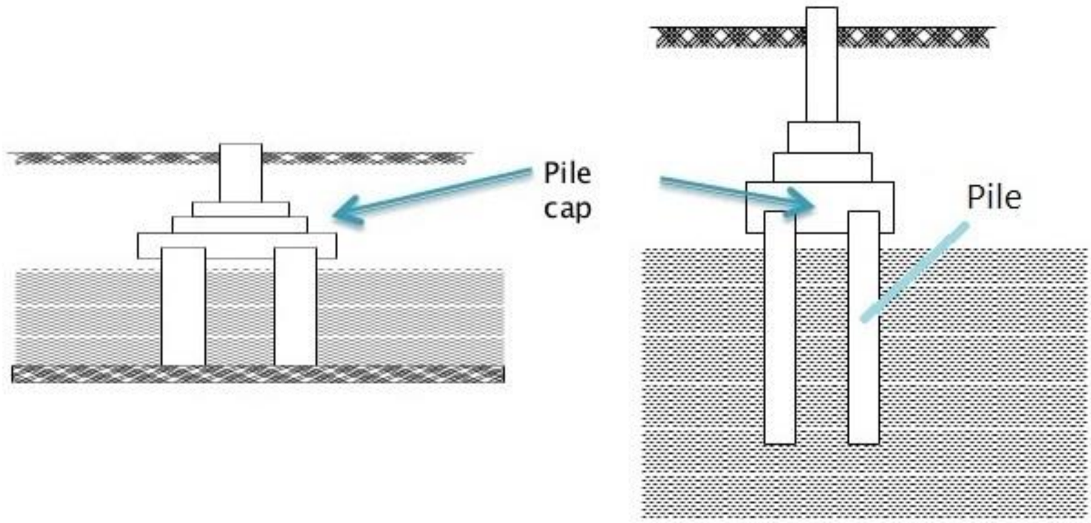


Figure 1.5. The pile parts

As pile foundations carry many loads, therefore it must be considered very carefully. A qualified engineer will examine the soil in which the piles are set to ensure that it is not overloaded beyond its bearing capacity. When a foundation depth greater than three times its width then the foundation is described as 'piled'. Pile foundations are naturally used for large constructions and in cases where the shallow depth soil is inadequate to resist excessive settlement, uplift, and other problems.

On the surrounding soils, every pile has an impact zone. It's critical to spread the piles far sufficient apart so that the loads are well disseminated throughout the soil bulb that bears them, rather than crowded in a few places. The main purposes of pile foundations are as follows:

- Carry vertical compressive loads.
- Carry tensile or uplift forces.
- Resist horizontal or inclined loads.
- End bearing or compressive strength.
- Scour depth: Construct the foundation within the scour depth and through the waterway bed to build a construction within the water river or canal bed.
- Tension or uplift: The thrust of wind on a tower holding high-power transportation lines may cause overturning, which must be attacked by tension piles, other possibilities contain a deep foundation or a heavy raft, both of which are occasionally uneconomical.
- Vibration control: The base of structures supporting vibrating machinery such as turbines and silos, where the vibrations are important and can cause failures, there are two choices for absorbing vibrations: use a giant block or utilize deep foundations, however, the massive block is more expensive.
- Compaction piles: piles that are driven into weaker layers of soil to raise the soil bearing capacity called compaction piles. Using compaction piles can thereby increase the soil bearing capacity.
- Rapid construction: when time is of the essence, deep foundations and particularly piles are a great way to deal with or avoid any problem relating to the soil. They're easy to put together and don't take long to build.

1.2. Types of Piles

Based on different criteria, piles can be classified in several ways:

- Action or function,
- Composition and material, and
- Installation.

(Figure 1.6.) Below representing pile foundation types discussed above.

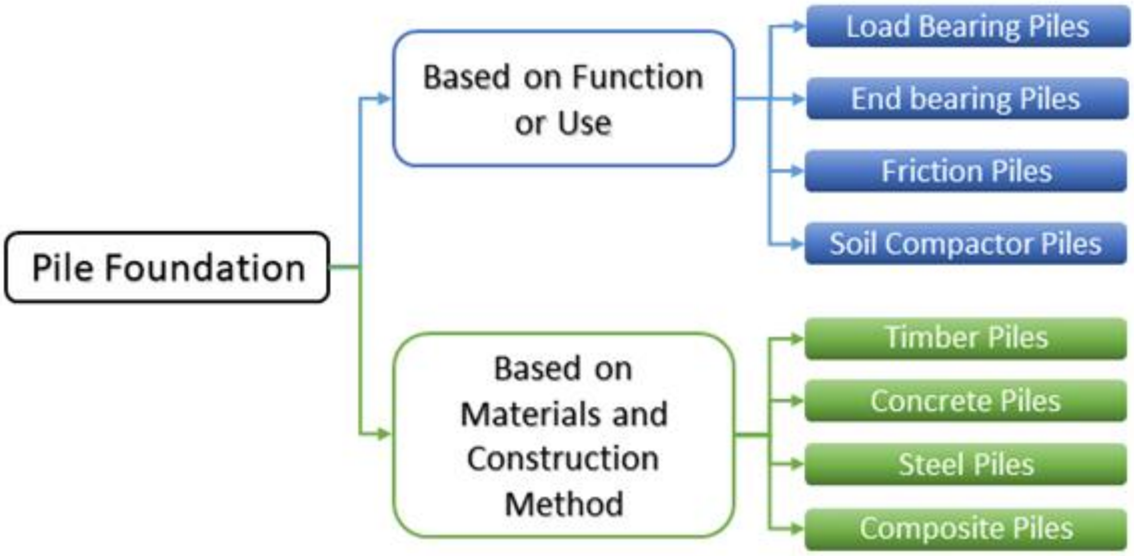


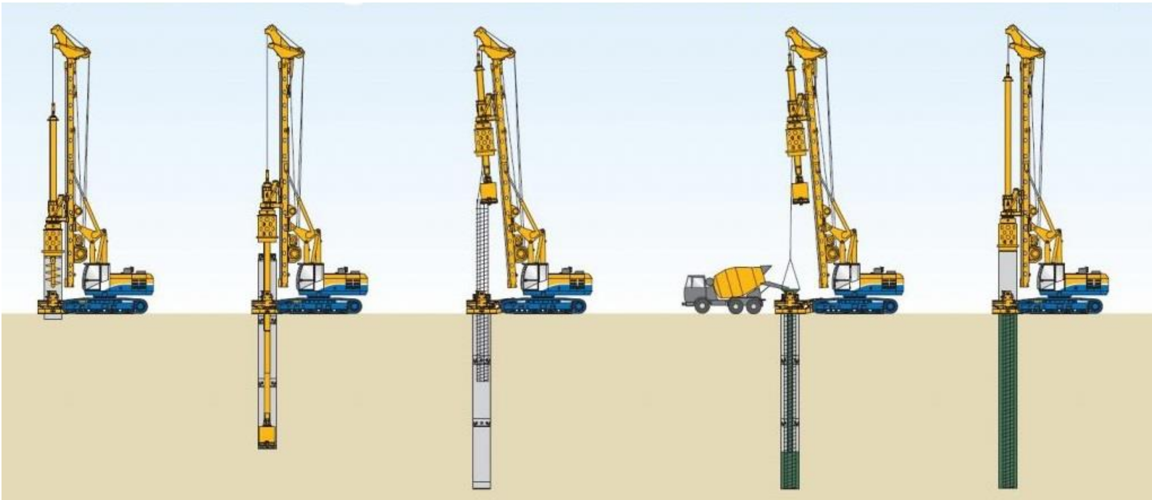
Figure 1.6. Pile classifications

Piles are structural elements, and there are a variety of pile machinery available, each of which is best suitable to specific situations. The widest pile types which are mostly used based on methods of installation are:

1.2.1. Driven piles

A driven pile is the earliest type of deep foundation, which is made up of a long, narrow manufactured structural member that is vibrated or pushed into the ground. Also called displacement piles, these are a common type of foundation that provisions structures by transporting their load to soil strata or rock that have sufficient bearing capacity and appropriate settling features.

The most cost-effective deep foundation solution is driven piles, which are commonly used to support structures, tanks, towers, walls, and bridges. Embankments, retaining walls, bulkheads, and cofferdams are all examples of where driven piles can be found. Driven piles are highly compliant, and they can be used to sustain compression, friction, or lateral loads, depending on the structure's needs, budget, and soil conditions. (Figure 1.7.) Shows the driven pile installation:



(a) (b) (c) (d) (e)

Figure 1.7. Installation of Driven Piles step by step, (a) cassing installation, (b) drilling, (c) installation reinforcement, (d) pouring concrete, and (e) extracting the casing [1]

1.2.2. Continuous flight auger piles (CFA)

Continuous flight auger (CFA) piles are a form of augur cast-in-place replacement pile. The high-specific, instrumented rigs drill and concrete the piles in one continuous operation, allowing for a substantially faster installation time than previous piles of this type. After molding, reinforcement is applied to the wet concrete, allowing the pile to resist a wide range of structural loads. (Figure 1.8.) Installation of CFA augar piles.

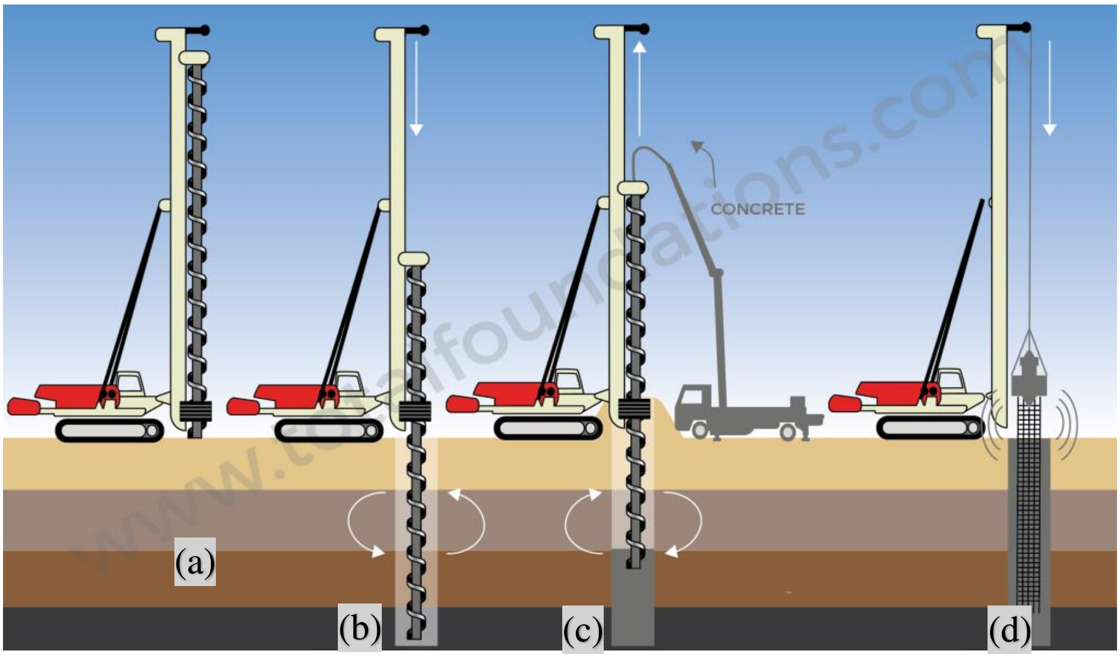


Figure 1.8. Installation of CFA Augar Piles step by step, (a) set-up CFA, (b) drilling, CFA drilling, (c) pouring concrete while recovering augar, and (d) insertion of steel reinforcement with vibration [2]

1.2.3. Drilled shafts or bored piles

Drilled piers, bored piles, or caissons, are other names for them, which are deep foundation solutions. To backing constructions with huge axial and horizontal stresses, cylindrical shafts are dug into the ground and filled with concrete. Drilled shaft piles are made by digging a hole in the ground, putting steel in the hole for reinforcement, and then filling it with concrete. Rotary bored piles can be used in all types of soils that have an active and its installation is very quick, also it's available in any large sizes, and can support large loads. In (Figure 1.9.) installation of bored piles can be seen.

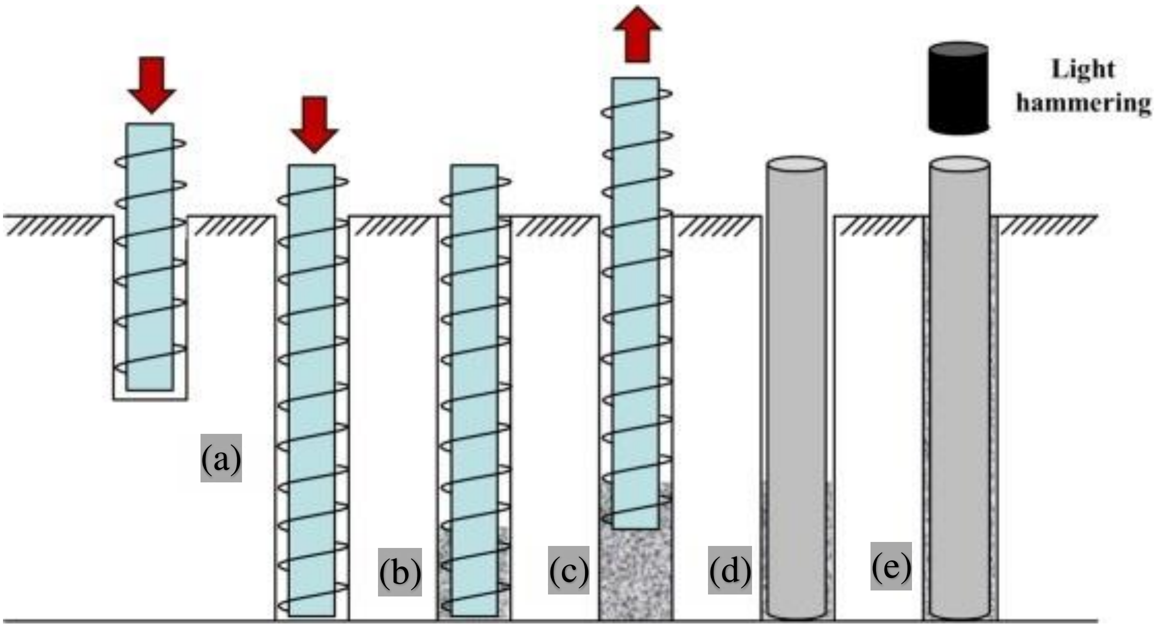


Figure 1.9. Installation of Bored Piles step by step, (a) boring, (b) 1st cement grout injection, (c) augar retraction, (d) pile installation, and (e) 2nd cement grout injection [3]

1.2.4. Other Type of Piles

While they are not widely used, there are several other pile technologies available, each with its own set of advantages that can be applied to specific circumstances. These include:

- **Franki piles:** Cast-in-place elements constructed with a drop hammer and temporary covering are known as Expanded Based Driven cast-in-situ piles. They have the ability to manufacture high-capacity piles with minimal connection depths.
- **Micro piles:** Mini piles, pin piles, needle piles, and root piles are deep foundation components consisting of high-strength, small-diameter steel casing, and/or threaded bars.
- **Jacked piles:** They're similar to driven piles, however, they're pushed into the ground instead of being beaten into it.
- **Helical piles:** Steel shafts with helical flights of different sizes are used to accommodate the site-specific ground conditions, also known as helical piers or screw piles.

- **Anchor Piles:** Tension piles, also recognized as uplift or anchor piles, are a type of pile foundation used to attack uplift forces that would or else cause the structure to be lifted off the ground. Uplift forces can be triggered by hydrostatic pressure, seismic activity, or overturning moments.
- **Batter piles:** To resist a lateral force, a pile is motivated at an angle to the vertical. Due to wind, waves, and ship influences, offshore platforms, towers, and bridges are exposed to overturning moments, to protect them, batter piles are commonly employed. As a result, batter piles are used in pile raft foundations, which can hold more weight in both the horizontal and vertical directions. To resist lateral loads, batter piles with different angles with verticals are used. (Figure 1.10.) Below shows the type of piles due to function or action.

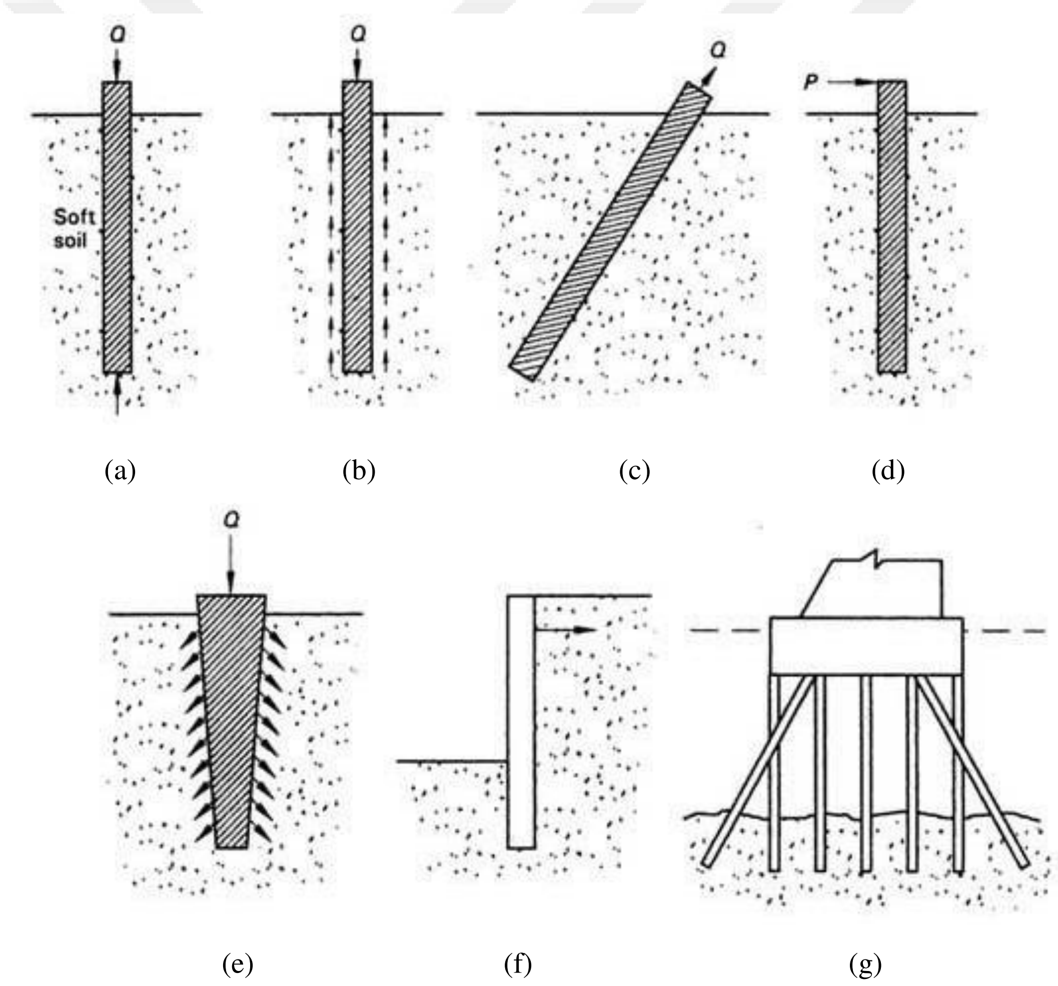


Figure 1.10. Types of piles due to function or action, (a) point bearing pile, (b) friction pile, (c) tension or anchor pile, (d) laterally loaded pile, (e) compaction pile, (f) sheet pile wall, and (g) piles to safeguard foundation against scour

- **Composite Piles:** This kind of pile is used to lower the cost of piling work by driving piles of two different materials one on top of the other, allowing them to act as a single pile. (Figure 1.11.) Below shows the type of composite piles:

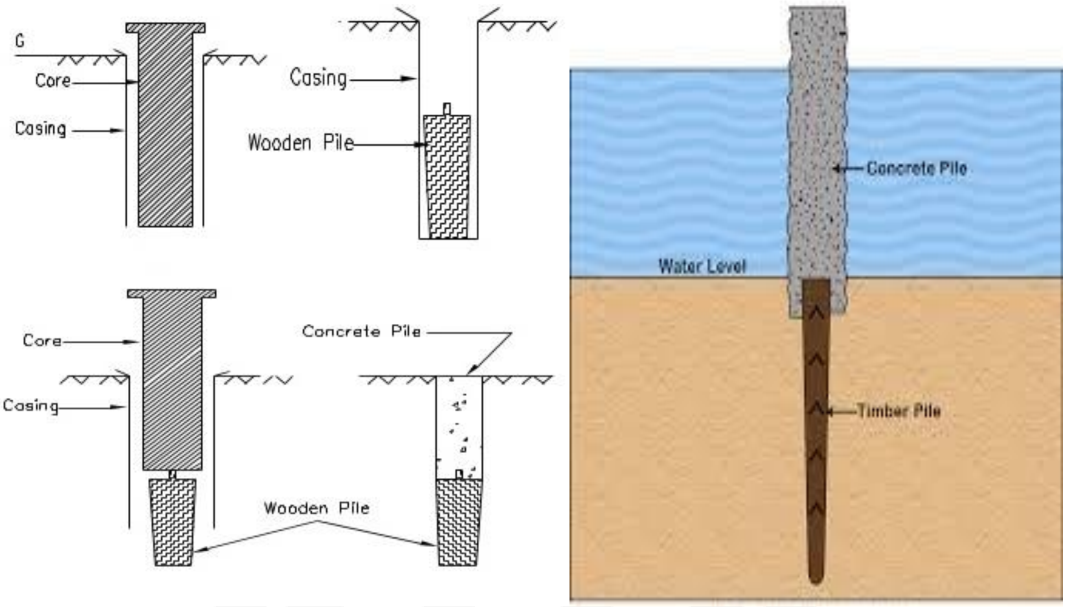


Figure 1.11. Composite piles

The diagram as shown in (Figure 1.12.) below representing pile types due to the materials:

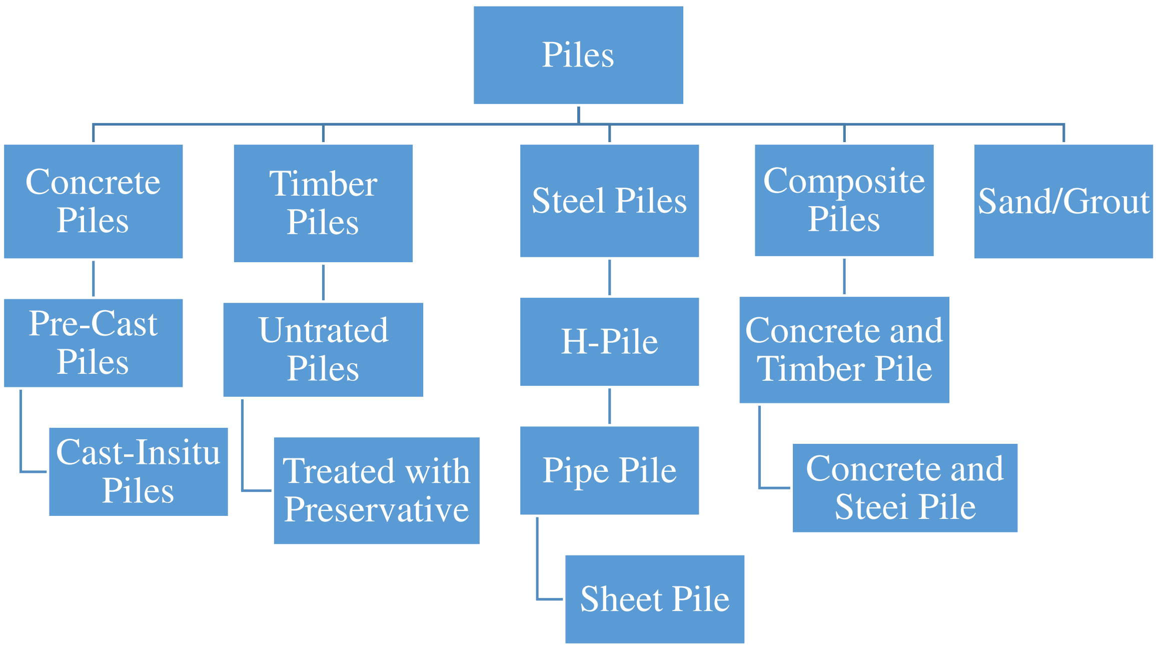


Figure 1.12. Pile classification based on their material

1.3. Factors Affecting Type of Pile Materials Selection

For a certain project, there are several types of piling foundations to choose from. The choice of a specific form of pile foundation is influenced by a few factors. These factors are:

- Type and loads from the superstructure.
- Soil properties.
- The depth of the soil layer capable of supporting the piles.
- Variations in length of pile required.
- Materials availability.
- Durability required.
- Available equipment for pile driving.
- Cost.
- The depth of water level and intensity of underground water flow.
- Surrounding structures type.

1.4. Pile Foundation Failures

For strongly loaded constructions and in circumstances where poor soil conditions are found at a narrow depth, a pile foundation is one of the most preferred options. However, pile foundations can fail for a variety of causes. Before planning pile foundations, suitable steps must be taken to decrease the risk of failure. Causes of failure in pile foundation are mentioned below:

- The pile's suggested load is higher than the designed load.
- The workmanship is defective.
- Dislocation of pile reinforcement.
- End bearing pile resting on soft strata.
- Investigation of the soil was a fault.
- The wrong type of pile selection.
- The pile is under-reinforced.
- The deterioration of piles (like the attack of insects, rust, etc).
- Due to lateral loads, piles deform.
- The capacity of the pile was incorrectly estimated.
- When designing piles, lateral forces are not taken into consideration.

1.5. The behavior of Pile Materials and Deterioration Problems

In this section, the behavior of pile materials and deterioration will be discussed briefly.

1.5.1. Application History of Piles

The origin of driven piles can be traced back to the Stone Age. Four thousand to five thousand years ago, in Europe Alpine Lake Dwellers built their homes on timber piles. In 332 B.C., Alexander the Great drove piles in the Tyre city, and the Romans used them extensively. Piles were frequently used by Chinese bridge builders during the Han Dynasty (200 BCE–200 CE). These early builders used hand-lifted and fallen weights to drive their piles into the ground (Chellis, 1961). By the Middle Ages, cranes and leverage were used by builders to lift heavyweights.

During the industrial innovation, construction methods advanced more quickly, particularly when steam power became available, more efficient, and larger equipment was developed, allowing for enhanced pile driving capabilities. In Devonport England in 1845, the first steam-driven pile hammer was used. These developments were continued throughout the 19^{th} and 20^{th} centuries. In 1940 the first diesel hammers were designed 1940 and used in North America for the first time in 1952. The vibratory hammers were used for the first time in 1961 (Parkhill, 2001).

Today, even in hostile conditions driven pile foundations can withstand extremely heavy loads. Perhaps offshore oil drilling platforms are the most impressive. These foundations are made up of 3 m (10 ft) diameter driven piles that must withstand massive lateral loads caused by wind, wave, and earthquake forces.

The pile materials' quality has also improved. Since the first piles were all made of wood, their length and capability were reduced. Fortunately, in the 1890s the introduction of steel and reinforced concrete allowed for the building of larger and stronger piles, as well as the installation of them with better driving equipment. Without these enhanced foundations, many of today's main constructions would not have been imaginable.

1.5.2. Steel Piles

Steel had become readily accessible by the 1890s, and many buildings were being constructed with it. The first steel I-beam segments were propelled as piles in 1899, which was a natural evolution. China is widely credited with being the first mass manufacturer of high-quality steel in the third century AD. They possibly used techniques similar to the Bessemer method, which was developed and popularized in Europe only in the nineteenth century.

Steel piles are usually pipe piles or H-section piles that are pushed into the ground with either an open or closed-end. After the steel pipe piles have been driven into the ground, they are frequently filled with concrete. In any structure cases where long steel piles are required, they can be connected with welding or by riveting together. During taking boreholes from the ground in the site exploration of the suggested area if hard layers of soil are found such as soft rock, dense gravel, and shale, the driving method would be exposed to challenging circumstances, therefore the bottom of the steel pile can be fitted with driving shoes or pints.

Corrosion problems are one of the big problems exposed to steel piles. For instance, peats, swamps, and organic soils are corrosive. When the pH of the soil is greater than 7 the soil is considered not very corrosive. Many manufacturing firms are currently attempting to reduce the rate of steel corrosion to the bare minimum. For example, British Steel Corporation estimates that steel corrosion in an industrial setting will reach 0.2 mm/year. Despite this, the highest corrosion rate reported for an extracted steel pile after 25 years in the harsh soil environment was 0.03 mm/year.

For treating the problem of corrosion in steel piles extra steel thickness is applied to the actual design cross-section to reduce the effect of corrosion. The use of epoxy coating is also effective in preventing steel corrosion. During pile driving, the epoxy coating cannot be easily vandalized. Sometimes after driving, steel pipe piles are often filled with concrete. Owing to their heavyweight, they would have greater uplift power, increased shear and moment capacity due to the concrete's strength, and longer useful life in corrosive environments.

Advantages of Steel Piles

- Can withstand high driving stresses.
- Cutoff and extending deep to the required depth are simple tasks.
- It is capable of penetrating stiff soil layers or boulders.
- Load-carrying capacity is high.
- The whole process of steel pilling takes a few times than the others, by another name the process is quicker.
- The process of driving steel piles requires less excavation, therefore there is less disturbance to the pilling field, and steel piles are more environmentally friendly.

Disadvantages of Steel Piles

- Corrosion and electrolysis have a high risk of causing damaging piles.
- They are very costly.
- During pile driving, there is a lot of noise.
- During driving through hard layers of past major obstruction, damaging or deformation from vertical may appear in H-section.

1.5.3. Pipe Piles

Pipe piles are a simple and easy-to-understand method of piling. Big impact hammers are used to push a prefabricated steel pipe framework into the ground. The piles remain in place mostly through soil friction. The designs of piles will vary depending on the ground situations and support potentials, allowing the pile systems to be adapted to any particular requirements. Since the late 1980s, pipe piling has grown in popularity and application by leaps and bounds. Although driving pipes is involved in all of the various piling techniques, diverse varieties of pipe piles are designed for different soil conditions and structural requirements. Here are a handful of the more common ones:

- **Unplugged Open-Ended**: These pipes are entirely open-ended. The ground level inside and outside the pipe should be the same after installation. They mainly use friction to move their load to the soil.
- **Plugged Open-Ended:** The bottom end of the pipe is fitted with a plug. As a result, the soil within the pipe is a precise quantity lower than the soil outside.
- **Bottom Plate:** This is one of two types of plugged piles that are commonly found. A steel plate is joined to the lower end of this situation. The plate aims to minimize sliding by creating compression and increasing friction. These are used on rocky terrain where the rock and the pile are separated by a thin layer of soil.
- **Steel Pipe with Rock Shoe:** Another famous plug is this one. When the pile comes into direct contact with a rock surface, rock shoes are employed similarly to steel plates. The shoe must be able to carry the entire load while also preventing sliding on the rough surface.
- **Franki Pipe Pile:** They are filled with wet concrete and can withstand significantly greater driving force than their competitors.

(Figure 1.13.) Below shows the pile system classification (based on U.S. Army; 1998 and Prezzi and Basu, 2005).

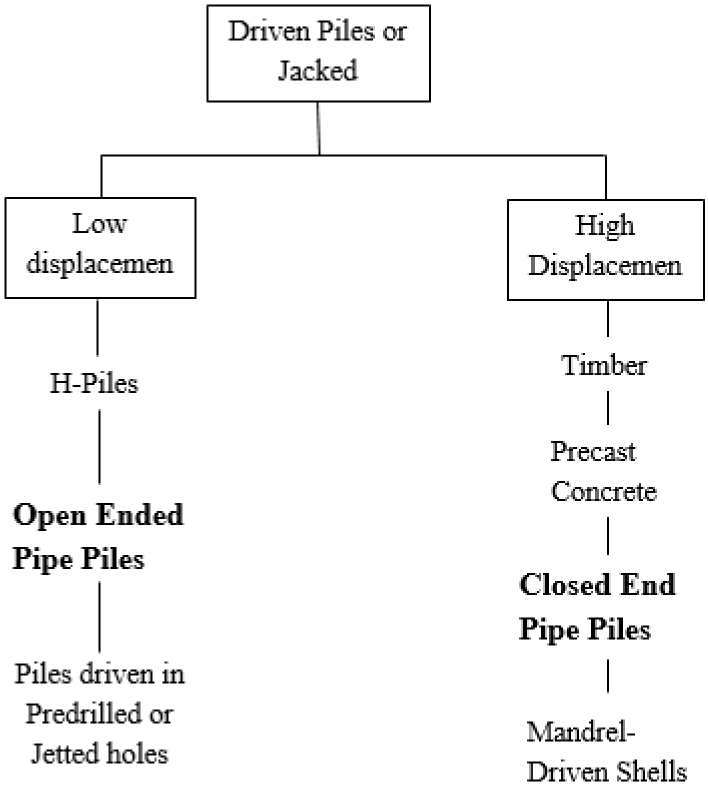
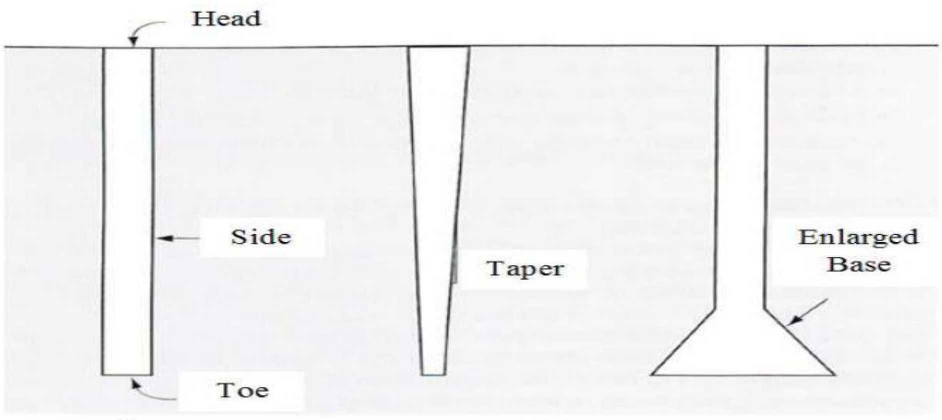


Figure 1.13. The pile systems classification (Prezzi et. al, 2005) [4]

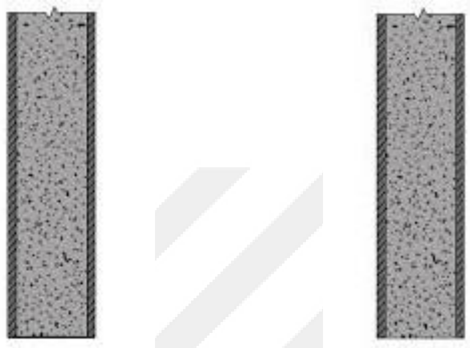
Pile foundations are typically straight, with a constant cross-section across their depth; however, some are tapered, meaning the cross-section of the pile decreases with depth. Some piles are known as belled piles because they have an expanded base at the bottom of the pile. The foundation's axis is a line that runs along the pile's centroid and follows its longest dimension. (Figure 1.14.) Shows the parts of the pile foundation.



(a) (b) (c)

Figure 1.14. Parts of Pile Foundations, (a) straight foundations, (b) tapered foundations, and (c) enlarged base foundations

There are two types of pipe piles: open-ended and closed-ended. It has been known that the behavior of open-ended piles differs from that of closed-ended piles [5]. The number of blows necessary to drive an open-ended pile to a specified depth in sands is lower than for a closed-ended pile [6]. As a result, it is widely accepted that, under the same soil circumstances, an open-ended pile takes less installation effort than a closed-ended pile. On the other hand, in other investigation findings, [7, 8] the method of pile driving is a significant factor in driving resistance. Soil joins the pile at the same rate as it advances when it is driven in a completely coring (or fully unplugged) mode. (Figure 1.15.) Below show the two types of steel pipe piles.



(a) (b)

Figure 1.15. The two categories of steel pipe piles, (a) closed-ended steel piles, and (b) open-ended steel piles

Pipe piles can have either a closed or open end when being driven. The toe of a closed-end pipe is welded with a flat steel plate or a tapering steel tip. Since they displace a large amount of soil, these piles are referred to as large displacement piles. This increases load ability while also making driving more difficult. The toe of an open-end pipe is unblocked, and soil arrives the pipe as it is pushed. Due to how the pile is driven and the soil circumstances, the lower part of open-end piles may or may not become jammed with soil, generating a soil plug. As a consequence, depending on whether or not the toe becomes plugged, a large or small displacement pile can be made from an open-ended pipe pile. Offshore construction often employs open-ended piles. Since the interior of closed-end pipe piles is clear from the ground surface, they can be inspected after driving. As a consequence, integrity and alignment can be verified. There are also special steel pipe piles existing, such as the Monotube pile, which is narrowing and has longitudinal channels.

To decrease driving resistance and make installation to a design penetration easier, open-ended piles are frequently used instead of closed-ended piles. During installation, a plug of soil will transfer up inside the open-ended pile. In the framework of pile bearing capacity, the problem of soil plugging in open-ended piles has been considered [8-12]. (Figure 1.16.) Below shows the soil plugging in an open-ended pile.

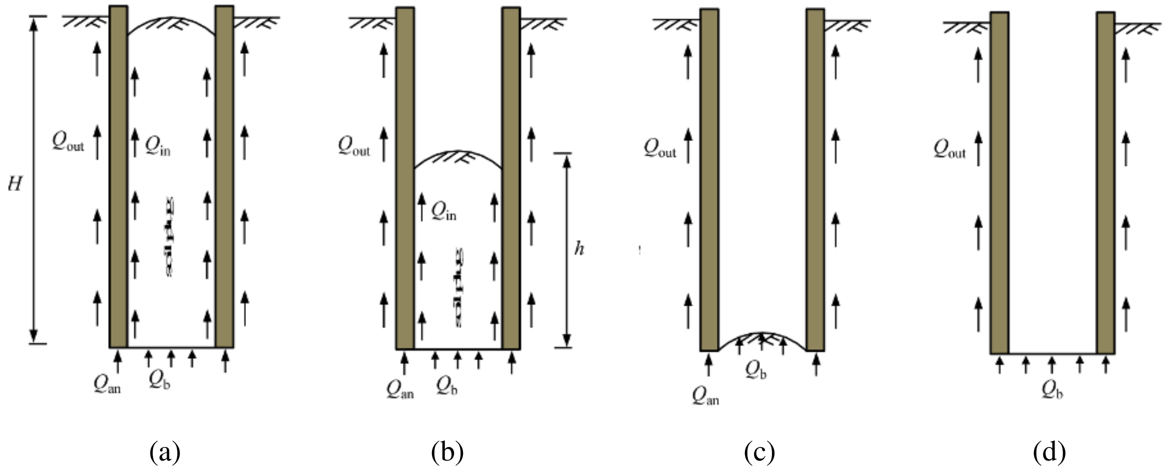


Figure 1.16. The soil plugging in an open-ended pile. (a) fully coring mode, (b) partially-plugged mode, (c) fully-plugged mode, and (d) a closed-ended pile

1.6. Load Transferring in Pile Foundation

A pile cap and individual or group piles make up the pile foundation. Piles carry loads from superstructures to hardened subsurface rock or soil layers with high bearing capacity. (Figure 1.17.) Below show the pile's load transferring.

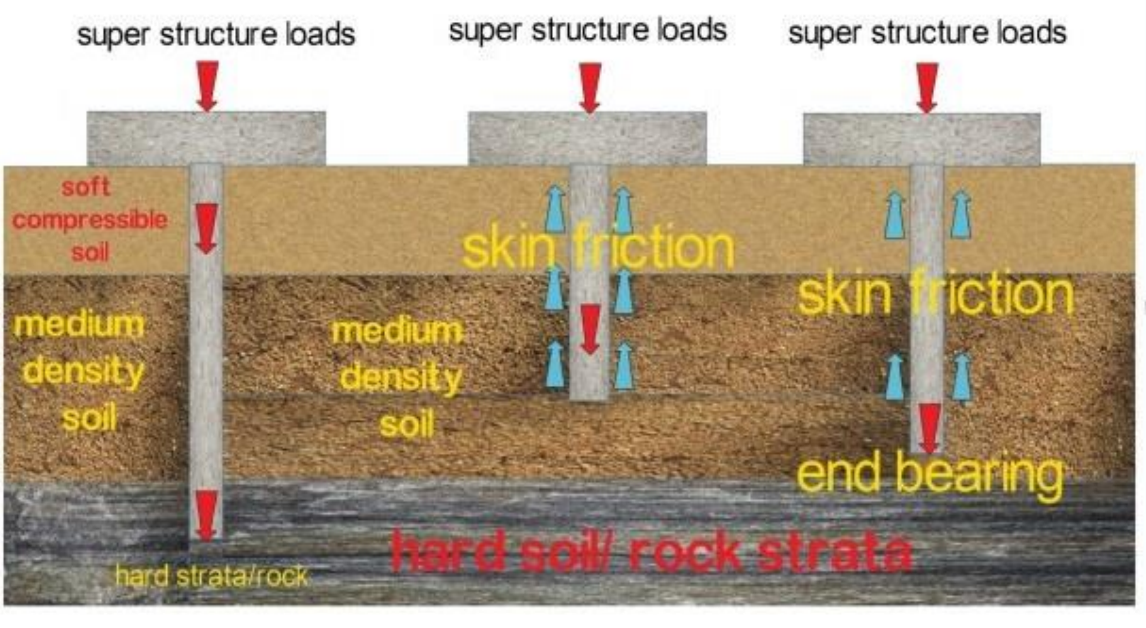
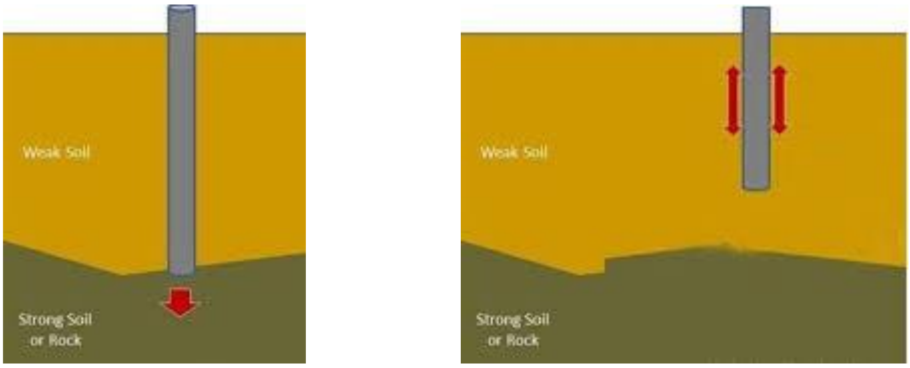


Figure 1.17. pile's load transferring

Piles are used to support massive loads, such as bridges and skyscrapers, and in situations where the soil supporting the structure is not strong and the bearing capacity is limited. The loads are transmitted to the soil through two systems, which are skin friction and end bearing. As shown in (Figure 1.18.) below.



(a) (b)

Figure 1.18. Two mechanisms of pile load transferring. (a) end bearing piles, and (b) friction piles

When it comes to moving structural loads through pile foundations and into the soil, the logistics are complicated. Because piles transport load to the soil mutually along their sides and at the base or end of the foundation component, they are a good choice for foundations, as shown in (Figure 1.19.), the mechanics are more complex than shallow foundations. There are also major variations in how moment loads and applied shear are transferred.

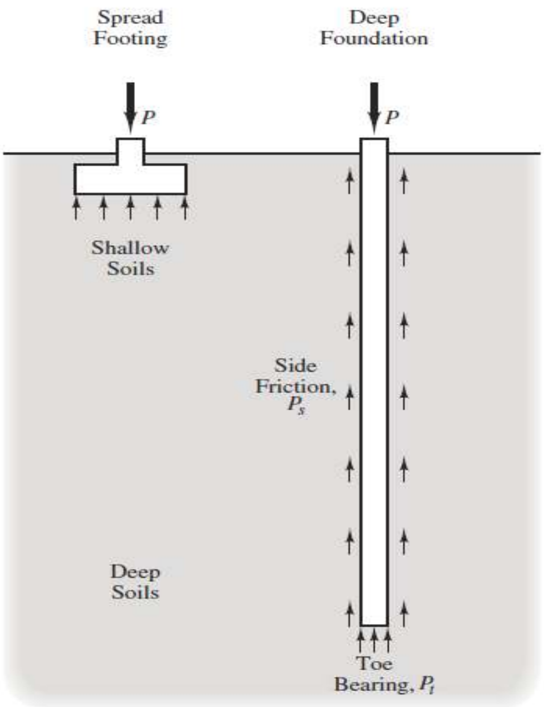


Figure 1.19. The load transfer mechanisms comparison in shallow with pile foundation

Generally, piles are used to transfer loads from the construction to the desired depth of strong soil layers, but if strong layers are very deep, the length of the pile becomes very long and the end-bearing piles will not be economical. In this case, the piles can be driven into the ground at a given depth. This type of pile is called a friction pile because shear stresses along the sides of the pile produce the majority of the pile-bearing capability, and friction piles are ideal where harder layers are too deep to reach economically. The load is transported to the surrounding soil by linkage or friction between the pile's surface and the soil; the pile's entire surface (cylindrical) works as a force transmission mechanism. The load is carried via friction between the pile's sides and the surrounding soil (skin friction).

Most piles must have the adequate axial load capacity to withstand the applied loads, which is the most critical geotechnical design requirement. Static load tests, analytic methods, and dynamic methods can all be used to assess this ability.

Since there are many uncertainties in soil properties and the soil-pile materials interface, determining pile capacity is not easy and complex. Many theories and analytical methods are available, but they will not give the same value of bearing capacity, particularly for friction piles [13].

For calculating the ultimate bearing capacity of pile foundations, several methods and empirical equations based on experimental work are available, the majority of which are based on shallow foundation equations. (i.e., Terzaghi (1943), Hansen (1970), Janbu (1976), Meyerhof (1976), Vesic (1977), and Coyle and Castello (1981). (Figure 1.20) Shows the ultimate bearing capacity calculating.

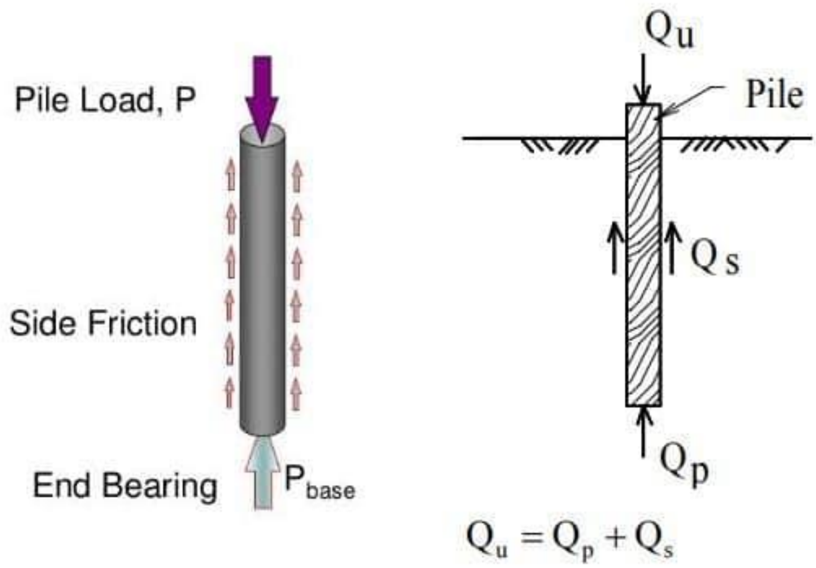


Figure 1.20. The ultimate bearing capacity calculating

$$Q_u = Qp + Qf \tag{1.1}$$

Where;

Qu = ultimate bearing capacity of the pile

Qp = end(point) bearing capacity of the pile

Qf = Shaft friction resistance capacity of the pile

Burland (1973) proposed a general equation for estimating skin friction pile capacity based on the effective stress method from bored pile load studies. It is a function of the skin friction angle (δ) among pile materials and surrounding soil and the coefficient of side earth pressure (K). This equation is commonly used for cohesion-less soil.

$$f_s = K\sigma'v \tan\delta' \tag{1.2}$$

Where:

f_s: is skin friction, K: is lateral earth pressure coefficient, $\sigma'v$**:** is effective overburden pressure at any depth and δ΄: is an effective skin friction angle between soil and pile materials.

The pile shaft friction resistance can be calculated by multiplying the unit skin friction f_s by the surface area of the pile.

$$Qf = fs\,PL \tag{1.3}$$

Where:

Qf is pile shaft friction resistance, P is the pile perimeter and L is an embedded length of the pile.

The most difficult factor to locate is the soil pressure coefficient K. The value of K is dependent on the stress degree, density, friction angle of the soil, roughness, and the pile diameter, according to numerous field tests. It was discovered that K does not remain constant throughout the pile's length. (Gavin and Gallagher, 2005). For the design and construction of friction piles, the American Petroleum Institute (API, 1984) recommends that K = 0.8 be used.

The amount of K varies with depth; near the head of the piles, it is roughly equal to the passive Rankine earth's pressure coefficient; at the highest depth, Kp may be less than the earth's pressure coefficient at rest; (Table 1.1.) Shows K values proposed based on available results. (Braja M. Das, 2014).

Table 1.1. Shows K values proposed based on available results

Pile Type	K
Bored or Jetted	$\approx K_0 = 1 - \sin\phi'$
Low-displacement driven	$\approx K_0 = 1 - \sin\phi'$ or $1.4(1 - \sin\phi')$
High-displacement driven	$\approx K_0 = 1 - \sin\phi'$ or $1.8(1 - \sin\phi')$

Since piling causes substantial compression in the surrounding soils, the side earth pressure coefficient, K, is usually larger than the side earth pressure coefficient in the ground before building K0. The K/K0 ratio is influenced by several factors, including the high and low displacement piles, types of soil, the consistency of the soil, vertical effective stress, positions on the pile, and special construction techniques.

Several authors attempted to estimate the value of K using a variety of pile test programs. (Table 1.2.) Summarizes several K values proposed by various authors; it is clear from the table that there is no very fine agreement on which K value to use.

Table 1.2. Summarizes several K values proposed by various authors

	Pile Type					
Source	H-Piles	pipe	Precast concrete	timber	tapered	Tension tests
Mansur and Hunter (1970)	1.4 - 1.9	1.2-1.3	1.45-1.6	1.25		0.4-0.9 All types
Tavenas (1971)	0.5		0.7		1.25	
Ireland (1957)						1.11-3.64
API (1984)		0.8 or 1.0				

1.7. Research Aim

This thesis aims to determine the differences in load-settlement behavior of closed-ended and opened-ended piles under axial loading in four relative densities: 10%, 40%, 65%, and 90%, as well as the effect of friction between sandy soil and piles, which was visible in open-ended piles.

The interface direct shear test will be used to investigate the skin friction angle between sand and pile materials, and a static axial load test will be performed using a specially designed loading machine system. Piles will be embedded in the sand at four different relative densities: 10%, 40%, 65%, and 90% the axial load will be applied, and the settlement rate will be maintained at around 1 mm/minute. The computer program system records the applied load and settlement values.

It also aims to calculate the model piles' ultimate bearing capacity using common geotechnical theoretical methods found in the literature, as well as to perform finite element analysis using the Plaxis 3D finite element software. Experiment results will be compared to traditional theoretical approaches and finite element analysis. Finally, future researchers on this topic should be recommended.

2. LITERATURE REVIEW

The behavior of a structure under static or dynamic loading is influenced by the soil-structure interaction. It has an impact on the action of the soil as well as the response of the pile when loaded. The study is critical for bettering structural protection under severe loading conditions by predicting more reliable structural behavior. The performance of the soil–pile system is primarily nonlinear, which complicates the issue. The load is resisted in a laterally loaded pile by the soil–pile interaction effect, which is dependent on the properties of soil, the material of the pile, the diameter of the pile, the type of loading, and the ground bed slope.

Klos et al., Al-Ansari, and Lee et al, reported that pipe piles can be either closed-ended or opened-ended. The behavior of open-ended piles differs from that of closed-ended piles. According to Szechy's (1958) field test results, the blow count needed to drive an open-ended pile to a specified depth in the sand is lower than for a closed-ended pile [14]. Thus, under the same soil circumstances, it is widely accepted that an open-ended pile needs less installation effort than a closed-ended pile [5, 15].

Brucy et al., Randolph et al., Raines et al., DeNicola et al., and Lehane et al., studied that to minimize driving resistance and make installation to a design penetration easier, open-ended piles are often used instead of closed-ended piles. A plug of soil can move up within the open-ended pile during installation. In relation to pile-bearing capability, the issue of soil plugging in open-ended piles has received attention [8-12].

2.1. Previous literature determination of interface between sand and pile materials

Deep foundations for offshore and onshore infrastructure are progressively being built with steel pipe piles. The Hangzhou Bay Bridge, for example, was built with over 5,000 steel pipe piles, making it the world's longest cross-sea bridge at the time [16]. In most cases, steel pipe piles are open-ended and driven to the base on capable strata such as compressed sand. Determining the base potential of open-ended pipe piles is a complicated problem with a lot of unknowns. The complexity of soil plugging activity is primarily to blame for the difficulty. As soil reaches the pile from the pile tip throughout the pile connection, a column of soil tends to form. The majority of previous design methodologies didn't distinguish between open- and closed-ended piles. Given the increasing demand for large diameter open-ended pipe piles in offshore engineering, a lot of work has gone into studying the loading performance and bearing capacity of pipe piles in the sand in recent years.

Paik et al., specified that during the pouring of open-ended pipe piles some quantity of soil will primarily enter into the hollow pipe. Due to the soil state (dense or loose) and type (fine-grained or coarse-grained), pile diameters and its length, and the driving method, the soil inside the pile may or may not allow more soil to enter the pipe. Driving is said to take place in a fully coring (unplugged) mode if soil reaches the pipe during the driving process, and the behavior is more like that of a non-displacement pile. However, driving is said to be performed in a completely plugged mode when the soil forms a plug at the pile base that prevents further soil entry. If a pile was driven in the plugged mode the entire time, the load response would be similar to that of a displacement pile. In real field situations, the behavior is somewhere between completely plugged and coring. Furthermore, the behavior of a pipe varies depending on whether it is jacked or driven into the earth [17].

Kikuchi et al., conducted that the wedge formation condition beneath the open-ended pile was obviously different from the wedge formation condition beneath the closed-ended pile, as evidenced by the results. Although the open-ended and closed-ended piles exhibited similar penetration resistance, the open-ended pile's soil movement was limited, as seen by irregular increases and decreases in penetration resistance throughout pile penetration [18].

2.2. Previous literature determination of Skin friction of opened and closed-ended piles

Geotechnical engineers use friction between soil and pile materials as a key component in their designs. In the design of civil engineering constructions such as retaining walls, sheet piles, diaphragm walls, and piles, frictional forces between the structure and the soil are taken into attention. The effect of pile point tip resistance on bearing capacity is known to be ignored, particularly in loose sand soils, and the bearing capacity is completely taken equal to the skin friction. Hence, it is well understood how important it is to correctly calculate the skin friction angle, which is used extensively in engineering calculations.

Paikowsky et al., resulted that open-pipe piles are often used for foundations together in on-land and offshore construction. Soil reaches the pile at an amount equal to the pile penetration during the initial stage of setting up. As the pile continues to be penetrated, the inner-soil cylinder can produce enough frictional confrontation to prevent further soil interference, resulting in the pile being "plugged". The open-ended pile then takes on the features of a closed-ended pile in terms of penetration. During and after construction, the mode of pile penetration has a major impact on the soil-pile interaction. During open-ended penetration, the deformations and pressures in the surrounding soil induced by plugged (closed-ended) or partially plugged (partial soil penetration) piles differ significantly [19].

In their designs, many designers make the skin friction angle (δ) equal to 2/3 of the soil's internal friction angle (ϕ) (Terzaghi and Peck 1948). It is understood, however, that in the event of frictions between the same soil and different materials, may vary [20]. Even today, the exact skin friction angles (δ) between soil and pile materials are unknown, so designs are based on approximate values. δ values used in designs are of prime importance in the determination of the number of piles, pile length, and diameters. A low value (δ) eliminates cost-effective design and significantly raises project costs. A high value, on the other hand, causes security problems.

Smith et al., and Brucy et al., revealed that the pile driving mode has a significant factor in driving resistance. Soil reaches the pile at the same intensity as it advances when it is pushed in a completely unplugged mode. When a pile is pushed under plugged or partly plugged circumstances, however, a soil plug forms on the pile's inside surface, avoiding new soil from entering the pile. A pile motivated in the plugged mode acts in the same way as a closed-ended pile [8, 21].

Nell et al., Randolph et al., Kraft, and Raines et al., who researched the open-ended pile's plug load transmission mechanism in sand agree that when loaded statically, open-ended piles behave like closed piles. The fact that the pile can be closed-ended during fixed loading but not during installation increases the complexity of the problem [10, 22-24].

Aksoy et al., studied that the skin friction angle (δ) between soil and common pile materials such as wood, steel, and FRP was measured using a direct shear test. They used a sand-clay mixture with different mixing ratios of 100:0, 80:20, 70:30, 60:40, 55:45, the internal friction angles of the sand-clay mixture were 43°, 39.5°, 41.5°, 35°, 28° consecutively. They provided a design chart for determining the skin friction angle for the materials described, as well as a known value for the soil's internal friction angle [25].

2.3. Field and Model Piles Bearing Capacity

Szechy, examined that the effect of the pipe pile's wall thickness on bearing capability and the creation of a soil plug within the pipe pile. It was revealed that while the soil plug's bearing capacity was unaffected by wall thickness, the driving resistance was affected [26].

Szechy, studied that the settlement of an open-ended pile is bigger than that of a closed-ended pile for the same load and soil circumstances. This means that the load capacity of closed-ended piles is normally bigger than that of open-ended piles when the ultimate load capacity is determined using a standard settlement of 10% of the pile diameter, for example. However, depending on the degree of soil plugging while driving, the modification in load capacities varies widely [27].

Paikowsky, has explained that the soil depth, relative movement among the pile and the soil, density of the soil, the diameter of the pile, and other factors all influence the formation of arching in the internal soil plug. Soil plugging is a complicated phenomenon. The skin friction of the soil inside and outside a pipe pile determines its bearing capacity. Internal skin friction is determined by the internal soil's arching [28].

Klos et al., and Whitman et al., studied that a short open-ended pile is considered to have a lower load capacity than a comparable closed-ended pile. The bearing capacity of the open-ended pile exceeds that of the corresponding closed-ended pile as pile length (or penetration depth) increases. This is due to the increasing soil plugging that happens as penetration depth is increased [19, 29].

Paik et al., reported that with increasing driving depth, the difference in bearing capacity between closed- and open-ended piles reduces as the soil plugging effect increases. The behavior of a plugged-mode pile is identical to that of a closed-ended pile. Large-diameter pipe piles (those used in offshore piling) are typically pushed entirely coring (unplugged) into the sand, while smaller-diameter piles are typically plugged, at least partially [30].

Kyuho et al., conducted that the degree of soil plugging affects open-ended piles bearing capacity, which can be calculated using the incremental filling ratio IFR. The variance of pile load capacity with IFR is not taken into account in most open-ended pile design criteria, and no specific technique for calculating IFR during pile fixing has yet been suggested [31].

Kyuho et al., found that both the driving reaction and the static bearing capacity of open-ended piles are affected by the soil plug that forms within the pile during pile driving. To examine the effect of the soil plug on the static and dynamic reaction of an open-ended pile, as well as the load capacity of pipe piles in common, field pile load tests, were done on instrumented open- and closed-ended piles motivated into the sand. During pile driving for the open-ended piles, the soil plug length was constantly measured, allowing the pile's incremental filling ratio to be calculated. The open-ended pile had a 16% lower total blow count of the hammer than the closed-ended pile. The limit unit shaft resistance and limit unit base resistance of the open-ended pile were 51% and 32% lower than those of the closed-ended pile, respectively. It was also discovered that he averages unit frictional resistance between the soil plug and the open-ended pile's inner surface was 36% greater than the unit outer shaft resistance, and the unit soil plug resistance for the open-ended pile was only around 28% of the unit annulus resistance [32].

Basack, reported that oil drilling platforms, jetties, stress leg platforms, and other offshore structures are protected by pile foundations. The open-ended piles have been commonly used for foundation construction on offshores and lands [33]. Shighait, studied that the open-end pipe pile is a low-displacement pile that has no impact on the soil around it during installation [34].

Mohammed et al., concluded that plugging increases horizontal tensions between the pile and the surrounding soil, resulting in increased skin friction. By increasing the length of the plug length ratio, the load capacity of the piles increase and this ratio is lower in medium and loose sand than in dense sand. If open-ended piles are driven or pressed in the completely unplugged or partly plugged mode, the plug contributes to the static pile's base capacity [14].

They also studied that the load-carrying capacity of piles in dense sand is numerous times more than in loose and moderate sands, particularly for closed-ended or open-ended piles. This could be due to the fact that a pipe pile in dense sand can induce outside and interior skin friction, as well as end-bearing resistance, resulting in a total pile capacity comparable to a closed-ended pile. The removal of soil plug, on the other hand, reduces the pile bearing capacity [14].

Liu et al., sourced that outside skin frictional resistance, annular toe resistance, and plug resistance make up an open-ended pile's bearing capacity (less of interior frictional resistance and base resistance on the soil plug). Frictional resistance is caused by relative movement between the soil (soil plug) and the pile shaft. Exterior and interior skin frictions, on the other hand, have different mobilization mechanisms. During the primary loading, as the pile descends, the exterior skin friction develops top-down, and the working load at the pile top is entirely carried by the exterior skin load passes to the soil below the pile annulus. Since the pile shaft is more solid than the soil plug, the soils underneath the pile annulus are compressed more than those beneath the soil plug. Despite the fact that the length of the soil plug is usually constant, i.e. the pile remains plugged during static testing, only a few soils are pressed into the pile shaft [35].

2.4. Finite Element Analysis

Different mathematical models have been anticipated to investigate the settling actions and bearing capability of open-ended pipe piles under various loading conditions. The mechanical performance of large diameter open-ended piles is studied using numerical systems such as the finite element method and coupled Eulerian-Lagrangian numerical technique. Cundall and Strack's discrete element method (DEM) has been shown to be useful, particularly in modeling soil arching within pipe piles.

Because of the state of soil heterogeneity, the boundary conditions for the design of geotechnical engineering structures are always very complex, and conventional research using simplified theories and equations is not possible. Numerical modeling may be used in the design of retaining walls, pile foundations, dams, and other earth-supported structures in this case. Many researchers have used finite element programs such as Plaxis 3D finite element software, ABAQUS, and ANSYS to investigate the action of single piles under axial loading.

Naghibi et al., investigated that the expected elastic settlement of single friction piles under vertical loading by running a linear finite element program on piles set in a homogeneous soil, creating a regression model, and then developing an easy mathematical expression for calculating the elastic settlement of friction piles in a homogeneous soil. Their mathematical equation agrees well with FE results and also matches well with Randolph and Worth's analytical solution for estimating pile settlement. The most significant benefit of their mathematical expression is that pile length can be easily approximated with a given amount of settlement, which can be useful in pile design and serviceability limits [36].

Kishanrao et al., studied using the two-dimensional finite element software Plaxis 2D, which offers a very good method to investigate the behavior of the soil-pile interface and its response to applied axial load, the behavior, settlement, and load transfer mechanisms of a single pile in layered soil under axial loading were studied. The load-settlement curve represents the effects of finite element analysis. The ultimate bearing capacity of a single pile increases as the slenderness ratio of the pile increases, and it was also discovered that a pile of the same slenderness ratio has a significantly higher ultimate resistance in the case of sand overlying the clay than in the case of clay overlying the sand [37].

Riyadh et al., studied models of piles at the site of the project “Three Raw Water Tanks in Basra Refinery”, and they concluded that, for piles with a length of 18 meters, increasing the diameter of the pile from (0.6m) to (0.8m, 1.0m, and 1.2m) increased the approximate ultimate load capacity, corresponding to settlement values of 10%, 51.4%, 123.8%, and 200% respectively from the pile diameter. Increases in pile diameter from (0.6m) to (0.8m, 1.0m, and 1.2m) resulted in a decrease in the maximum values of axial stresses measured at the top faces of piles for piles of (18m) length (15.4%, 16.6%, and 19.3%, respectively). The average ultimate load capacity for piles of (0.8m) diameter increased to around (19.5%, 127.8%, and 145.9%) when the pile lengths were increased from (16m) to (0.8m) (18m, 20m, and 22m, respectively). In all studied models, the designed compressive strength (37500kPa) for the concrete material of the piles was not exceeded [38].

3. MATERIALS AND METHODS

This chapter explains the qualities of the soil and how to prepare it for testing, the equipment, and loading frame manufacturing for the pile-driven scheme. It will also show all experimental pile model load testing as well as the apparatus used to perform static load testing on single pile behavior under axial load within sandy soil at various relative densities of model sand (i.e., Dr = 10%, Dr = 40%, Dr = 65%, and Dr = 90%).

3.1. Materials and Equipment

This section describes the materials and their qualities that were used in this investigation, as well as the technique and equipment that were used.

3.1.1. Soil Characterization

Clean river sand with a consistent gradation taken from Turkey's Murat River in Elazig has been used in the current study in the investigational work as a foundation soil as shown in (Figure 3.1.) and all physical properties of the sand are shown in (Table 3.1.). The soil is poorly graded sand, according to the ASTM standards the physical and mechanical properties of the sand have been determined. The sand has been washed, dried in the oven, and sieved through a 1 mm opening sieve, which has been retained on sieve #200. (0.075 mm). The sieve analyses and specific gravity tests were achieved according to standards (ASTM D422-63 and ASTM D854-14). The relative density of the sand was determined according to (ASTM D4254-16). The sand is classified as poorly graded sand (SP) according to (USCS) which is refer to Unified Soil Classification System according to ASTM D2487.

Table 3.1. The physical properties of the sand

Property	Value
Effective size, D_{10}, D_{30},D_{50}, D_{60} (mm)	0.19, 0.325, 0.475, 0.55
Coefficient of uniformity, C_u	2.895
Coefficient of curvature, Cc	0.980
Classification (USCS)	SP
Specific gravity, Gs	2.77
Maximum dry unit weight, γd (max.) kN/m^3	17.66
Minimum dry unit weight, γd (min.) kN/m^3	14.32
Maximum void ratio, e_{max}	0.898
Minimum void ratio, e_{min}	0.539
Maximum – Minimum grain size, D_{max}-D_{min} (mm)	1 - 0.074

Figure 3.1. Soil sample

The (Figure 3.2.) below shows the sand grain size distribution.

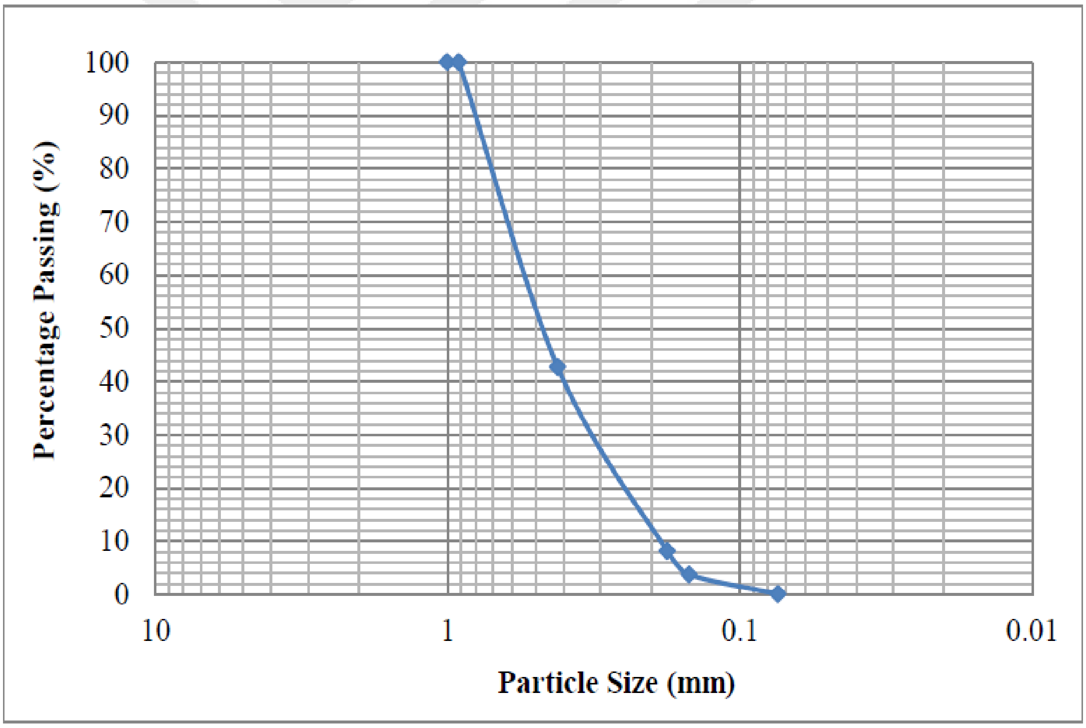


Figure 3.2. The sand grain size distribution curve

3.1.2. Details of Pile Models

Two models of steel piles were used (open-ended and closed-ended) piles, with 50mm diameter and 600mm height which is (500mm embedded in sand) Within sandy soil, the test was employed to carry out the testing (static compression loading). (Figure 3.3.) Shows the model piles which is used in this work.

Figure 3.3. Open-ended and closed-ended Steel pipe pile model

3.1.3. Surface Roughness of Pile Materials

The roughness of a surface is an important feature to consider when determining whether it is suitable for a given purpose. Rough surfaces degrade more quickly than smoother surfaces. Surfaces that are rougher are more prone to corrosion and cracking, but they can also improve adhesion. (Figure 3.4.) Below shows the pile's surface roughness.

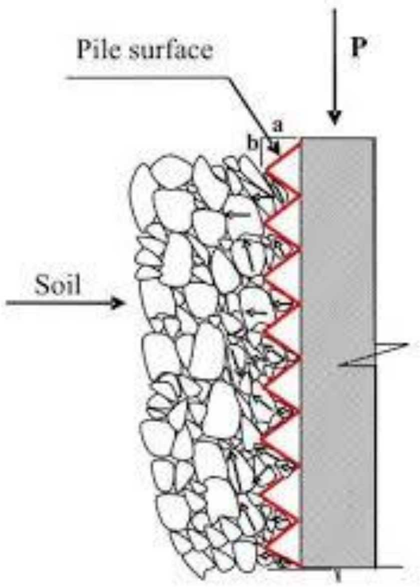


Figure 3.4. The piles surface roughness

As the roughness of the surface increases, so the lateral earth pressure coefficient increases. This shows that pile surface roughness causes the sand to dilate more during loading, increasing the magnitude of radial effectual stress beside the pile surface. The average unit shaft resistance increases as the surface roughness increases. However, the increase in radial effective stress induced by sand dilatation during loading also has an impact.

Ruben et al., indicated that the shaft resistance $q_{sL,\ avg.}$ mobilized in tensile loading increases with increasing pile surface roughness and sand relative density. The maximum values of $q_{sL,\ avg.}$ measured for the model pile with the rough shaft are 134 and 55 kPa in dense and medium-dense sand. Similarly, for the model pile with the medium-rough shaft, the maximum values of $q_{sL,\ avg.}$ are 124 and 41 kPa in dense and medium-dense sand. Finally, for the model pile with the smooth shaft, the maximum values of $q_{sL,\ avg.}$ are 58 and 26 kPa for dense and medium-dense sand. Therefore, they concluded that increasing the roughness of the pile shaft results in an increase of the average unit shaft resistance $q_{sL,\ avg.}$ this is observed for experiments performed in dense and medium-dense sand. The effect of the surface roughness is more pronounced in dense sand, for which sharper increases of $q_{sL,\ avg.}$ is observed for the rough surfaces (with relative roughness R^*_n 0.063 and 0.145) than for the smooth surface (R^*_n 0.002) [39].

Mutitoyo SJ-201 surface roughness tester was used to determine the surface roughness of the steel materials. The mean surface roughness parameters obtained as a result of the measurements performed are shown in (Figure 3.5.).

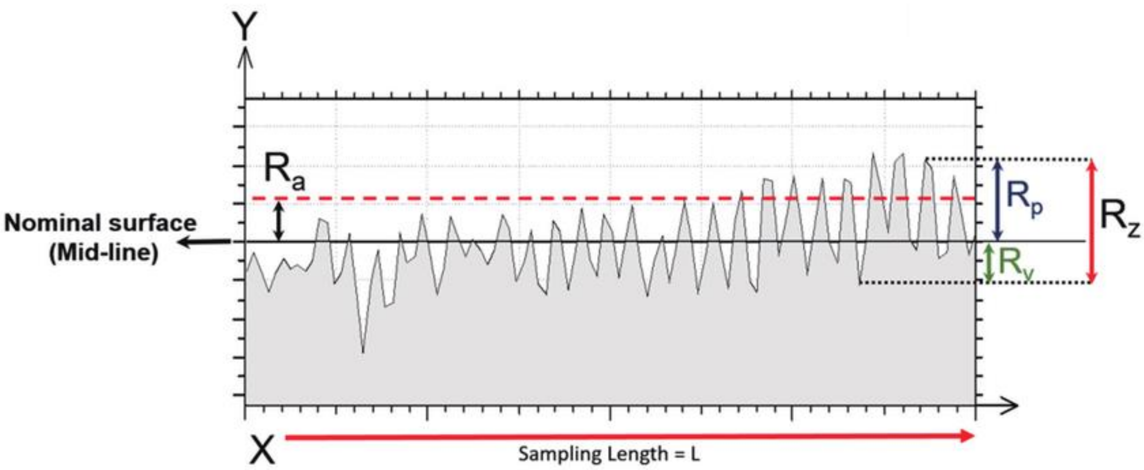


Figure 3.5. Surface roughness parameters

Where:

R_a : Arithmetical mean roughness

R_p : Maximum peak height

R_v : Maximum valley depth

R_z : Linear distance between the top of peak and base of the valley

$$R_z = R_p + R_v \tag{3.1}$$

The all values of R_a and R_y for steel pile material are shown in (Table 3.2.) below

Table 3.2. Values of *Ra*, *Ry* of pile materials

Model Pile	R_a	R_y
Steel	0.55	3.43

3.2. Relative Density of Model Experiments

The relative density of the model sand had to be determined (i.e., maximum and minimum relative density). A random sample of sand is taken and oven-dried for 24 hours, after which the relative density of model sand is measured according to ASTM D4253 - 16.

Hand compactors were used in this study to obtain four relative densities of sand, which are needed for pile-sand model experiments. A Proter brand electro-pneumatic hammer was used for this purpose, and a steel tamper plate (15 cm x 15 cm) was manufactured for compaction of the sand. To avoid crushing the sand particles, a plastic framework of the same dimensions as the steel plate was screw bolted to the bottom of the steel base. As shown in (Figure 3.6.) below.

Figure 3.6. Proter brand electro-pneumatic hammer

Generally, a wooden box with dimensions of 42 x 27.8 x 11.2 cm was used to determine the relative densities of sand. Calibration was carried out in the laboratory through a series of trial experiments, and four relative densities were discovered (Dr= 10%, 40%, 65 %, and 90%). 10% relative density was achieved by pouring sand into a box at a height of 15 cm using a plastic hose, 40% relative density was achieved by pouring sand into a box every 10 cm and compacting it with a hammer for one moment. Pouring sand into a box every 10 cm and compacting it with a hammer for 2 seconds yielded 65% relative density, whereas pouring sand into a box every 5 cm yielded 90% relative density after compacting each layer for 8 seconds. Since it was necessary to find the dry unit weight, a sample was taken at the end of each trial test to determine its moisture content. The calibration of relative density in the laboratory is shown in (Figure 3.7.). The dry unit weights of sand corresponding to relative densities, void ratios, and compaction method are shortened in (Table 3.3.).

Figure 3.7. Calibration of relative density in the laboratory

Table 3.3. Dry unit weights of sand corresponding to relative densities, void ratios, and compaction method

Compaction Process	Average Dry Unit Weight (γd), (kN/m^3)	Void Ratio (e)	Relative Density (Dr,%)
The model sand pours from a height of 15 cm until the model tank is filled to a required depth.	14.6	0.86	10
Each point (15 cm x 15 cm) of each 10 cm of soil layers is compacted for less than a second (for a moment only) after pouring the sand from a height of 5 cm.	15.5	0.75	40
Each point (15 cm x 15 cm) of each 10 cm of soil layers is compacted for 2 seconds after pouring the sand from a height of 5 cm.	16.3	0.66	65
Each point (15 cm x 15 cm) of each 5 cm of soil layers is compacted for 8 seconds after pouring the sand from a height of 30 cm.	17.3	0.57	90

3.3. Model set-up formulation

The load-bearing capacities of axially loaded piles were measured in a series of laboratory tests. Two model steel piles have been used in this study, closed-ended and opened-ended steel pipe piles, with a diameter of 50mm and height of 60mm while the embedded length of piles was L_b = 500mm, the surface roughness of each pile material are the same. Piles are mounted in the center of a specially built steel tank and filled vertically in the piles' center under various model sand conditions. A new apparatus was created to repeat the pile load test in the laboratory which consists of a soil tank with dimensions (75 cm x 75 cm x 100 cm). as shown in (Figure 3.8.).

Figure 3.8. Model set-up formulation

Sufficient details of the single-model steel piles load tests setup, as well as, the soil model tank and other facilities are shown in (Figure 3.9.). All of the accessories for the bearing capacity test system are listed below.

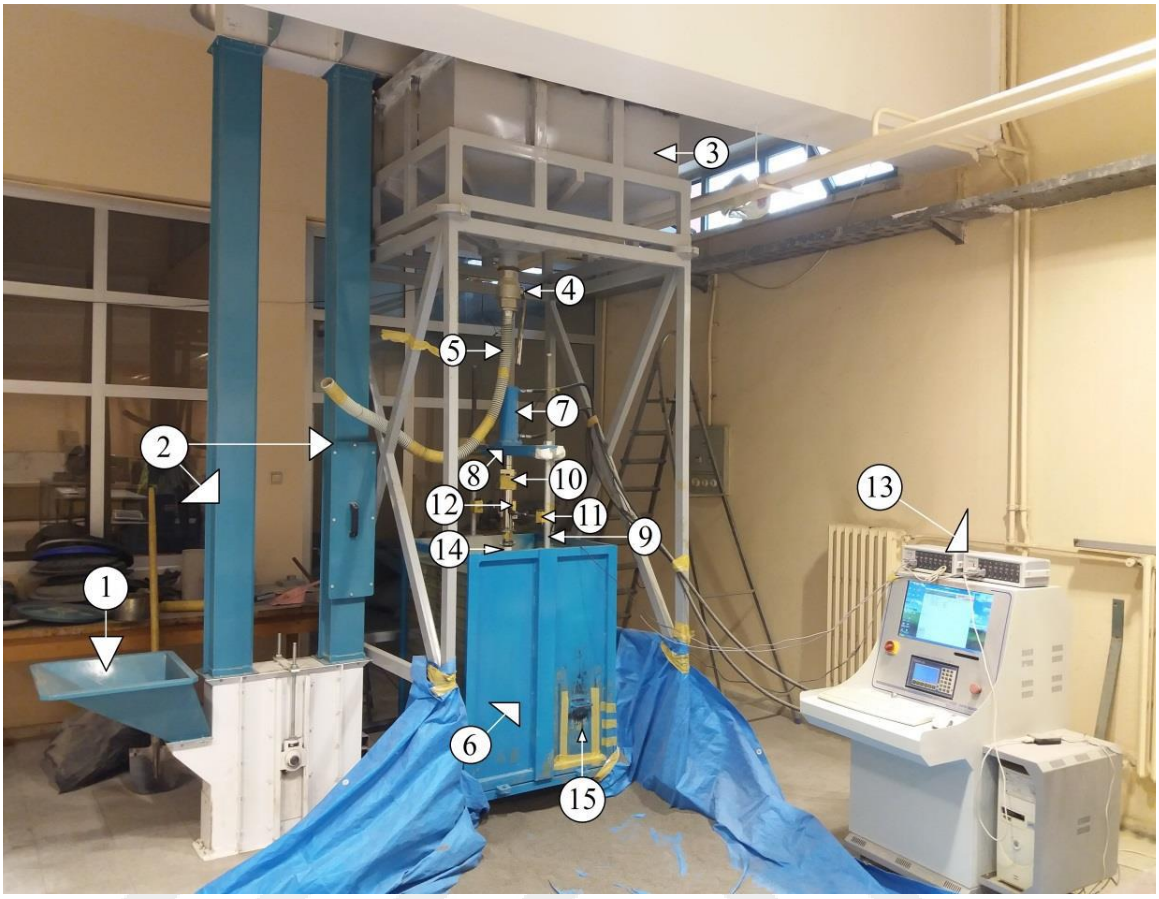


Figure 3.9. Test system of bearing capacity

The model of bearing capacity test system contains the following parts:

(1) Funnel

(2) vertical bucket elevator

(3) Hopper

(4) Valve

(5) Flexible plastic pipe

(6) Model tank

(7) Hydraulic jack

(8) Loading beam

(9) Steel pipe column

(10) Load cell

(11) Magnetic holder

(12) LVDT

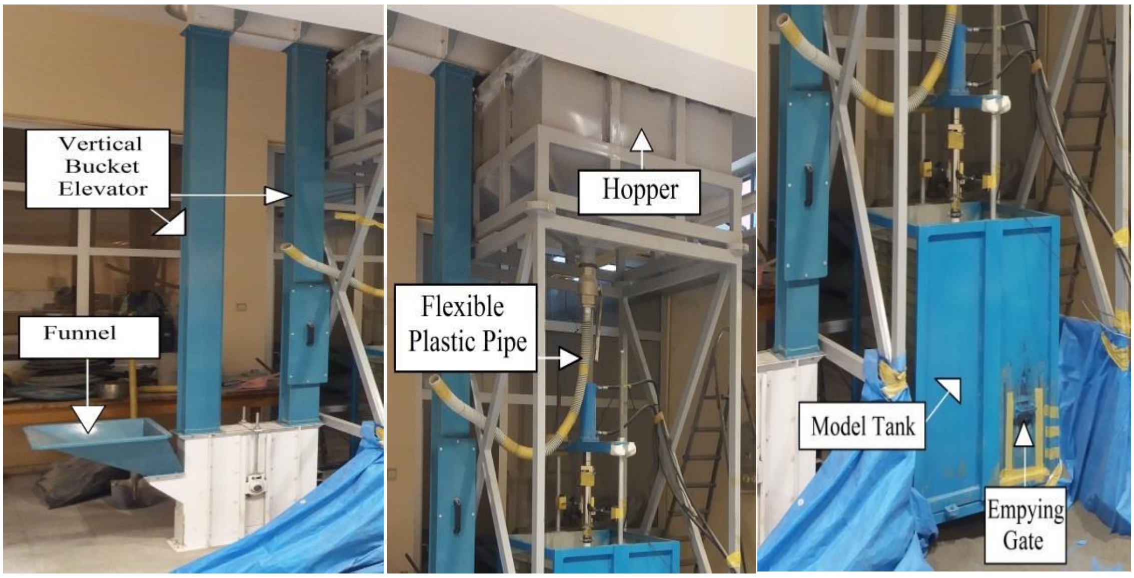
(13) Data acquisition system

(14) Single-Model pile, and

(15) Emptying gate

The soil tank that was used was made of steel and had the dimensions mentioned above. The tank's dimensions were chosen in this way to ensure that there was no interference between the failure area around the model pile and the tank's walls.

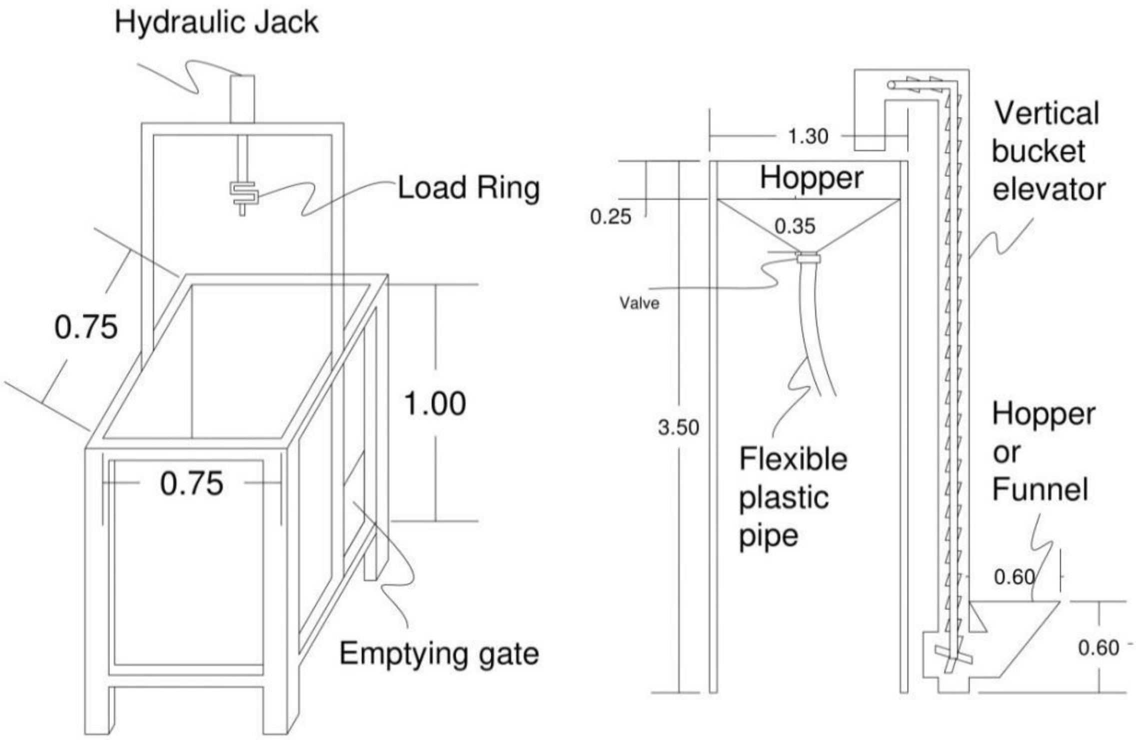
A flexible plastic tube is used to pour the sand into the model tank after it has been moved and stored at the top funnel or sand hopper (Figure 3.10.b.). Behavior is determined by conducting an axial load test on a single-model pile. The model tank is emptied after each experiment is completed by opening a small gate on the model tank's underside (Figure 3.10.c.). The model system is depicted in diagram form in (Figure 3.10.).



(a) (b) (c)

Figure 3.10. (a) Vertical bucket elevator, (b) hopper and flexible plastic pipe, and (c) soil model tank

The model system is illustrated schematically in (Figure 3.11.) below.



(a) (b) (c)

Figure 3.11. (a) Soil model tank, (b) hopper and flexible plastic pipe, and (c) Vertical bucket elevator

Bolton et al., proposed two guidelines to avoid the impact of boundary and scale on the model piles' bearing capacity. According to them, the ratio of the soil tank diameter to the model pile diameter (D_{tank}/D_{pile}) must be greater than 8, and the model pile diameter must be greater than the average diameter of the soil particles (20*D50). In this study (D_{tank}/D_{pile}) = 15 which is greater than 8, and the model pile diameter = 50mm which is greater than (20*D50 = 9.5mm). (Table 3.4.) Dimensions of soil model tank and model piles used by some researchers [40].

Table 3.4. Dimensions of soil model tank and model piles used by some researcher [41-46]

References	Soil model tank diameter (mm)	Model pile diameter (mm)	Soil model tank to model pile diameter ratio
Robinsky and Morrison (1964)*	501 x 711	20.5 - 37.5	24.44 – 13.36
Shin et al. (1993)*	457 x 457	25.4	17.99
Al-Mhaidib (2001)*	450	30	15
Mayoral et al. (2005)*	510	51	10
Nanda and Patra (2011)*	750	32	23.44
Sheikhtaheri (2014)	300	38.3	7.8
		31.75	9.45
		19.25	15.6
Current Study	750x750	50	15
Note: the remarked references with (*) adopted from (Taylan, 2013).			

According to foundation engineering design, applied load stress on the foundation will affect the soil layers up to a depth of (1.5B to 2B), where B is the foundation's short dimension. As a result, the mode piles were mounted such that the pile's bottom was 400 mm above the soil tank's bottom (400 mm >2B or 2D).

The pile was attached to the detachable loading shaft by special types of epoxy adhesive for mounting model piles (5 minutes), in each test, the tank was filled to 400 mm with the desired relative density, then the pile was mounted and lowered until the bottom of the pile sat on the sand, after which it was tested vertically on all sides as shown in (Figure 3.12.), and the tank was filled to the desired depth.

Figure 3.12. Attaching piles to the loading shaft

3.4. Hydraulic Jack and Loading Machine

In this experiment, a specially built steel tank (75x75x100 cm) is used. The test device, which has a loading capacity of more than 2.5 tons, is set up using a rectangular steel loading frame braced by two steel pipe columns. The hydraulic jack is fixed on the loading frame in the center of the model tank with screw bolts. The hydraulic machine has a capacity of 30 kN and is operated both electrically and mechanically. (Figure 3.13.) Below shows the loading frame and other accessories.

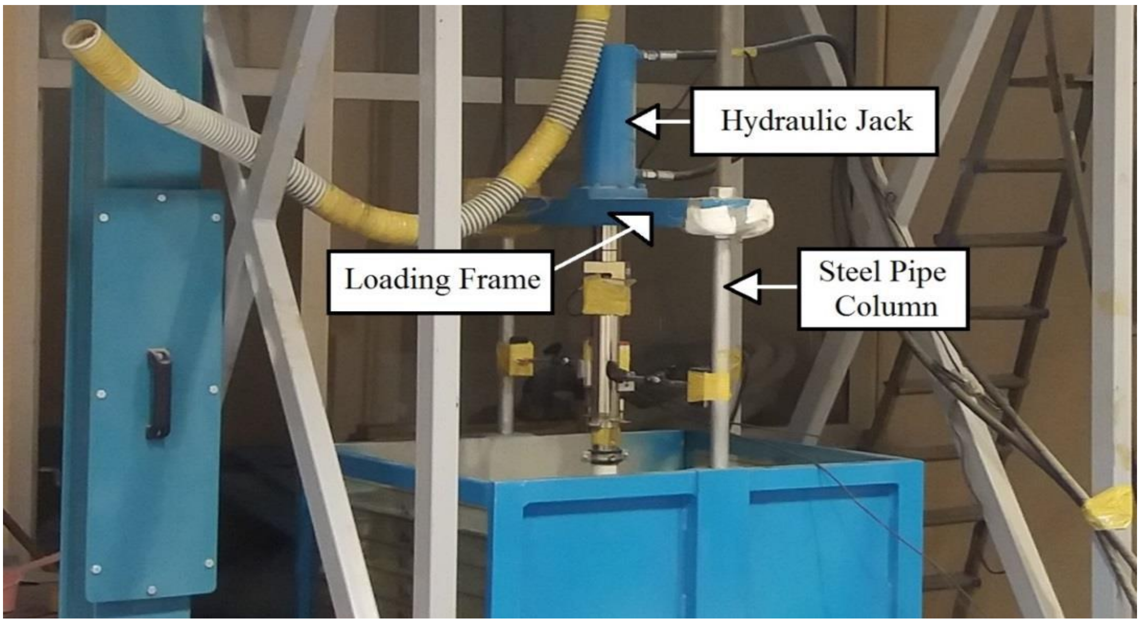


Figure 3.13. Loading frame and other accessories

3.5. Load-Displacement Measurement of Single-Model Piles

Two Linear Variable Displacement Transducers (LVDT) are used to calculate the vertical displacement of the single-model piles. Two small strong steel L-shape angle bracket bars (50 x 50 mm) are mounted on both sides of the pile head (i.e., the left and right sides of the pile head) with a pipe clamp, and then the light-weight LVDTs are put on them. LVDTs installed next to piles are kept in place by magnetic holders. The measurement capabilities of the LDVTs used in this study were 150 mm. A Keli brand S-type 5tons capacity load cell is used to calculate the practical load from the unit. The load cell is connected to the device via data loggers and records the applied load automatically. The data collection system measures and records the sum of load and vertical displacement in the computer. The load cell beam, as well as a few other accessories, are depicted in (figure 3.14.).

Figure 3.14. Load-displacement Measurement of Single-Model Piles

Where:

(1) LVDT

(2) Magnetic holder

(3) Steel pile

(4) Data collector (computer)

3.6. Testing Procedure

The bearing capacities (ultimate, base resistance or base capacity, and shaft capacity) of single-model steel piles in the model sand are determined through a series of model experiments.

In the subsections below, the proper procedures for measuring the bearing capacities of single-model steel piles are defined.

3.6.1. Measurement of a Single Model Pile's Total Bearing Capacity

This section explains how to fill a tank with sand and perform single model pile tests for open-ended and closed-ended piles under axial loading, as well as how to calculate their total bearing power.

The model tank is filled to a depth of 90 cm for each relative density under a given condition to perform the ultimate bearing capacity of single-model steel piles. For example, the model tank is filled to the appropriate depth (i.e., 90cm) by pouring model sand normally from a height of 10 to 15 cm using a flexible plastic pipe for Dr = 10% as in (Figure 3.15).

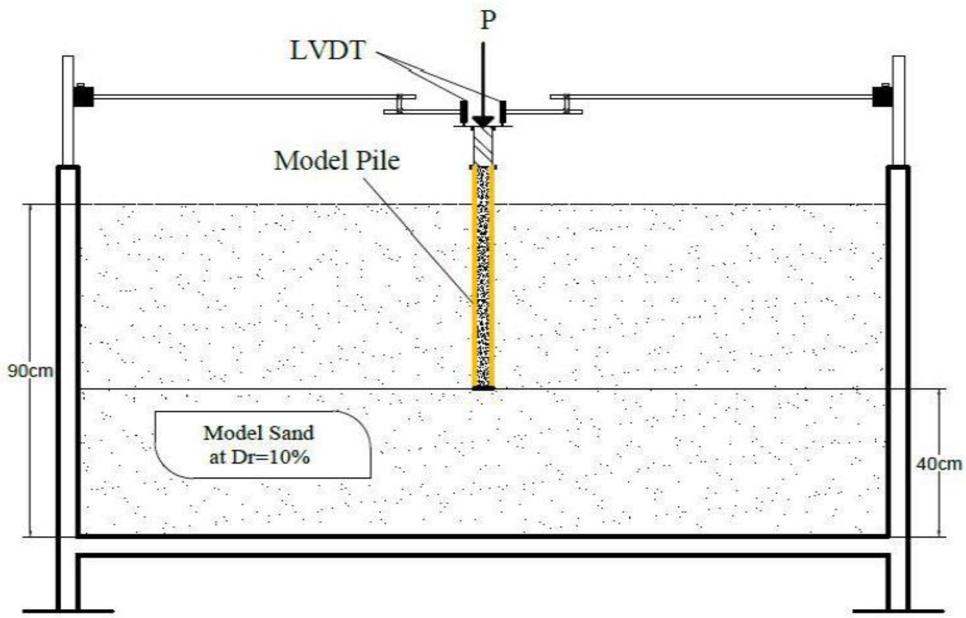


Figure 3.15. A single-model closed-ended pile installed in the model tank to conduct the ultimate bearing capacity model experiment at Dr = 10%

In addition, the needed depth of the model tank is filled in 10 cm soil layers by pouring model sand from a height of not more than 5 cm for Dr = 40% and 65% as cleared in (Figure 3.16, and 3.17.). Then, for Dr = 40% and 65%, each hammer point of (15 x 15 cm) in each (10 cm) sand layer is compacted for a moment (less than one second) and two seconds, respectively.

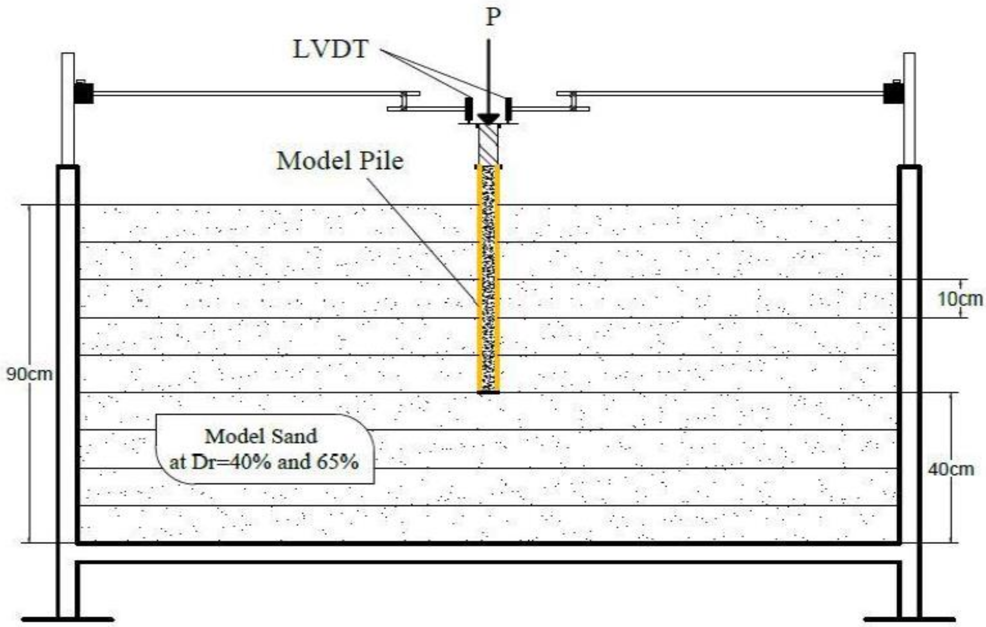


Figure 3.16. A single-model closed-ended steel pile was installed in the model tank to conduct the ultimate bearing capacity model experiment at Dr = 40% and 65%

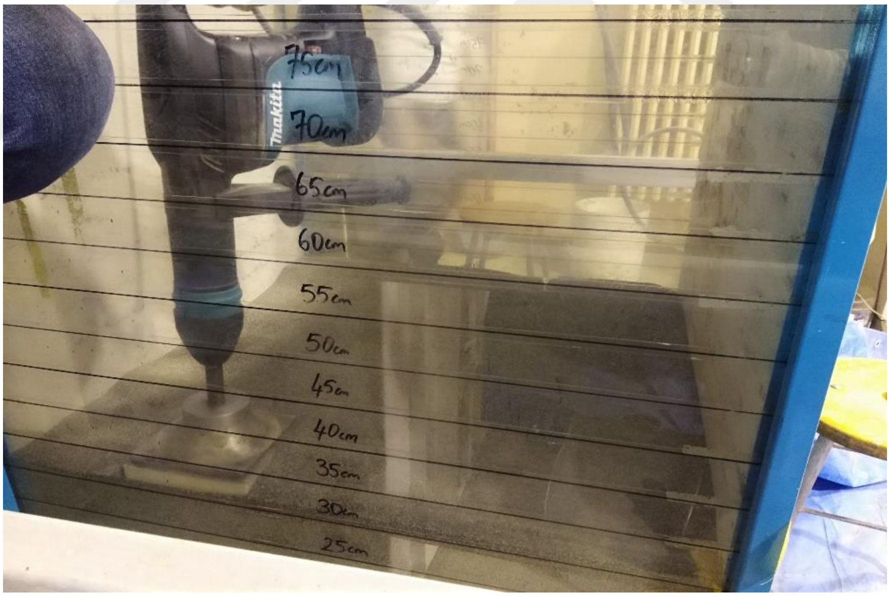


Figure 3.17. Hammer compacting each 10cm for Dr = 40% and 65%

However, in the case of Dr = 90% (Figure 3.18.), the model sand is poured from a height of 10 cm, the sand layers are 5 cm thick, and each (15 x 15 cm) hammer point in each (5 cm) sand layer is compacted for 8 seconds. A Proter brand electro-pneumatic hammer with a tamper plate (15 cm x 15 cm) is used to compact the model sand.

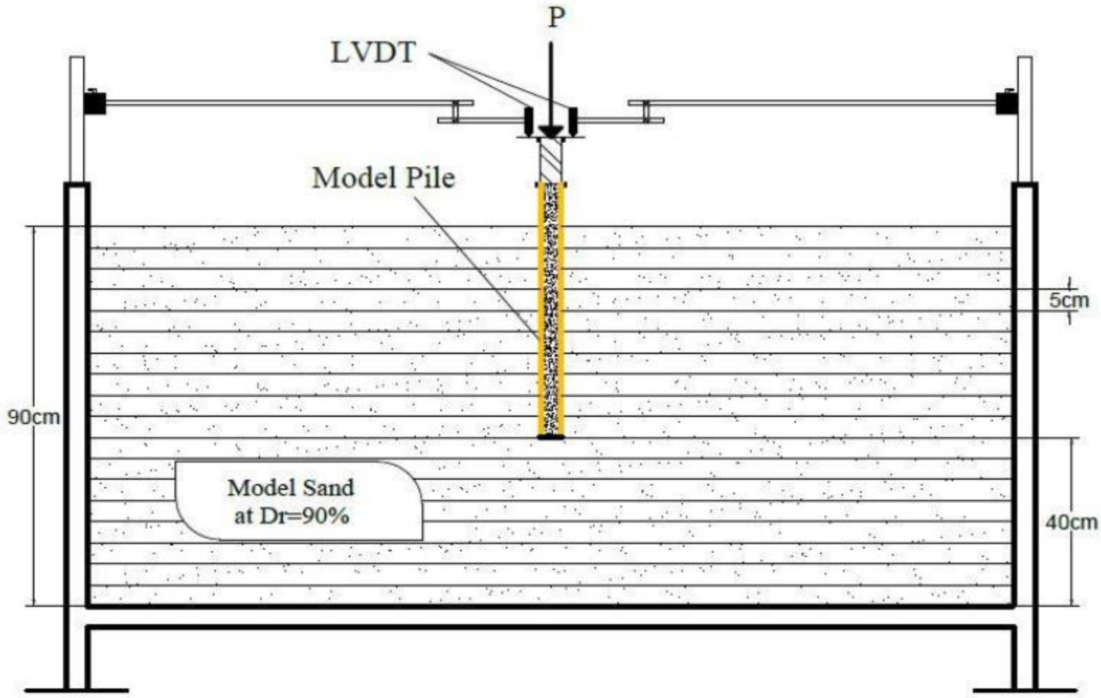
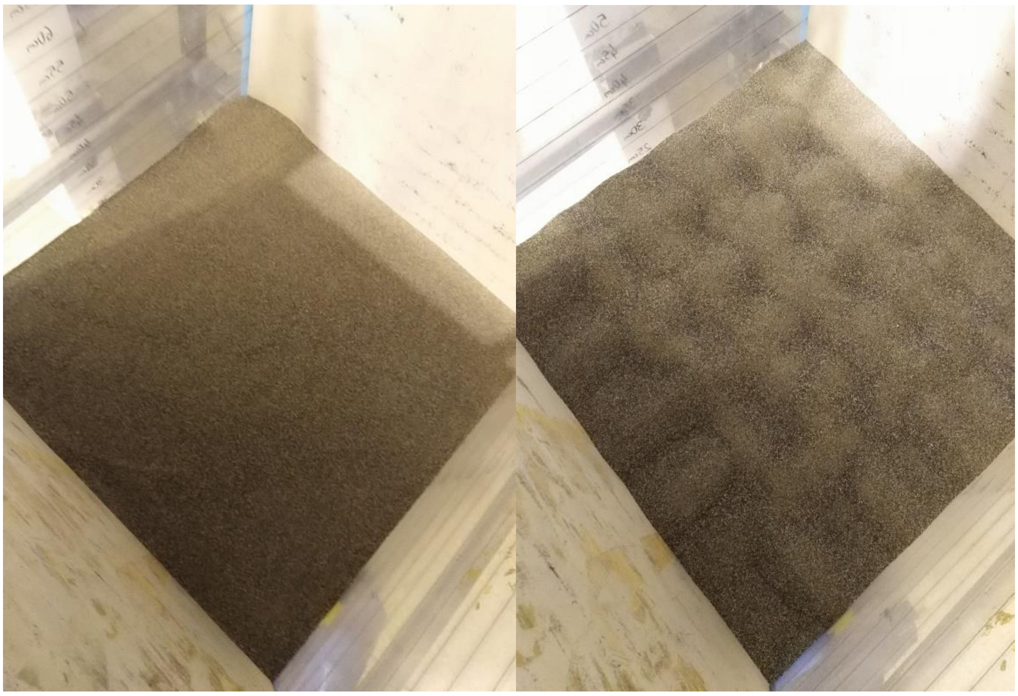


Figure 3.18. A single-model closed-ended pile was installed in the model tank to conduct the ultimate bearing capacity model experiment at Dr = 90%

Sand surface before compaction and after compactions are shown in (Figure 3.19.) below.



(a) (b)

Figure 3.19. The surface of sand layers. (a) before compacting, and (b) after compacting each (15 x 15 cm) hammer point

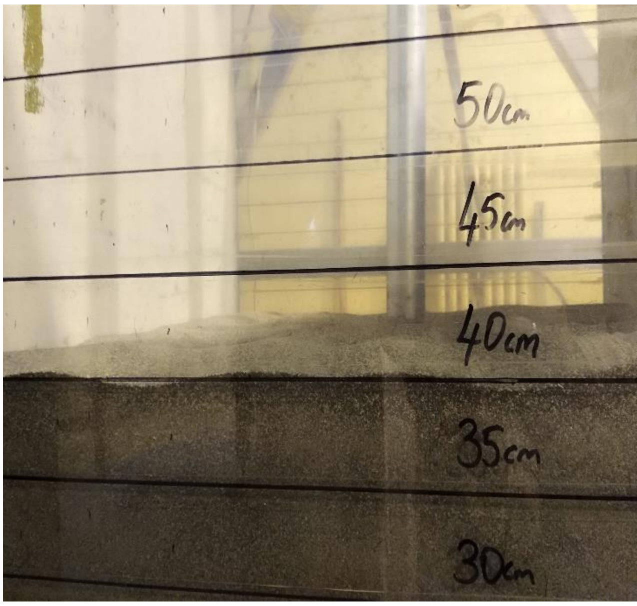
In this study, the hydraulic machine is used as a load control system, and single-model steel pipe piles are filled at various loading speeds based on relative densities until the pile displacement exceeds 40 mm. In (Table 3.5.) below cleared the all sand compaction procedures.

Table 3.5. A brief summary of the sand compaction procedures

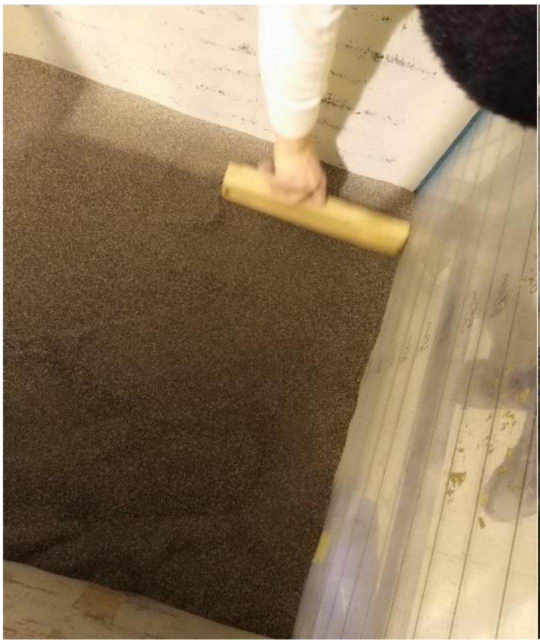
Relative Density (Dr,%)	Compaction Process	Dry Unit Weight(γd), (kN/m^3)	Void Ratio (e)
10	The model tank is filled to the necessary depth (90 cm for ultimate bearing capacity, pile shaft capacity, and pile base resistance, and 40 cm for pile base resistance). The model sand is poured normally from a height of 15 cm using a flexible plastic pipe; however, care must be taken because any mistake would significantly alter the relative density.	14.6	0.86
40	As previously stated in the Dr = 10% section, the model tank is filled to the appropriate depth (i.e., 90cm and 40cm). For each 10 cm layer of sand, a flexible plastic pipe is used to pour the model sand from a height of no more than 5 cm. Then, for a moment (less than one second), each point of (15 * 15 cm) in each layer of 10 cm sand is compacted.	15.5	0.75
65	The same process as for Dr = 40% is followed, with the exception that each point (15 * 15 cm) in each layer of 10 cm of sand is compacted for 2 seconds.	16.3	0.66
90	As previously stated in the Dr = 10% section, the model tank is filled to the appropriate depth (i.e., 90cm and 40cm). For each 5 cm layer of sand, a flexible plastic pipe is used to pour the model sand from a height of 10 to 15 cm. Then, for 8 seconds, each point of (15 * 15 cm) in each layer of 5 cm sand is compacted.	17.3	0.57

3.6.2. Conducting Piles Base Capacity Model Experiments

The model tank was filled to a depth of 40 cm to test the base bearing capacity of a single model pile (figure 3.20 a and b). For each relative density, the same procedures were used as before. After the model tank has been filled to a depth of 40 cm, the surface of the sand was leveled and balanced using a bubble balance (figure 3.20 c) then the piles are carefully lowered to a level that just touches the sand (figure 3.20 d), and the load is applied. Figure (3.20) Shows a pile installed to conduct model experiments of the base-bearing capacity.



(a) (b)



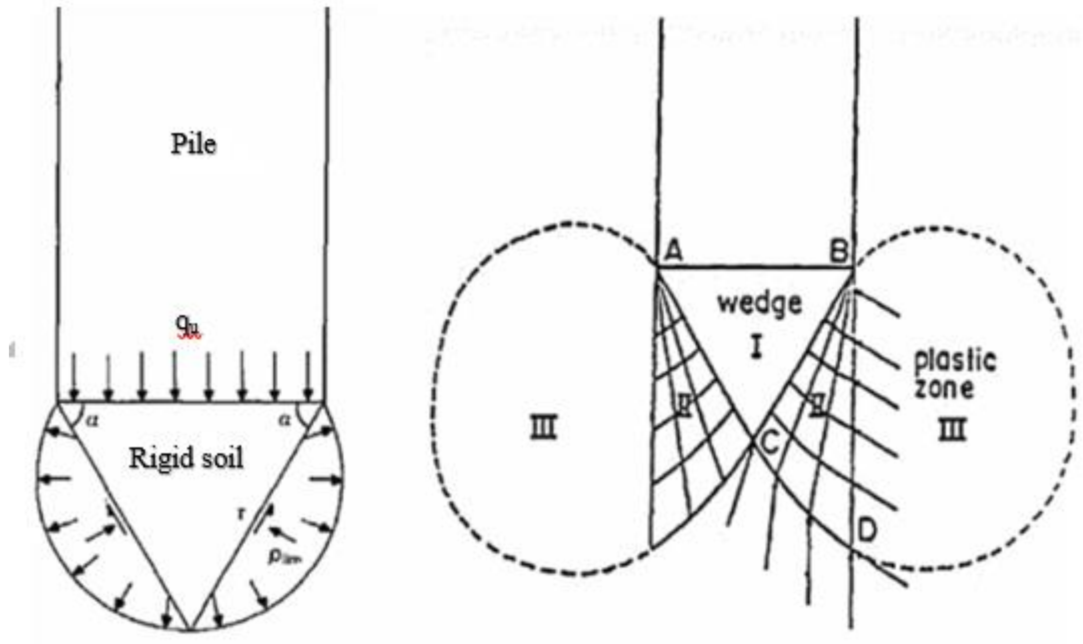
(c) (d)

Figure 3.20. (a), and (b) model tank filled to a depth of 40 cm, (c) is smoothing the sand surface by the small ruler, and (d) is the pile touching the sand in a depth of 40cm

3.6.3. Shape of Failure Surface Below the Pile Tip

As the pile enters the soil, the soil below the pile top may form a flat or conical failure mode. A cylindrical hollow is created when the soil underneath the plugged pile tip is pushed and expanded. The increasing cylindrical cavity thus has a relationship with the soil pressure induced by penetration resistance. The relationship between pile bearing failure and the formation of a spherical cavity below the pile tip is described by Gibson (1950) [47], as shown in (Figure 3.21 a). When the rigid cone is under isotropic loads, the soil below the pile tip tends to form a rigid cone with an angle that is dependent on the angle of internal friction of the soil, and the stresses in the conical region outside the rigid cone are equal to the stresses in the spherical cavity expansion.

Vesic, describes how the spherical cavity beneath the pile formed The resistance of the cone tip below the pile is correlated to the tip [48], as shown in (Figure 3.21 b). Vesic, and Lehane et al., describe the highest radial effective stress at the location at the pile tip that creates peak shaft friction values (a few diameters above pile tip) [48, 49].



(a) (b)

Figure 3.21. The cavity develop shear under the pile tip; (a) Gibson (1950) the relationship between the cavity expansion limit pressure and the end bearing capacity [47], and (b) Vesic (1977) cavity expansion under pile tip [48]

The degree of soil plugging inside the pipe piles determines the form of the failure surface for open-ended pipe piles. Figure (3.22) depicts the flat shape of the failure surface created under classic open-ended pipe piles for pile penetration depth (500mm) due to partially plugged open-ended pipe piles.

Figure 3.22. Flat shape of the failure surface created under classic open-ended pipe pile

3.7. Effect of Loading Rate

The result of loading rate on the pile bearing capacity was studied by many researchers. Dijkstra, reported that the pile bearing capacity mounted in unsaturated sand can be significantly affected by the loading rate. The axial bearing capacity of a single-model pile installed in sand increases as the loading rates increase, and the axial bearing capacity of a model pile group installed in sand increases with the loading rate [50].

Researchers have used a variety of loading rates in the literature, but in general, no more than 2 mm/min is recommended, with 1 mm/min being the most common. As a result, the loading rates for ultimate bearing capacity and base resistance experiments of single-model piles in this study are held between 1 and 1.30 mm/min. Since the hydraulic jack used in this study does not have a displacement control, it is difficult to achieve the necessary loading rate (i.e. 1 mm/min) within this range.

4. Results And Discussion

Two single-model steel pipe piles (open-ended and closed-ended) have already been described and installed in the specially designed model steel tank with all necessary attachments. The model sand was compacted at varied relative densities, and then the single model steel pipe piles were loaded, first open-ended pipe pile, then closed-ended pipe pile, to determine their load vs settlement behavior. This chapter examines the experimental results of model piles and compares them to theoretical predictions.

4.1. Ultimate Bearing Capacity

For the relative densities of (10%, 40%, 65%, and 90%), pile load experiments were done for both open-ended and closed-ended steel pipe piles. The outcomes are represented by load-settlement curves as shown in (Figures 4.1. to 4.4.).

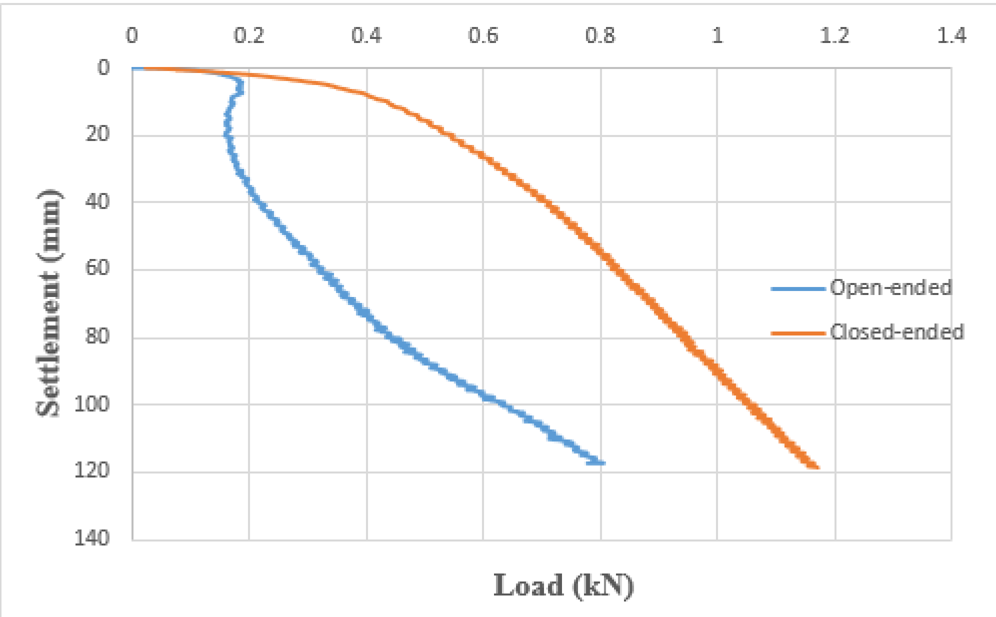


Figure 4.1. Load-displacement curves of model piles for total bearing capacity test at Dr = 10%

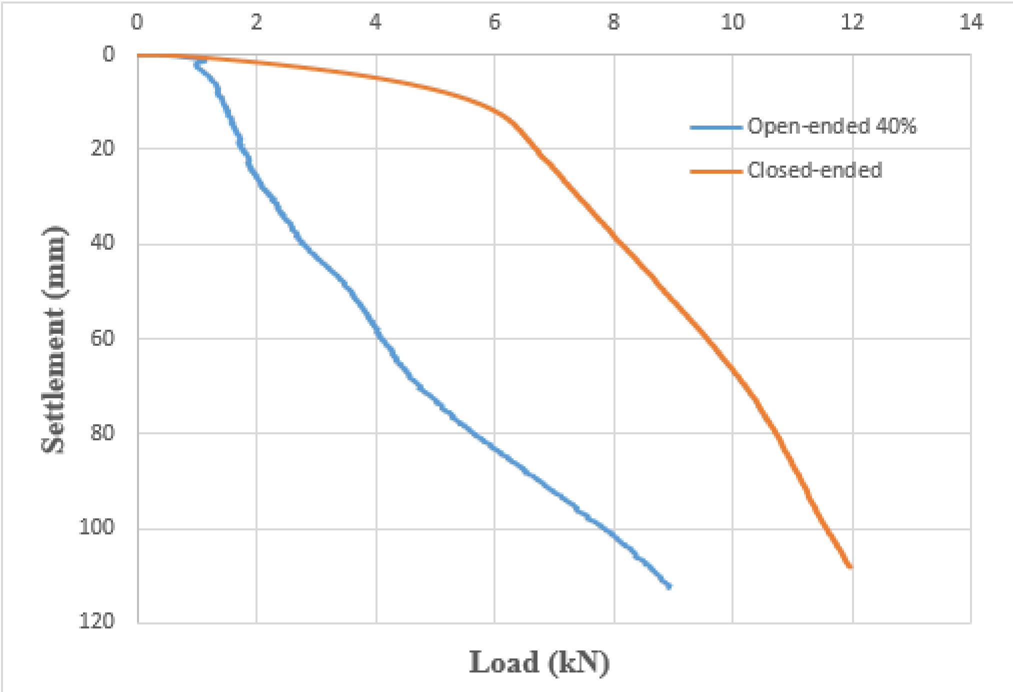


Figure 4.2. Load-displacement curves of model piles for total bearing capacity test at Dr = 40%

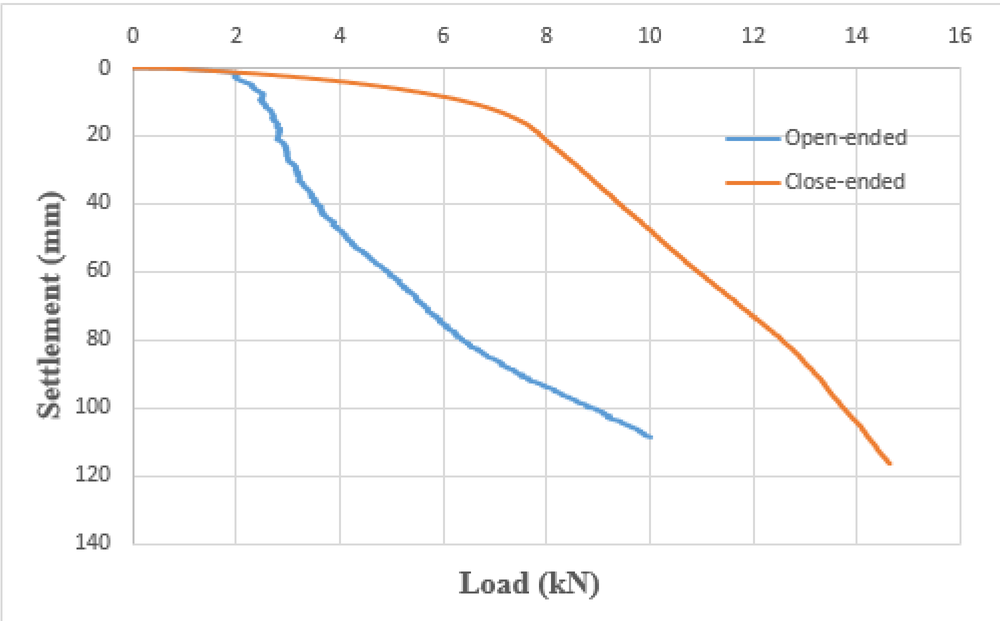


Figure 4.3. Load-displacement curves of model piles for total bearing capacity test at Dr = 65%

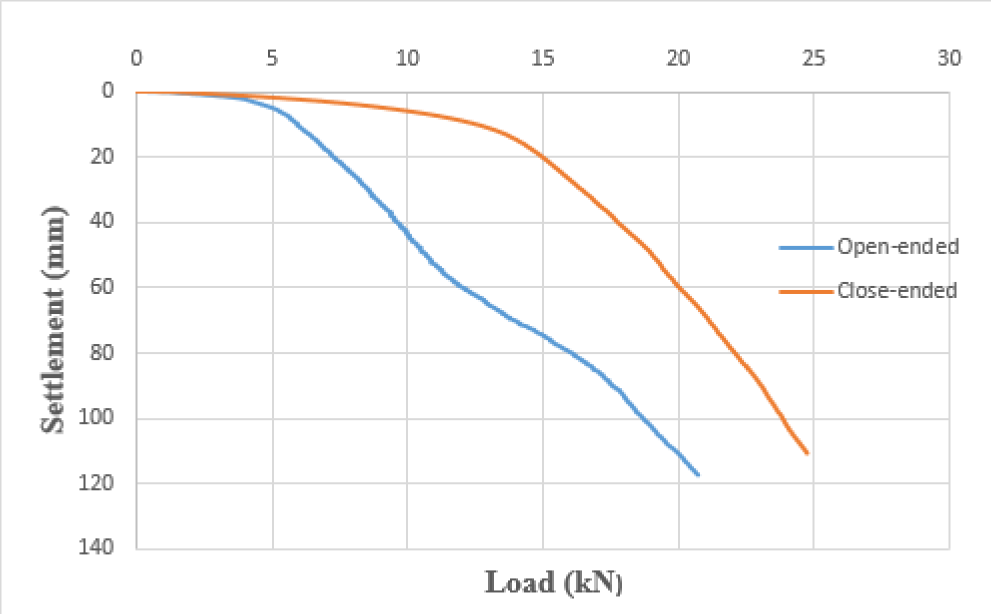


Figure 4.4. Load-displacement curves of model piles for total bearing capacity test at Dr = 90%

The ultimate bearing capacity of single-model steel piles in (Table 4.1.) included the detachable shaft weight. In addition, all (mm and kN) are represented settlement at model failures and ultimate bearing capacity of single-model composite piles, respectively.

Table 4.1. Ultimate bearing capacity selected from the load-settlement curves of the model piles plus the weight of the detachable shaft used in the experiments

	Model Sand							
	Dr = 10%		Dr = 40%		Dr = 65%		Dr = 90%	
Steel pile model	Settlement (mm)	Load (kN)	Settlement (mm)	Load (kN)	Settlement (mm)	Load (kN)	Settlement (mm)	Load (kN)
Open-ended	3.9426	0.186	4.0668	1.15	4.6836	2.229	6.3001	5.33
Close-ended	4.5454	0.3194	9.5466	5.5724	11.5024	6.8084	11.9266	13.28

The ultimate bearing capacity of the model piles achieved in the laboratory demonstrated that the total bearing capability of single model piles (opened-ended and closed-ended) piles increases in a non-linear relationship with the increasing relative density of sand. Additionally, with increasing relative density, the settlement required for mobilization of the entire ultimate bearing capacity of the soil also increases non-linearly in (closed-ended piles) and decreasing non-linearly in (opened-ended piles). The ultimate bearing capacity and settlements of (opened-ended and closed-ended) steel piles are plotted against the relative density of the sand in (Figures 4.5. and 4.6.), respectively.

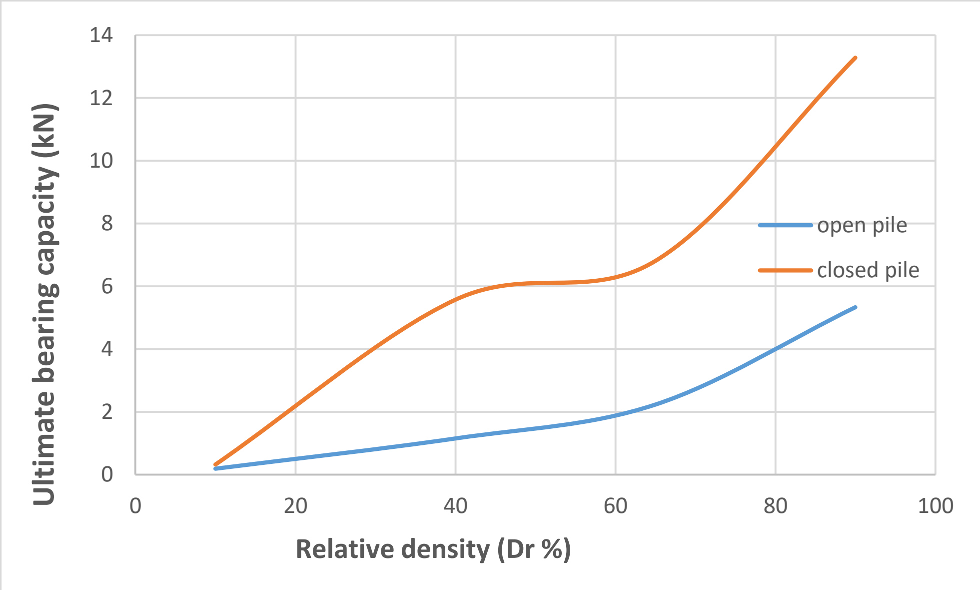


Figure 4.5. Ultimate bearing capacity of model piles versus relative density

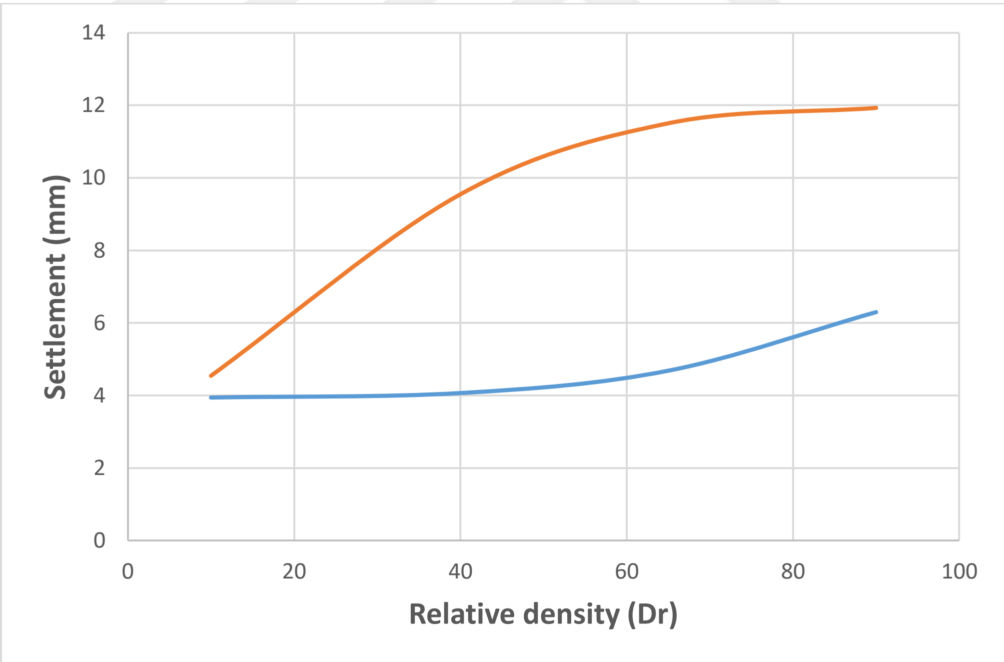


Figure 4.6. Displacement versus relative density for the total bearing capacity of model piles

4.2. Finite Element Analysis

Geotechnical engineering problems can very difficult and complicated, because of their boundary conditions. However, some researchers have devised certain simpler theories that can be used to solve these types of situations. These problems can get more complex as a result of soil variability, and numerical analysis can be quite valuable in this instance.

While traditional pile design approaches are based on empirical correlations, they still produce unreliable pile bearing capacity estimates. For investigating the behavior of the pile-soil interface under axial loading, the finite element analysis developed recently has produced more reliable results [51]. Although field load tests can more reliably estimate pile bearing capacity, they need time, cost, experience, professional training, and heavy equipment, thus they are not desirable for economic reasons, especially for low-budget projects. As a result, it has recently been suggested that pile bearing capacity be determined using finite analysis methods.

In the technique of the finite element analysis, the domain of the problems is meshed into small elements, which are composed of hundreds or thousands of small elements and nodes, suitable boundary conditions and proper essential models, such as Mohr-Coulomb and linearly elastic, are applied, and equations are created for all of the nodes, and by solving these equations all variables are found at the nodes.

Some people develop their own finite element program that can be used to solve geotechnical engineering challenges. PLAXIS and GEO-SLOPE are two common numerical finite element programs used by geotechnical engineers on a regular basis. Other more powerful software, such as ABAQUS and ANSYS, can be used in a variety of engineering elements, including materials, structures, and concrete, as well as in the analysis of geotechnical engineering problems. And both of these programs are used in many colleges since they are effective for both teaching and research.

4.2.1. Plaxis 3D Program

Finite element analysis has recently been used to investigate laboratory work, theoretical investigations, and field load tests. Model tests of two single-model steel pipe piles were conducted in the laboratory at varied relative densities of model sand (i.e., Dr = 10%, Dr = 40%, Dr = 65 %, Dr = 90 %) and have already been presented and discussed in Chapter Three, and are analyzed with PLAXIS 3D in this Chapter.

PLAXIS 3D is the most widely used graphical user interface geotechnical program. It is based on finite element analysis and is frequently used by geotechnical engineers to model and analyze soil-structure interactions such as foundations, retaining walls, soil slope stability, etc. The program is set up such that the user may simply model any soil-structure interaction problems and investigate the behavior of the structure under load.

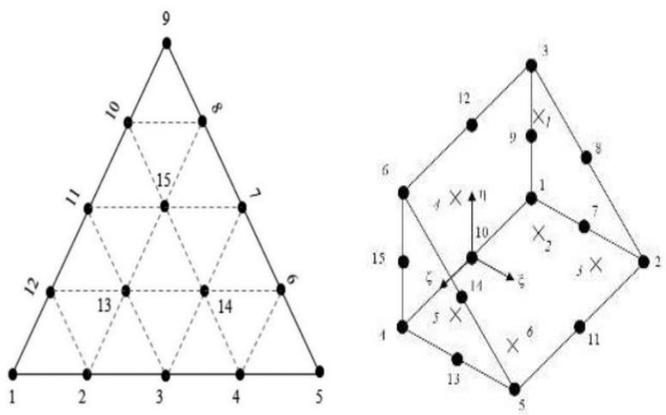
4.2.2. Single Pile Finite Element Analysis

Typically, three major alternative methodologies are taken into account in the finite element investigation of a single model pile such as (i) Linear Elastic (LE) model where the soils around the pile toe and under the pile toe are considered to be linearly elastic, or a Complete Non-Linear (CNL) analysis such as (ii) Mohr-Coulomb (MC) model and (iii) Hardening Soil (HS) model, where the soil modeled completely based on the Hardening Soil (HS) or the Mohr-Coulomb (MC) model, or sometimes an analysis from the combination based on (NL-LE) is performed, in this combination method the soil near the pile shaft (interface zone) is modeled using the HS model, and the other remaining area of the soils is demonstrated using either LE or MC material.

In this study, the computational finite element software PLAXIS 3D was utilized to analyze single model steel pipe piles (open-ended and closed-ended). The dry state was considered for the model sand, and the Mohr-Coulomb failure criteria were employed in the finite element analysis. The four relative densities of sand indicated earlier in this study were used to examine the total of eight model pile load tests. The results were obtained in terms of pile displacement vs axial load in each test.

4.2.3. Boundary Conditions

Plaxis 3D has specified "Standard Fixities" for the boundary condition that is made automatically by the software in the analysis of model piles. Furthermore, rigid interfaces were constructed, implying that no relative movement exists between the nodes of the finite elements representing the model pile and those representing the ground soil. 15-node wedge elements are commonly employed in the three-dimensional analysis. The 15-node elements employed in the analysis are depicted schematically as shown in (Figure 4.7.).

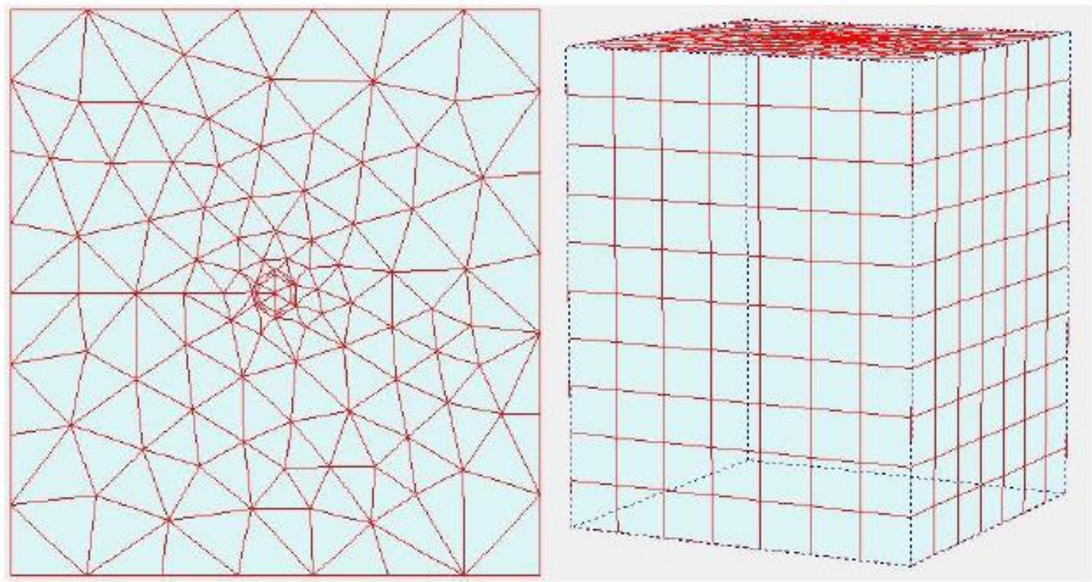


Nodes (●) and strain points (x)

Figure 4.7. Node Wedge Elements in 3D Analysis (Plaxis 3D Foundation Tutorial Manual, 2007)

4.2.4. The Mesh Generation

The mesh is automatically produced by the usual PLAXIS 3D technique, then refined once globally, as in the two-dimensional analysis, but this reasoning does not apply to the three-dimensional analysis (Kaltakci) [52]. In general, the two-dimensional mesh of the top view of the ground soil should be constructed first in the PLAXIS 3D, and then refined for the cluster in which the raft is put in the case of the piling group. The three-dimensional mesh is then produced using the PLAXIS 3D's usual technique. A typical 2D and 3D generated mesh in PLAXIS 3D is shown in (Figure 4.8.).



(a) (b)

Figure 4.8. (a) Two-dimensional generated mesh, and (b) Three-dimensional generated mesh in PLAXIS 3D

4.2.5. The Parametric Study

In the current study, a total of eight PLAXIS 3D three-dimensional analyses are carried out. Single-model steel pipe piles with lengths and diameters of 50 cm and 5 cm, respectively, are used in the parametric analysis. After the mesh was built and the pile was loaded for analysis, this is the typical configuration of the piles in the PLAXIS 3D environment is shown in (Figure 4.9.).

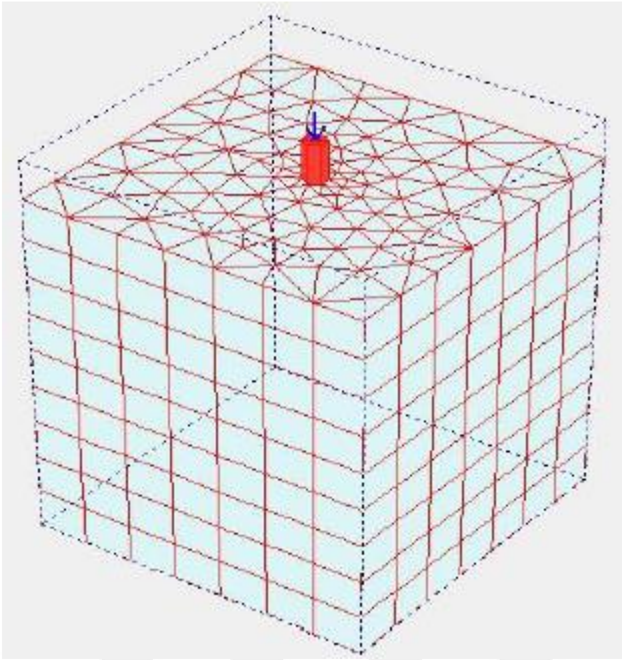


Figure 4.9. A single-model composite pile installed in PLAXIS 3D environment and loaded for Analysis

In this study, the angle of dilatancy of the sand model, and modulus of elasticity and poisson's ratio of model steel pipe piles calculated using the following equations;

$$\psi = \varphi - 30 \quad (4.1)$$

Where;

ψ = angle of dilatancy of model sand.

φ = internal friction angle of model sand.

4.2.6. The Material Parameters Used in the Analysis

Under drained conditions, the sand was modeled to obey the Mohr-Coulomb failure criterion, and the dry unit weight of the sand corresponding to relative density was input to the Plaxis 3D. The model piles (open-ended and closed-ended steel) were designed to be linearly elastic and non-porous, and their unit weight also was given to Plaxis 3D program. (Table 4.2 and 4.3) shows the parameters of the sand and pile materials used in Paxis 3D.

Table 4.2. The parameters of the sand used in Plaxis 3D program [53, 54]

Relative Density (Dr,%)	Average Dry Unit Weight (γ_d), (kN/m^3)	Modulus of Elasticity of the Sand (E) (kN/m^2)	Poisson's ratio	Internal Friction angle of the sand (ϕ)°	Dialatancy angle of the sand (ψ)°	R_{int}	Cohesion kN/m^2
10	14.6	800	0.3	41	11	0.67	0.001
40	15.5	6300	0.3	44.3	14.3	0.67	0.1
65	16.3	12000	0.3	48.7	18.7	0.67	0.3
90	17.3	15500	0.3	52.4	22.4	0.67	0.5

Table 4.3. The parameters of the model piles (open-ended and closed-ended) steel used in Plaxis 3D program [55, 56]

Model Pile	Average Dry Unit Weight (γ_d), (kN/m^3)	Modulus of Elasticity of the Piles (E) (kN/m^2)	Poisson's ratio
Open-Ended Steel Pile	30.79	2 *10^8	0.3
Closed-Ended Steel Pile	30.79	2 *10^8	0.3

4.2.7. Results from Finite Element Program

After the sand and model piles were modeled in the Plaxis 3D, the ultimate bearing capacity was chosen from the experimental load-settlement, the same load value was applied to the pile in Plaxis 3D by using the parameters mentioned above. The results showed that there is a good agreement of the Plaxis 3D finite element program compared to the experimental results for relative densities 10% and 40%, but for 65% and 90% of relative density, there is a small difference between results (results are very close to each other). The comparison of the experimental results with Plaxis 3D for open-ended steel pipe piles are shown in (Table 4.4.) below.

Table 4.4. Comparison of the experimental results with Plaxis 3D for open-ended steel pile

Dr (%)	Load (kN)	Modulus of Elasticity of the Sand (E) (kN/m^2)	Experimental Settlement (mm)	Plaxis 3D Settlement (mm)
10	0.186	2500	3.9426	10.9
40	1.15	24900	4.0668	12.6
65	2.229	45000	4.6836	10.75
90	5.33	80000	6.3001	11.7

The comparison of the experimental results with Plaxis 3D for closed-ended steel pipe piles are shown in (Table 4.5.) below.

Table 4.5. Comparison of the experimental results with Plaxis 3D for closed-ended steel pile

Dr (%)	Load (kN)	Modulus of Elasticity of the Sand (E) (kN/m^2)	Experimental Settlement (mm)	Plaxis 3D Settlement (mm)
10	0.3194	2500	4.545	1.831
40	5.5724	24900	9.546	8.458
65	6.8084	45000	11.5024	9.181
90	13.285	80000	11.9266	5.283

To get a better view and easily compare the results of the experimental tests with results achieved from Plaxis 3D finite element, the results from experimental and Plaxis 3D combined in a graphical figure together. The graphical comparisons between experimental results with Plaxis 3D results are shown in (Figures 4.10 and 4.11). (Figure 4.12) Show the typical vertical displacement contours of the pile. Figures 6.6 through 6.13 show the load-displacement curves of the model piles analysis by Plaxis 3D.

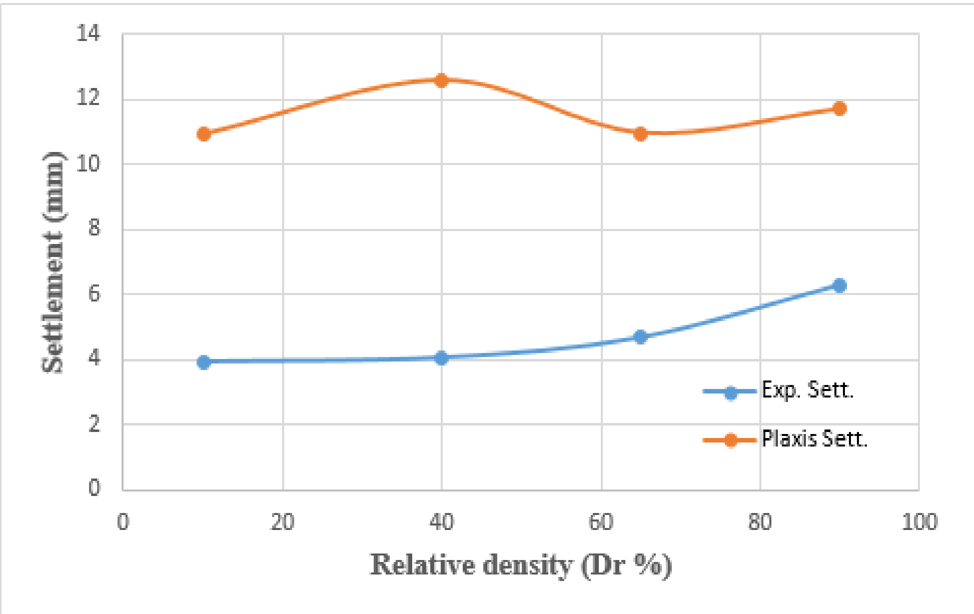


Figure 4.10. Comparison of the experimental results with Paxis 3D for open-ended steel pile

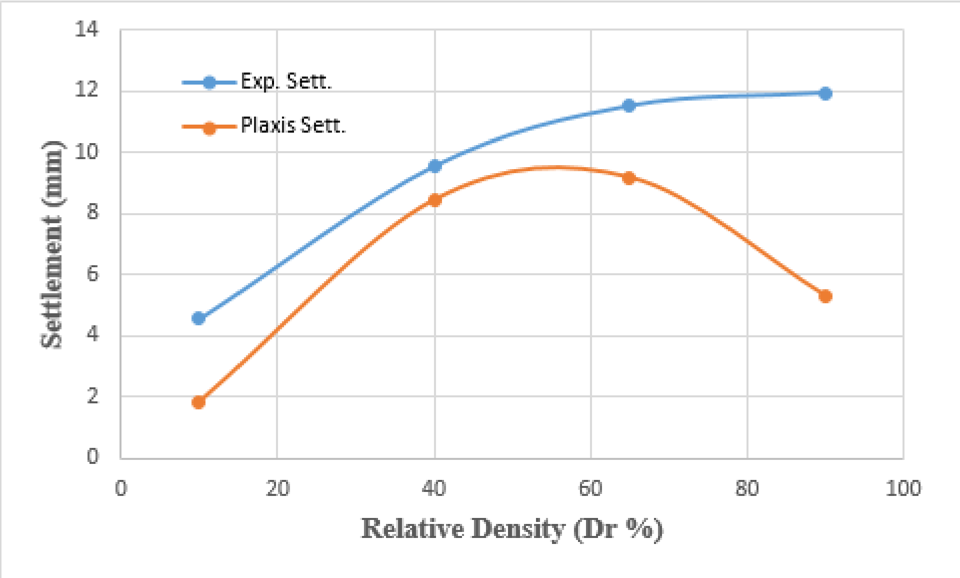


Figure 4.11. Comparison of the experimental results with Paxis 3D for closed-ended steel pile

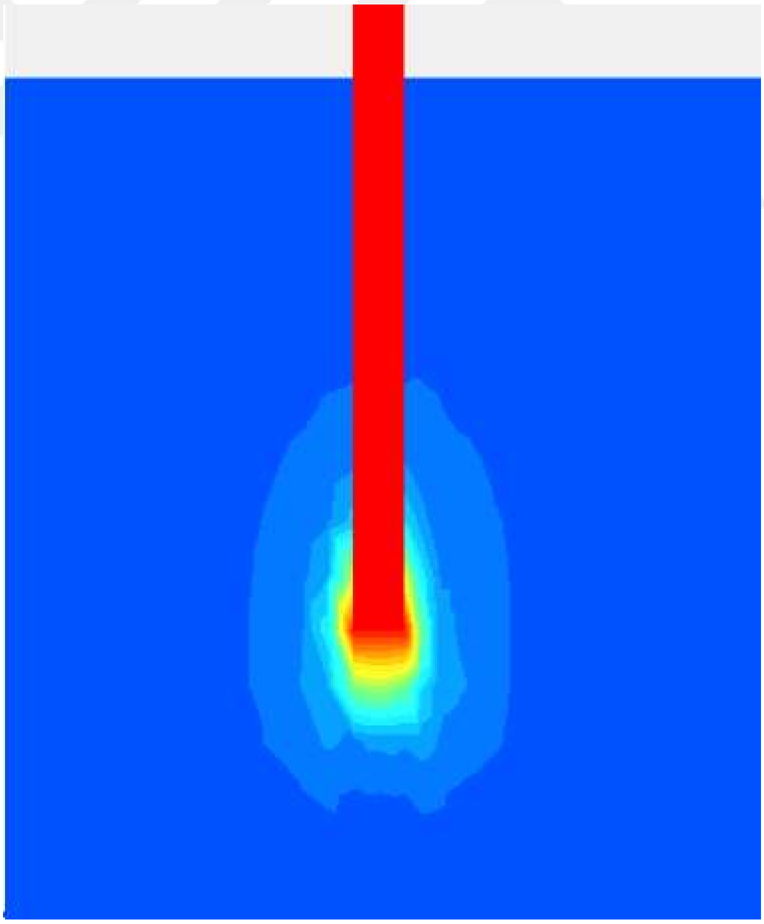


Figure 4.12. Typical vertical displacement contours of the pile analyzed by Plaxis 3D

(Figures 4.13 to 4.20) show the Load- displacement curves for both open-ended and closed-ended steel model piles by Plaxis 3D for each relative densities (10%, 40, 65, and 90%) respectively.

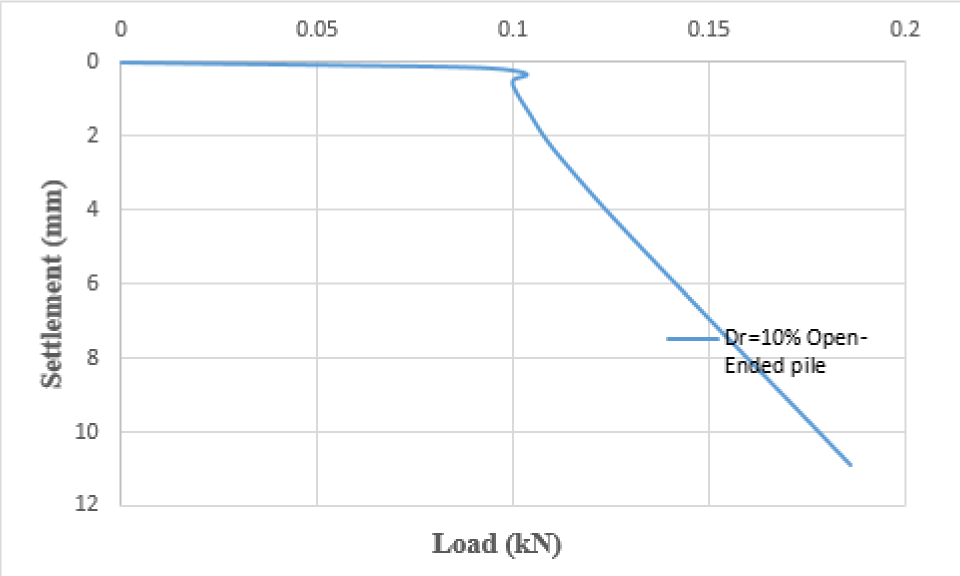


Figure 4.13. Load- displacement curve of open-ended steel model pile by Plaxis 3D for Dr = 10%

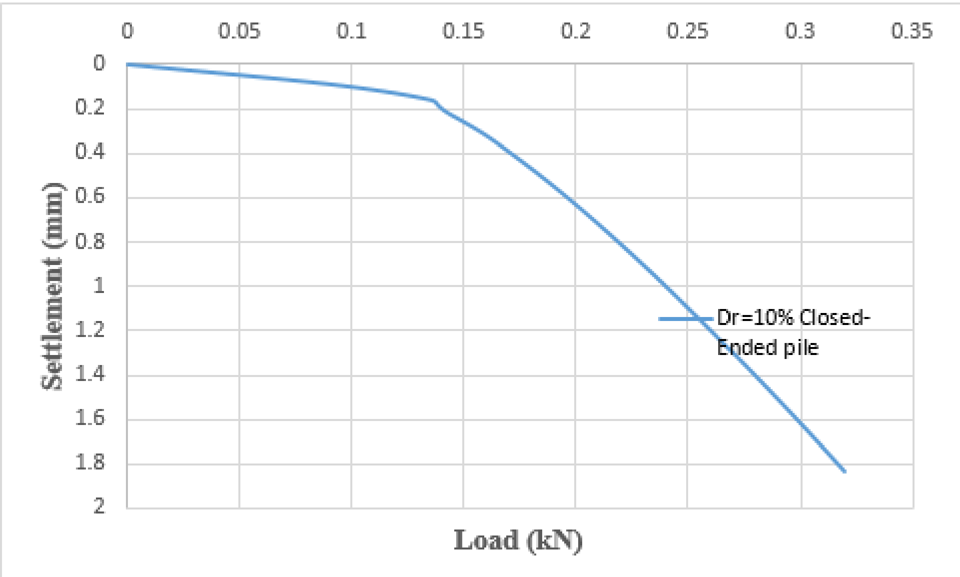


Figure 4.14. Load- displacement curve of closed-ended steel model pile by Plaxis 3D for Dr = 10%

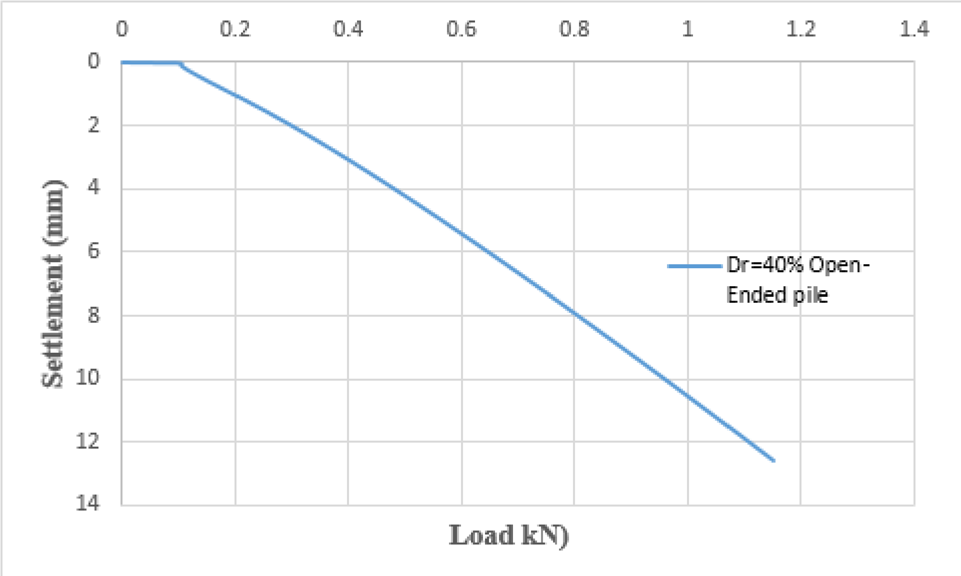


Figure 4.15. Load- displacement curve of open-ended steel model pile by Plaxis 3D for Dr = 40%

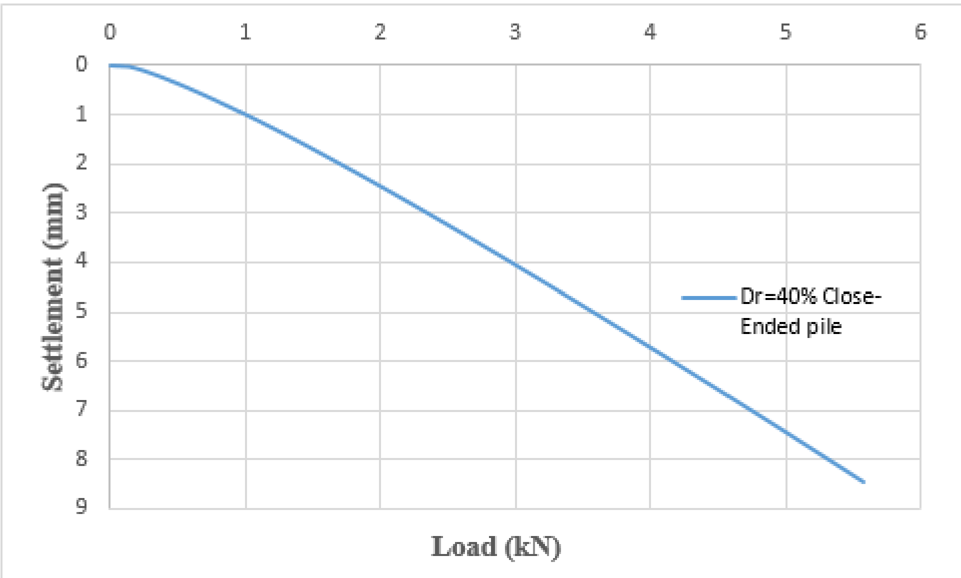


Figure 4.16. Load- displacement curve of closed-ended steel model pile by Plaxis 3D for Dr = 40%

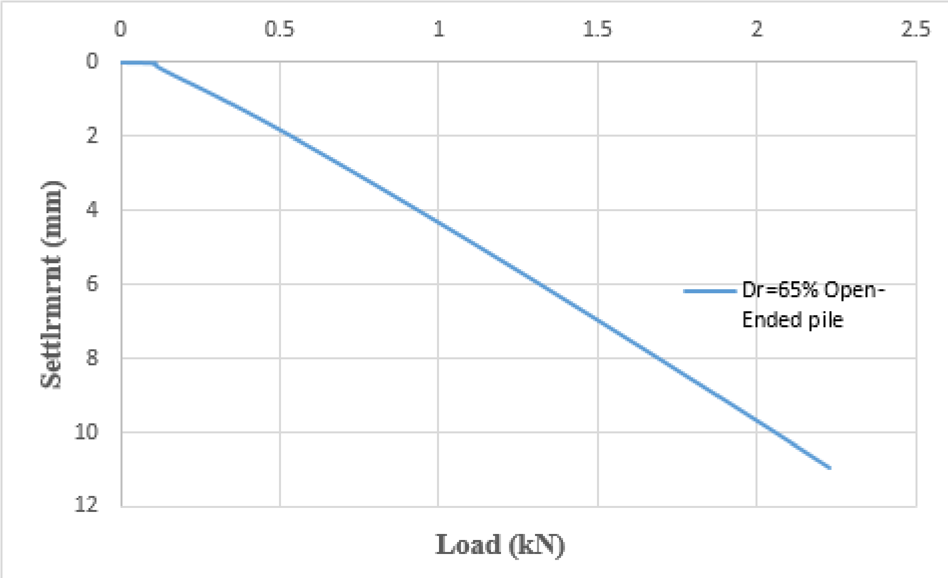


Figure 4.17. Load- displacement curve of open-ended steel model pile by Plaxis 3D for Dr = 65%

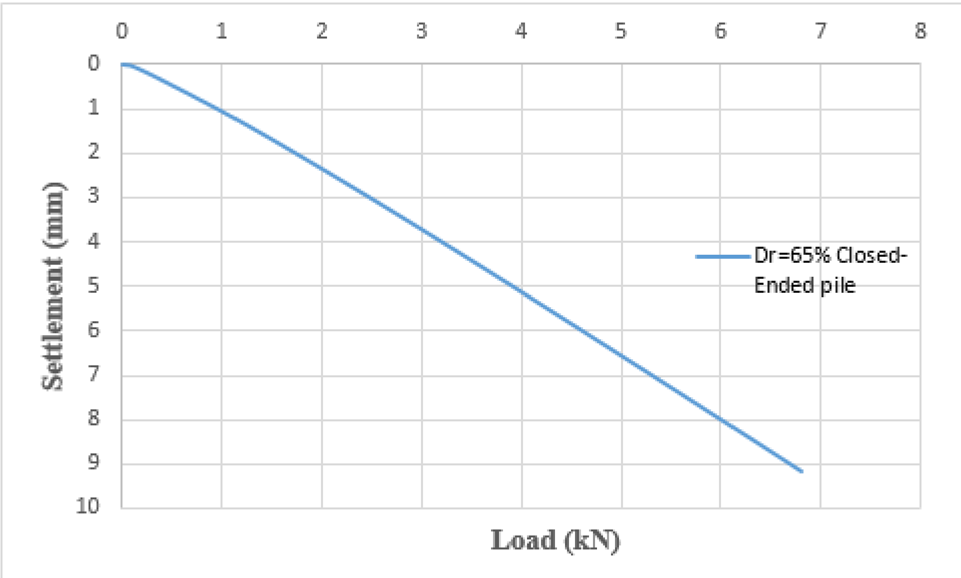


Figure 4.18. Load- displacement curve of closed-ended steel model pile by Plaxis 3D for Dr = 65%

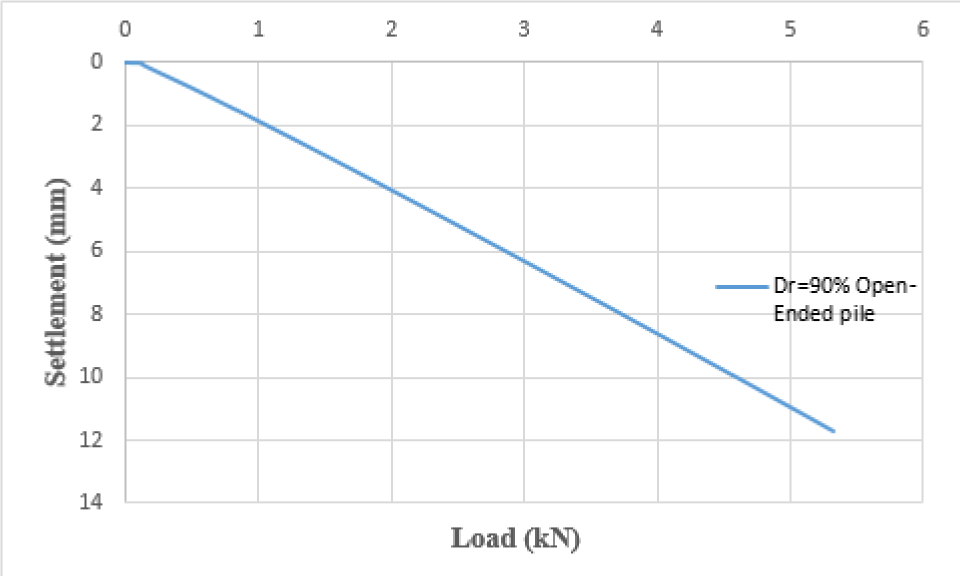


Figure 4.19. Load- displacement curve of open-ended steel model pile by Plaxis 3D for Dr = 90%

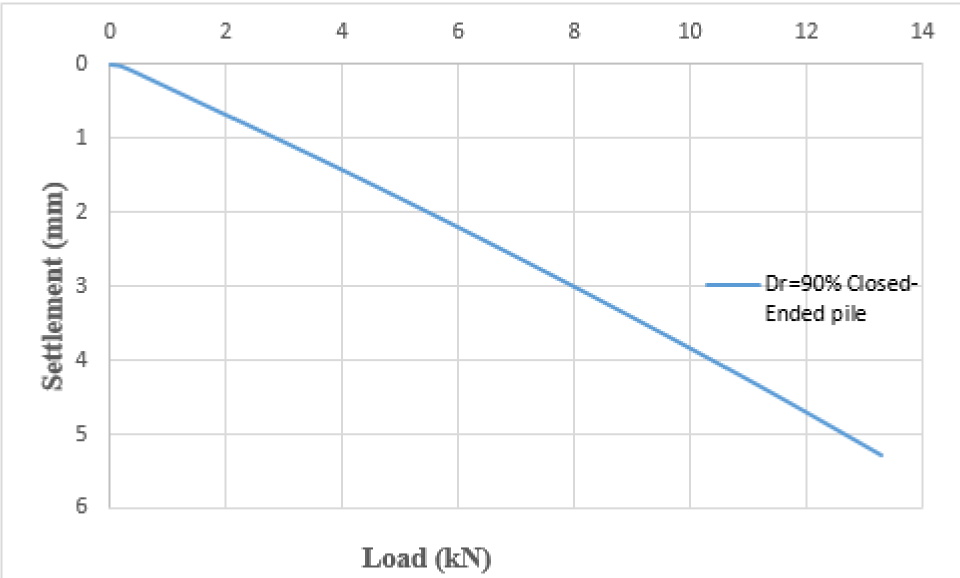


Figure 4.20. Load- displacement curve of closed-ended steel model pile by Plaxis 3D for Dr = 90%

5. CONCLUSION

In this study, model experiments in terms of load-displacement behavior of two single-model steel piles (open-ended and closed-ended pipe piles) at different relative densities (i.e., Dr = 10%, 40%, 65%, and 90%) of the model sand were performed experimentally and numerically. The results of experimental and numerical analysis can be concluded as below:

- In dense sand, pile load-carrying capacity is several times more than in loose and medium sands, especially for closed-ended or open-ended piles. This could be due to the fact that a pipe pile in deep sand can cause external and internal skin friction, as well as end-bearing resistance, resulting in a total pile capacity that is comparable to a closed-ended pile.
- If the soil plug inside the piles is in a partial or full plug state, open-ended pipe piles act like closed-ended pipe piles. The length of a soil plug is determined by the installation type and density.
- According to the pile model load tests, the overall bearing capacity of the model pile increases in a non-linear relationship with increasing relative density. With increasing relative density, the settlement corresponding to ultimate bearing capacity also increases.
- It is noticed from the ultimate bearing capacity load-settlement curves, the ultimate bearing capacity mobilized at the settlement about (10-25) % of the pile model diameter.
- From back-calculation of the earth pressure coefficient by using experimental results, it was discovered that it increases with increasing relative density, and also depends on the degree of stress, the density, and angle of friction of the soil, the roughness, and the diameter of the pile.
- From the finite element analysis like the experimental results, the bearing capacity of the model pile increases with increasing relative density. The most parameter which influences the settlement is the modulus of elasticity and the unit weight of the soil. The load-settlement curve achieved from the Plaxis 3D programs is different from the experimental load-settlement curves. In relative density 10% the load-settlement curve from Plaxis 3D and experimental are non-linear. But in relative density, 40%, 65% and 90% the load-settlement curves from plaxis 3D are linear, while they are no-linear from experimental results.

As a recommendation on this subject, further studies considering submerged piles as in offshore projects in field are necessary. Data developed in this study are expected to be useful to civil engineer designers and site engineers in the design of foundation of any projects with further construction works.

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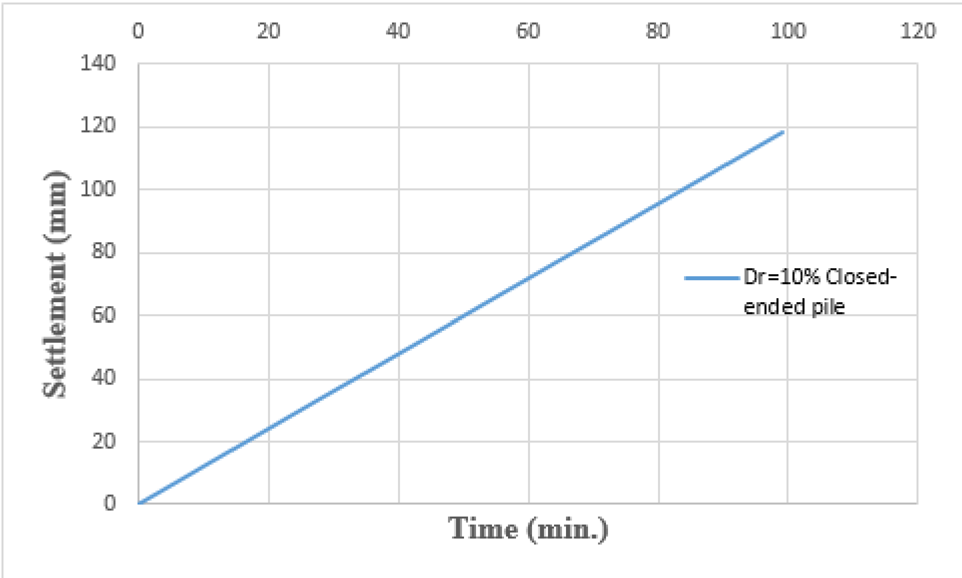
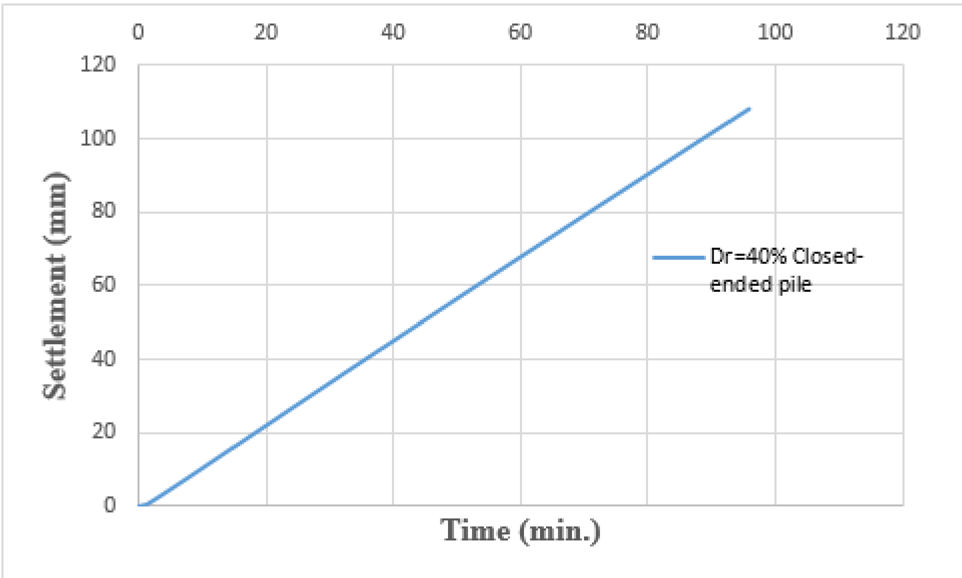
APPENDICES

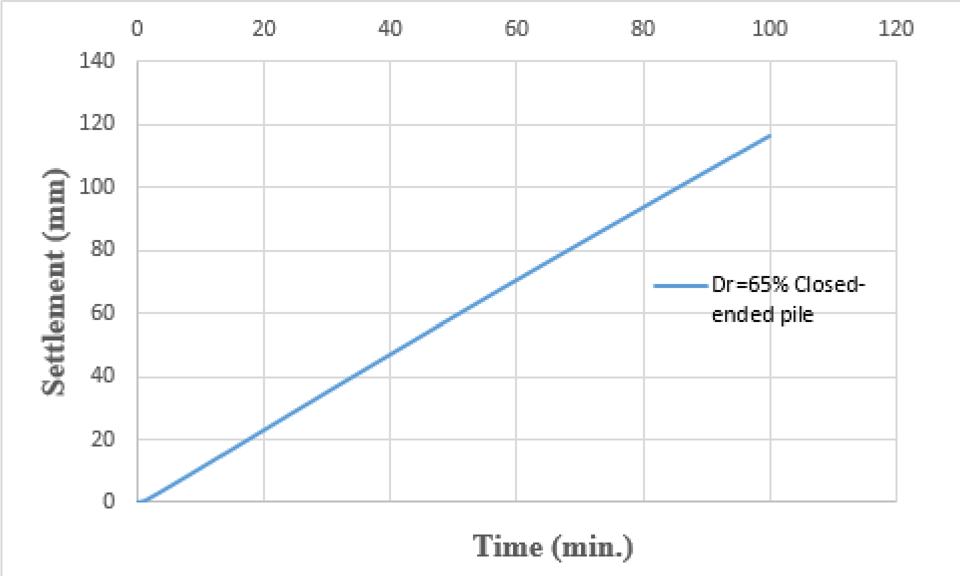
APPENDIX- 1: (EXPERIMENTAL TIME-LOAD AND TIME-DISPLACEMENT CURVES OF TOTAL BEARING CAPACITY OF CLOSED-ENDED STEEL PILE)



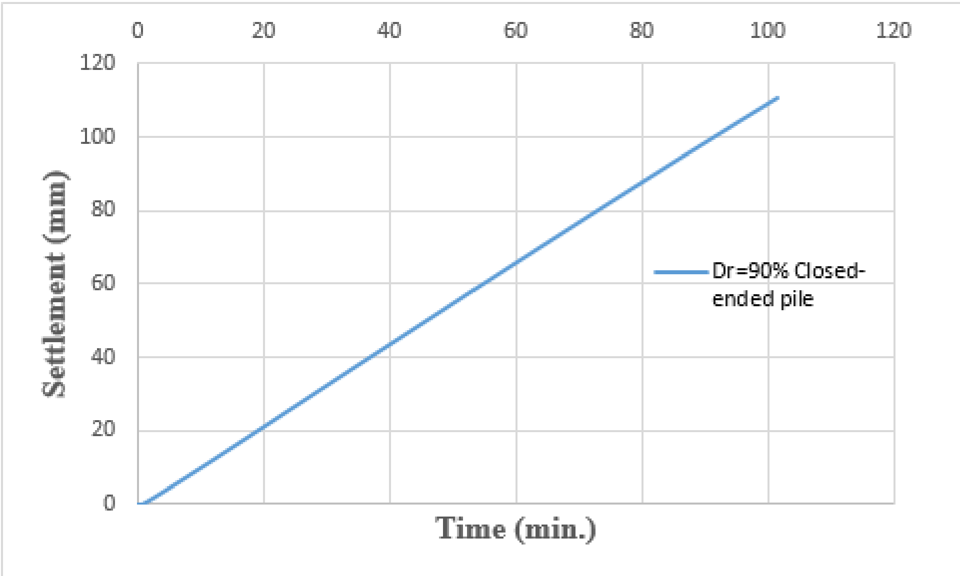
a) Time-Settlement Behavior



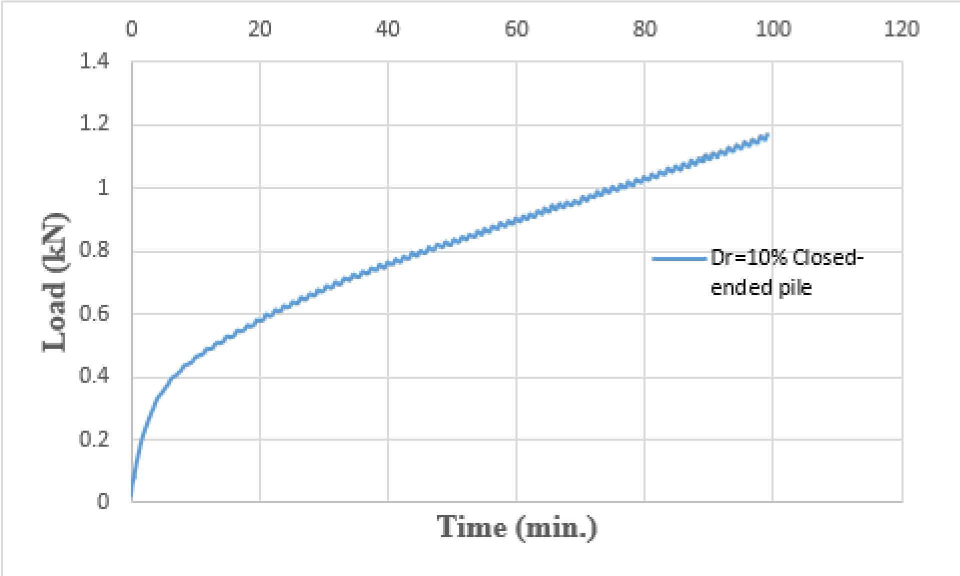
b) Time-Settlement Behavior



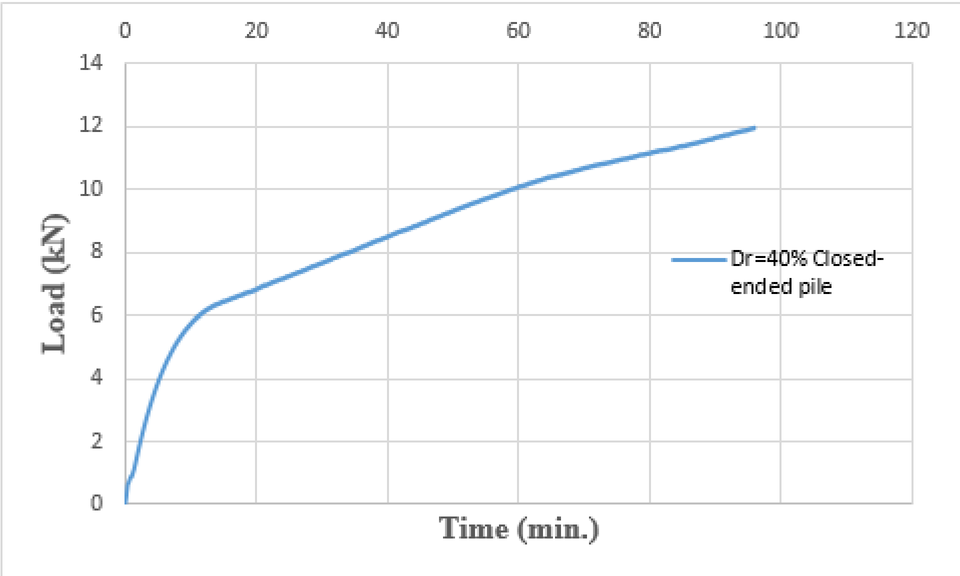
c) Time-Settlement Behavior



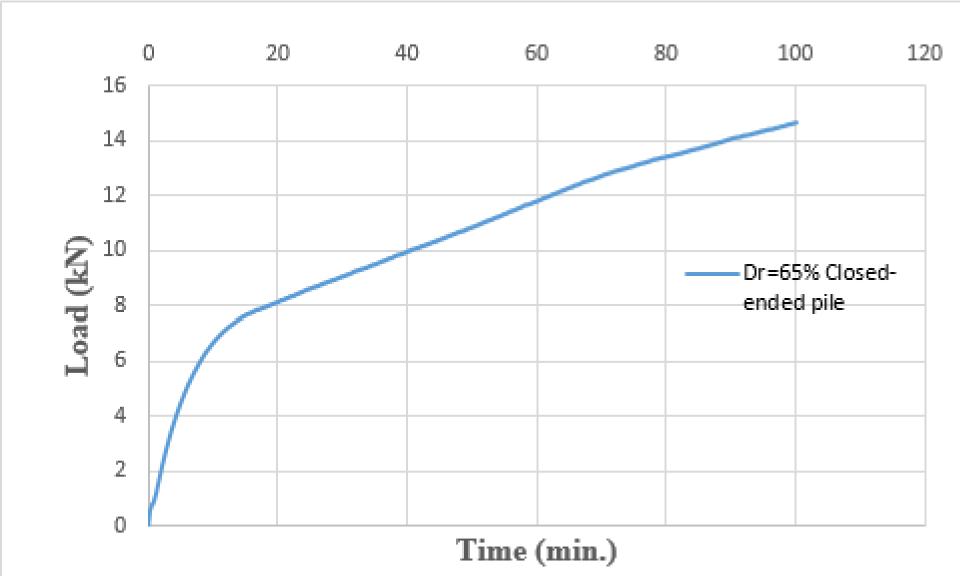
d) Time-Settlement Behavior



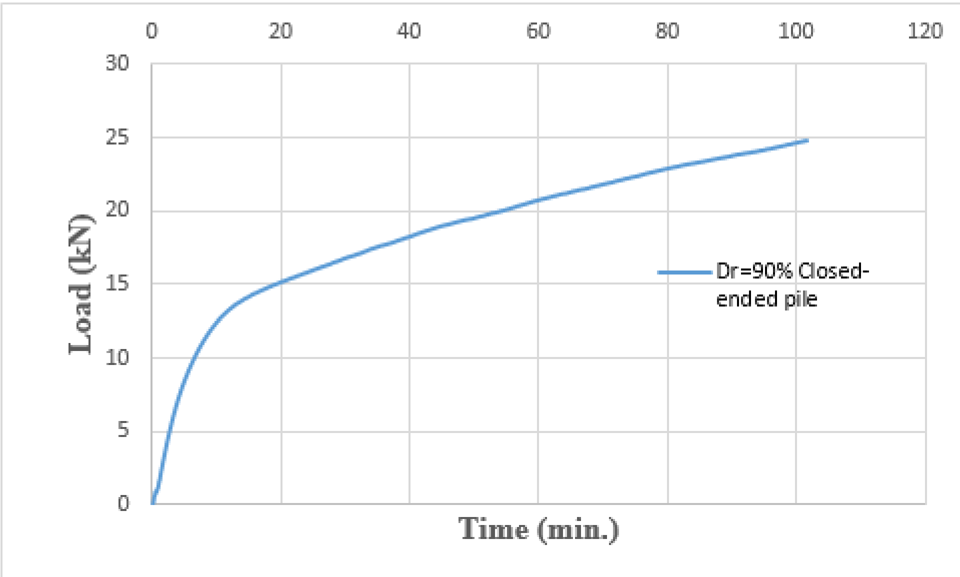
e) Time-Load Behavior



f) Time-Load Behavior



g) Time-Load Behavior



h) Time-Load Behavior

Figure A1. 1. a), b), c), d); Time-settlement behavior, and e), f), g), h); time-load behavior curves of Closed-ended steel pile at (Dr=10%, 40%, 65% and 90%), respectively

CURRICULUM VITAE

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