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PILE-RAFT FOUNDATIONS: A REVIEW OF SOIL-STRUCTURE INTERACTION AND BEARING CAPACITY ANALYSIS FOR CLAYEY SOILS IN AL-NASIRIYA, IRAQ"

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ABSTRACT

The research reviews the behavior of pile-raft foundations and the impact of pile driving in clayey soil, focusing on the resulting soil movement, pore water pressures, and their effects on slope stability, especially in the city of Nasiriyah, southern Iraq, where clayey soil prevails. Previous studies reviewed include load-bearing capacity using experimental and numerical models to determine the maximum load and the relationship between load and settlement, with observations on changes in pore pressures after pile driving , pile-raft foundations through numerical and experimental research studying the distribution of loads between the piles and the raft and the impact of pile configuration, raft thickness, and soil type on performance . Local studies have shown that the soil in nasiriyah is predominantly composed of high or low plasticity clay (CL–CH), with a small percentage of sand, and there is a lack of realistic studies on the local soil. The main findings included advancement in modeling methods, but a deficiency in real field studies of clayey soil in nasiriyah, absence of standardized criteria for assessing the risks of pile driving in clay and need for comprehensive models that consider the interaction between the soil and the structure during execution..

KEYWORDS

Piled raft ,Soil–structure interaction ,Finite element analysis ,seismic loading , raft footing and driven piles.

1. INTRODUCTION

Pile driving in clay soils presents significant challenges due to the soil's low permeability and tendency to generate excess pore water pressures during installation. These pressures can lead to soil heave, lateral displacements, and potential stability issues in nearby structures. This review delves into the effects of pile driving in clay soils, focusing on induced ground movements, pore pressure behavior, and implications for slope stability. Knowing these factors is necessary to ensure the developing effective mitigation strategies and ensuring the safety and integrity on geotechnical structures (Skempton & Brogan,1994).

Studying the behavior of pile- raft system in clay soil and find the sharing on soil and pile with raft foundation and recognize each factors effect on this system by using many testing to find equation control on this system for bearing capacity of pie raft system. Moreover, the use of this system will be compare with the use of mat foundations alone and the use of the pile system alone. (al-Damluji, O. & Al-Baghdadi, N. H. ,2012).

The investigation of framed buildings has seen major developments throughout the last several decades. Because of these structures depend on soil media, the phrase "soil-structure interaction analysis" entered calculations and transformed researchers' perspectives. Many new techniques and hypotheses are reported, either to enhance existing methods or to provide new approaches, with the majority focusing on earlier flaws identified by scholars (Omer K. & Vassilis A. G. ,1992). Researchers have consistently demonstrated the impact of incorporating flexible foundations, or soil-structure interaction, when analyzing and designing buildings to resist static or dynamic loads (Al-Baghdadi, N. H. (2013), As for the most important uses of the Pile foundations are to transfer loads from the structure to the soil when the structure is buried in problematic soil. In axially loaded piles, the load is transferred to the soil through lateral friction at the soil pile interface and the foundation resistance provided by the soil bed. In addition to vertical forces, pile foundations are also subject to significant lateral forces. (A.Marine & I.Anastasopoulos ,2021). The significant of the subject lies in the fact that clay soils have low permeability and generate excessive pore water pressure during pile driving, which can cause soil swelling, lateral movement, and risks to adjacent structures. The issue is particularly significant in the city of Nasiriyah in southern Iraq, where this type of soil predominates.

The main objective of preparing this study is to review the literature related to the topic Pile-Raft Foundations and summarize the latest findings of researchers in this field in order to facilitate the analysis and design processes of the foundations of structures.

The deep foundations of important topics in the science of engineering, especially building engineering section related to the subject of the foundation because of its importance in the process of building construction, especially buildings with multiple floors. Tomlinson,(2014) has considered that piling is a combination of art and science, the artistic aspect involves choosing the appropriate pile type and installation method based on the ground conditions and the type of load. There are three methods of installing piles as Pile Driving Methods (Displacement Piles), Boring Methods (non-displacement piles) and Driven cast –in situ piles. (Tomlinson & john W.,2014). This research deals with the subject of the driven piles in clay soils, where clay soils are the predominant type of soil of Nasiriyah' city (the place of conducting the research), which is located in southern Iraq and this type of soils considered from the weak soils that needs to improvement as mentioned (Jasim, M, et al ,2014). Also understanding the most important research that has addressed methods for evaluating piles exposed to dynamic loads.

Fig. 1. driven pile installation

2. RELATED PREVIOUS STUDIES

The most important previous studies related to bearing capacity of the soil as well as the failure criteria methods have been reviewed, in addition to the studies related to piled raft foundation and as follow.

2.1. BEARING CAPACITY

Chin_Kondner (1970) has suggest, a way assumes that the curve of settlement load have a shape as hyperbolic at the failure load condition. Each load is separated by its respective settlement, and the resulting values are then plotted against the applied load. the plotted value fall on a straight line, so the inverse of the slope of this line is the Chins failure load case

Roy et al. (1981) has worked a comprehensive investigation using appropriate machines for inspection test of piles for knowing the behavior of the friction piles in soft sensitive soils. They observed that pile driving induces significant pore water pressures at both the surface and pile tip, which dissipate over time. directly after Hammering process, with strength nearly fully recovering after pore pressure dissipation.

Decourt (1999) proposal; a method by which each load is separated by its respective settlement, and the resulting values are then plotted against the applied load. A linear regression over the apparent line determines the line. The researcher identified the ultimate load as intersection of this line with load axis.

Mendonca and de Paiva (2003) employed a numerical analysis method that combined finite element and boundary element methods, accounting for the interaction between the soil and the piled raft foundations.

Giustolisi and Savic (2006), combining the strengths of numerical regression with the GP symbolic regression method. The development of an EPR model involves two stages: (i) structure identification and (ii) parameter estimation. In the first stage, EPR employs a genetic algorithm (GA) for an evolutionary search to identify symbolic structures. In the second stage, the coefficients of the selected polynomial terms are estimated using a numerical regression method, specifically the least squares approach. The general form of an EPR model is defined by the corresponding equation.

Julio A. Garcia (2008) conducted an analysis and design of a 6-storey reinforced concrete frame building with a basement. Two models were simulated, reflecting different conditions: soil-structure interaction and fixed-base behavior. The results indicated that the soil-structure interaction led to an increase in the vibration period and system damping, compared to the fixed-base model, which did not account for the supporting soil. In terms of seismic design, the inclusion of soil-structure interaction resulted in reduced horizontal spectral acceleration values. Structural analysis incorporating the soil provided more accurate results for displacement and stress, compared to the fixed-base model.

Massumi & H.R. Tatabaiefar (2008) investigated the impact of soil-structure interaction on reinforced concrete buildings. Since the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800-05) does not explicitly address soil-structure interaction, this study examined its effects on buildings with ductile moment-resisting frames designed according to Iranian Building Codes. The research utilized the direct soil-structure interaction method and analyzed four types of buildings—3, 5, 7, and 10 stories—representing typical structures in high-risk earthquake zones. These buildings were analyzed in conjunction with three soil types, as categorized by Iranian Standard No. 2800-05 (types II, III, and IV).

G. Saad, F. Saddik and S. Najjar. (2012) investigated the study focused on examining the seismic performance of reinforced concrete buildings with multiple basement levels. The research aimed to provide guidance regarding the appropriate number or proportion of underground stories to include in the analysis of shear wall structures. They modeled buildings with a fixed condition at ground level, incrementally increasing the number of basements to study the resulting performance changes. The analysis was conducted using local site conditions from Beirut, evaluating base shear, inter-story shears, and moments to assess the effects of soil-structure interaction on design.

Massarsch and Wersäll (2013) explored soil heave caused by pile driving in clay, proposing methods to predict ground heave through model tests and numerical analyses. Their research showed that soil heave primarily results from lateral movements along the pile shaft, which can cause surface uplift and impact nearby structures.

Oustasse Abdoulaye Sall et al. (2014) examined the behavior of soil under a plate subjected to uniformly distributed load, with a focus on soil-structure interaction, considering a linear variation in soil properties with depth. Their analysis showed that assuming a constant modulus of elasticity for the soil leads to larger displacements, while the Poisson's ratio and the concrete's mechanical properties have little effect on displacement. This study also found that the upper half of the soil thickness is most sensitive to model parameters. Additionally, it provides a summary of soil-structure interaction (SSI) literature and suggests techniques for evaluating SSI phenomena such as foundation-soil compliance and damping, as well as kinematic interactions in engineering practice. Specific recommendations are made for modeling seismic SSI effects on building structures.

Table 1 showing a summary of studies on the bearing capacity

Study	Soil Conditions	Type of Analysis	Main Findings
Chin_Kondner (1970)	Soft soils at failure load	Empirical	Settlement-load curve follows a hyperbolic shape at failure load.
Roy et al. (1981)	Soft sensitive soils	Experimental	Pile driving induces pore water pressures, which dissipate over time.
Decourt (1999)	Not specified	Empirical	Ultimate load identified via linear regression of load-settlement curve.
Mendonca and de Paiva (2003)	Soil-piled raft interaction	Numerical (FEA, BEM)	Combination of FEA and BEM for soil-pile interaction in raft foundations.
Giustolisi and Savic (2006)	Not specified	Numerical Regression (EPR)	Symbolic regression (EPR) used to model soil-structure interaction.
Julio A. Garcia (2008)	Soil-structure interaction	Numerical (FEA)	Soil-structure interaction affects seismic design and reduces spectral acceleration.
Massumi & H.R. Tatabaiefar (2008)	Seismic zones with different soil types	Experimental (SSI)	Soil-structure interaction affects performance of buildings in earthquake zones.
G. Saad, F. Saddik and S. Najjar (2012)	Seismic performance in Beirut	Numerical (FEA)	Study on seismic performance of buildings with multiple basements in Beirut.
Massarsch and WersÃ¤ll (2013)	Clay soils	Model tests and Numerical analysis	Soil heave due to pile driving results from lateral movements along the pile shaft.
Oustasse Abdoulaye Sall et al. (2014)	Uniformly distributed load, linear soil properties	Analytical (SSI, Linear)	Soil displacement under a plate varies with depth; soil properties influence displacement.

2.2. PILED RAFT FOUNDATION

Russo (1998) for the analysis of piled rafts the researcher presented an approximate by a numerical method for knowing the analysis of piled rafts. The (hybrid model) categorized by it takes into accounts the nonlinearity of the One-sided communication at the (SSI) and the nonlinearity of the settlement_ load curve. And also concluded; the nonlinear analysis of substrate foundation should be considered when piles are used as leveling attenuators, since piles can be reached to their maximum.

Mendonca and de Paiva (2000) employed a boundary element method for analysis the piled raft foundations system. The soil was modeled as an elastic linear homogeneous half space while, each pile in the group was modeled as single element and a thin plate present the raft. In this analysis the interaction between the (SSI) have taken into consideration.

Prakoso and Kulhawy (2001) proposed a numerical approach for predicting the performance of piled raft foundations by utilizing simplified linear elastic and nonlinear (2D elasto-plastic) plane strain finite element models, implemented through the PLAXIS program. Building on this work, they introduced a displacement-based design procedure for the piled raft system. It has been suggested that the 2D plane strain results could be used for analyzing similar problems in piled raft systems, offering efficient modeling and computation without excessive time consumption. Poulos (2001) proposed a simplified analysis technique as a tool for the preliminary design of piled raft foundations. Additionally, the researcher has addressed the limitations of numerical modeling by introducing hybrid models as an alternative solution deals with the piled raft foundation system.

El-Mossallamy (2002) developed a numerical model combining the boundary element method and the finite element method. This technique incorporates the stiffness of the raft, the nonlinear behavior of the piles, and the slip along the pile shafts to analyze piled raft foundations.

EI Sawwaf (2010) conducted experimental work on short piles under foundations, both connected and disconnected, and found that this approach reduced the settlement of the raft foundation, increased its load-bearing capacity, and led to more economical design solutions.

Al-Mosawi et al (2011) conducted an experimental study to analyze the behavior of a (piled-raft system) in sand soil. A small-scale “prototype” model was set up in a sand soil, with load applied through a compression machine. The settlement at the center of the raft was measured, and strain gauges were used to determine the total load carried by the piles and the resulting strains. Four pile configurations (2×1, 3×1, 2×2, and 3×2) were tested, along with rafts of varying sizes. The study also evaluated the impact of raft thickness on the load-carrying capacity of the piled raft system, considering factors such as pile length and diameter in the load-settlement analysis.

G. Saad, F. Saddik & S. Najjar,(2012)" investigated the study focused on examining the seismic performance of reinforced concrete buildings with multiple basement levels. The research aimed to provide guidance regarding the appropriate number or proportion of underground stories to include in the analysis of shear wall structures. The modeled buildings with a fixed condition at ground level, incrementally increasing the number of basements to study the resulting performance changes. The analysis was conducted using local site conditions from Beirut, evaluating base shear, inter-story shears, and moments to assess the effects of soil-structure interaction on design.

Pallavi Ravishankar & Dr. D. Neelima Satyam (2013) analyzed a 150-meter tall asymmetrical building with two foundation (pile- raft system) assuming homogeneous sandy soil. They studied the structure's response under dynamic loading due to Bhuj ground motion (2001, M=7.7) and compared the soil-structure interaction effects. The study found that displacements at the top of the building were greater than at the bottom, and stresses were higher in the soil layer directly beneath the foundation.

Massarsch and Wersäll (2013) explored soil heave caused by pile driving in clay, proposing methods to predict ground heave through model tests and numerical analyses. Their research showed that soil heave primarily results from lateral movements along the pile shaft, which can cause surface uplift and impact nearby structures.

Jaymin et al. (2014) conducted small-scale laboratory tests on sand to investigate the load-settlement behavior and load sharing between the raft and piles This study explain that the performance of piled raft foundation in clayey soil, sandy soil and, layered soil carried through experimental and numerical analysis methods .

Hussein H. H.(2015), conducted several field and laboratory tests, dividing his study into two parts: the practical section and the theoretical section. The practical side dealt with a group of piles in the sandy soils belonging to the city of Karbala. He used static load tests and dynamic load tests in the field part of the research to determine the contribution ratio of the shaft in bearing loads compared to the piles, where the piles were tested in groups and individually. The researcher categorized the groups into (1×1, 1×2, 1×3, 2×2, 5 piles and 2×3) . The researcher concluded that the participation rates were as follows: the raft foundation is about (46.3, 28.5, 27.6, 26.4, 25.7 and 25%) for the piled raft groups (1×1, 1×2, 1×3, 2×2, 5 piles and 2×3), respectively.

Lee et al. (2015) used finite element analysis to study the load-sharing behavior of piled rafts embedded in sands, incorporating the effects of pile-raft interaction. Their analysis considered various factors such as pile configuration, spacing, and relative density. Cristian Cruz and Eduardo Miranda (2017) examined the impact of soil-structure interaction on damping ratios of buildings during earthquake ground motions. They developed transfer functions for horizontal accelerations of multistory buildings on an elastic half-space subjected to horizontal ground motions and found that effective damping ratios of higher modes increased with decreasing wave numbers, indicating stronger SSI effects, and the researcher has shown the effect of the effective ratio of damping for multi-story buildings through in the figure (No.2) below.

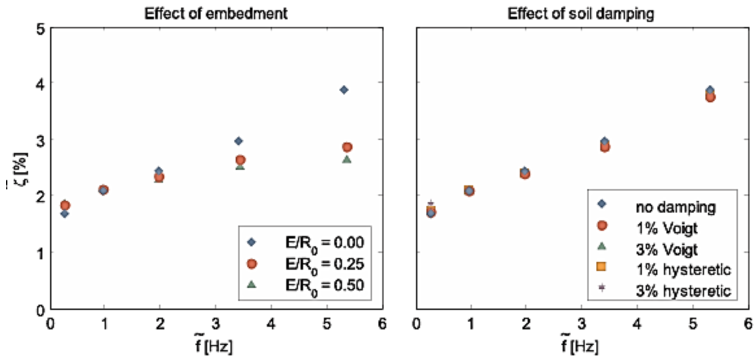

Fig.2. (Left) Effect of embedment and (right) effect of soil damping on the effective damping ratios (after Cristian Cruz and Eduardo Miranda ,2017)

Kein T. Nguyen,et,al.(2022) discussed and provided analytical solutions were derived for the dynamic stress intensity factors (SIFs) of an infinitely long cylindrical structure embedded within a homogeneous, linear elastic half-space. The mixed-boundary-value problem was addressed in the frequency domain, incorporating harmonic displacement at the interface between the structure and the soil, while assuming a traction-free boundary condition at the ground's free surface. The derived analytical solutions offer practitioners highly accurate values for spring stiffness and dashpot damping coefficients, which can be applied in the seismic design of spatially distributed underground structures, and the researcher has shown through the numerical method(model) as shown in Fig.3 how to estimate of the dynamic stress intensity factors (SIFs).

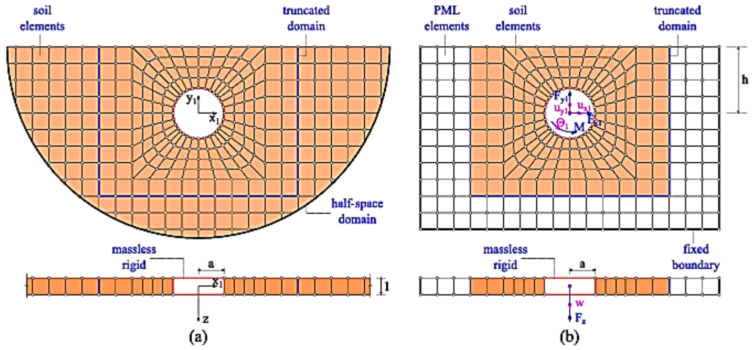

Fig. 3. (a) infinite half-space FE model, and (b) truncated half-space FE model using PML elements (after Kein T. Nguyen,et,al.,2022)

Attari et al. (2023) examined the impact of pile driving on slope stability in clay soils by analyzing the stress changes during installation. The study highlighted the absence of standard methods for evaluating the reduction in slope safety due to pile installation and stressed the need for more precise predictions to mitigate associated risks and costs.

Ivan Negrin et al. (2023) used conventional heuristic methods and Kriging-based metaheuristic optimization to reduce CO2 emissions from spatial reinforced concrete frame structures. Their research, which incorporated often-overlooked aspects such as soil-structure interaction (SSI), focused on two main points: the effect of SSI consideration and the application of their proposed metamodeling approach. The methodology involved performing basic experiments on a case study and validating the results with two other models, while also analyzing the behavior of the structure under various conditions.

Xue-Qian Fang et al. (2023) presented a review of various imperfect interface models and related studies, discussing the characteristics of different models. Their findings emphasized the importance of the interfacial properties around tunnel linings in optimizing tunnel design, noting that many strategies have been proposed to enhance the dynamic strength of tunnels. They concluded that the dynamic interaction between the nonlinear properties of the medium and the interface characteristics complicates the distribution of dynamic stress around the tunnel.

Table 2. showing a summary of studies on the piled raft foundation

Study	Soil Conditions	Type of Analysis	Main Findings
Russo (1998)	Nonlinear settlement-load curve and soil-structure interaction (SSI)	Numerical (Hybrid model)	Nonlinear analysis of substrate foundation should be considered for piles as leveling attenuators.
Mendonca and de Paiva (2000)	Elastic homogeneous half-space	Numerical (BEM)	Interaction between soil and piled raft foundations using BEM, linear homogeneous half-space.
Prakoso and Kulhawy (2001)	Homogeneous sandy soil	Numerical (Finite element and elasto-plastic)	Introduced a displacement-based design for piled raft system, considering both linear and nonlinear behavior.
Poulos (2001)	Homogeneous sandy soil	Simplified numerical analysis	Simplified analysis for preliminary piled raft design, hybrid models introduced for better modeling.
El-Mossallamy (2002)	Nonlinear behavior of piles and raft	Numerical (BEM and FEM)	Combined BEM and FEM for analyzing raft foundations, considering pile nonlinearity and raft stiffness.
EI Sawwaf (2010)	Short piles under foundation, both connected and disconnected	Experimental	Experimental work on short piles shows improvement in load-bearing capacity and reduced settlement.

Study	Soil Conditions	Type of Analysis	Main Findings
Al-Mosawi et al. (2011)	Sand soil	Experimental	Impact of pile configuration and raft thickness on load-bearing capacity and performance in sand soil.
G. Saad, F. Saddik & S. Najjar (2012)	Beirut site conditions	Numerical (FEA, SSI)	Investigated seismic performance in Beirut, analyzing base shear and inter-story forces with SSI effects.
Pallavi Ravishankar & Dr. D. Neelima Satyam (2013)	Homogeneous sandy soil	Experimental (dynamic loading)	Asymmetrical building response under dynamic loading, studied soil-structure interaction under earthquake forces.
Massarsch and WersÃ¤ll (2013)	Clay soils	Model tests and numerical analysis	Soil heave due to pile driving in clay caused by lateral movements along pile shafts.
Jaymin et al. (2014)	Sand	Experimental and numerical	Load-settlement behavior of piled raft systems in clay, sandy, and layered soils.
Hussein H. H. (2015)	Sandy soils in Karbala	Field and laboratory tests	Contribution ratio of shaft bearing in sandy soils tested in different pile group configurations.
Lee et al. (2015)	Sands	Finite element analysis	Load-sharing behavior of piled rafts embedded in sands with effects of pile-raft interaction.
Cristian Cruz and Eduardo Miranda (2017)	Elastic half-space	Experimental and analytical	Impact of soil-structure interaction on damping ratios in earthquake ground motions.
Kein T. Nguyen et al. (2022)	Clay soils	Numerical (dynamic stress intensity)	Dynamic stress intensity factors of cylindrical structures embedded in an elastic half-space, applicable to seismic design.
Attari et al. (2023)	Clay soils	Experimental and numerical	Pile driving effects on slope stability in clay soils, need for more precise methods to evaluate slope safety.
Ivan Negrin et al. (2023)	Spatial reinforced concrete frame structures	Metaheuristic optimization and heuristic	Optimization of CO2 emissions in reinforced concrete frame structures considering SSI effects.
Xue-Qian Fang et al. (2023)	Imperfect interface models for tunnels	Review of interface models	Dynamic interaction of medium and interface properties affects stress distribution around tunnel linings.

3. THE SOIL IN NASIRIYAH CITY

Reviewing previous research and studies is important to know the literature of any subject or project and realize the most important findings of researchers in the same field of project or theses, where it is not possible to start from the starting point of the topic, but to start from what the last researchers have reached from the results, below are some of the most notable studies related to the soil of the Nasiriyah city, which is located in southern Iraq.

Yaser A., (2016), A case study conducted at Al-Hussein Hospital in Nasiriyah investigated the geotechnical properties of soil to evaluate foundation design parameters. The study found that soil properties varied with depth and provided recommendations for allowable bearing capacity and settlement estimates for shallow foundations.

Esraa A. M.(2022) The researcher conducted an analytical study of the soil of the city of Nasiriyah, which is the subject of research in the research tagged Assessment of the liquefaction susceptibility of Al-Nasiriya city soil. Based on plasticity properties, the researcher concluded several results, the most important of which is that most of the soils in the city of Nasiriyah have a clay characteristic, as well as: The soil in Al-Nasiriya city primarily consists of silt and clay, with a minimal proportion of sand. Based on the Unified Soil Classification System, the soil is mainly categorized as ranging from clays with high plasticity (CH) to clays with low plasticity (CL).

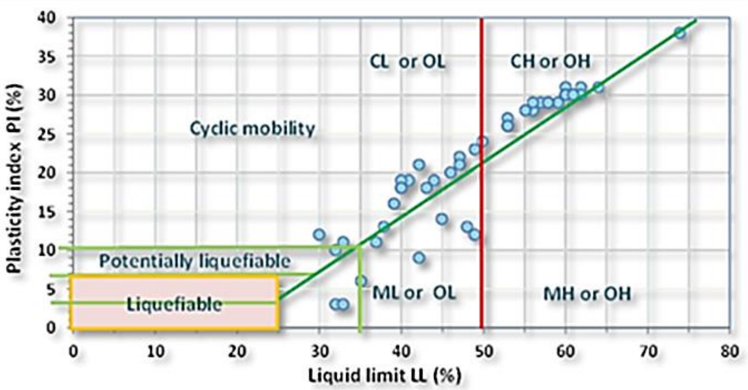

Fig.4. Liquefaction behavior on plasticity chart (after Esraa A. M. ,2022)

Duaa M. And Ressol S., (2023) relied a new method in the subject of taking and collecting samples. Several methods were relied upon to classify the soil (seven methods), based on the results of investigations at the study sites located in the city of Nasiriyah, southern Iraq. A detailed description was provided for each case or method. With 4 test points, six test holes were dug in the survey sites at a depth of (15-20) meters. The results were evaluated and compared based on the USCS classification system after converting the results of the SBT charts to the soil type groups in the USCS. It was found that the Robertson 2010 chart and the Islami and Vilnius 1997 chart gave the best results consistent with the test results.

Through the follow-up of scientific research in both theoretical and practical parts in the field of foundation engineering, especially the type of piles hammered in clay soils, the following was noted that the lack of research dealing with the subject in a 100% realistic manner, especially in the soil of the Nasiriyah city , in which clay soils constitute the largest percentage, which confirms the lack of access to information related to the practical side of the subject, considering that the study is related to private soils in the Nasiriyah city.

4. CONCLUSIONS

Based on the research reviewed in the literature review of the research topic related to the subject (piled raft behavior), several points were concluded, the most important of which are:

1- Research in modeling and foundation analysis is clear, but there is a gap in real-field studies, especially for clay soil in Nasiriyah.
2- There is a need for comprehensive models that take into account the interaction between the soil and the structure during pile driving, supported by complete field measurements.
3- There are no standardized criteria to assess the risks arising from pile driving in clay soil, necessitating the development of more accurate evaluation and treatment methods.
4- There is a limitation of studies that combine the experimental aspect (on a real scale) with numerical analysis under conditions similar to the soil in Nasiriyah.

5. RECOMMENDATIONS:

1- Enhance field research in clay soil in Nasiriyah using measurements on a full scale.
2- Develop standardized models to assess slope stability during pile driving.
3- Integrate the real interaction between the soil and the structure in the design to improve safety and efficiency.

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