Seismic Vulnerability of Pile-Supported Systems in Liquefiable Soils: Mechanisms and Design Implications

Amardeep Sharma[1], Sonam Chauhan [2], Dr. Prabhat Kumar[3]
Department of Civil engineering, COER University Roorkee*, Uttarakhand, India*

Abstract- ***Despite advancements in engineering, structural collapse or significant damage in pile-supported systems continues to occur in liquefiable soils following major earthquakes. The underperformance of pile foundations remains a critical issue for both earthquake and geotechnical engineers. This thesis presents a comparative analysis of how liquefaction impacts the design of pile foundations. Traditionally, pile failure has been explained through a flexural mechanism, where lateral forces—arising from seismic inertia or ground spreading—cause bending and ultimately failure in the pile. This approach, treating piles as laterally loaded beams, has been extensively studied. However, a newer perspective considers buckling instability, viewing piles as slender, laterally unsupported columns that may buckle in liquefied soil conditions. The aim of this research is to explore the practical design consequences stemming from both the flexural and buckling theories. It also evaluates international design guidelines, including Eurocode 8 – Part I (1997), in the context of pile foundation design. The outcomes of this study are intended to guide practical foundation design in seismic areas and assist professionals dealing with the seismic assessment or design of pile foundations in liquefiable ground conditions.***

The opening section introduces fundamental concepts of pile foundations, including their types, grouping methods, and their behaviour under seismic loading conditions. It also explores different failure mechanisms observed in individual piles and grouped pile systems during earthquakes. The next part provides a detailed literature review, summarizing previous research in the field and analysing the relevant design codes and standards currently used in pile foundation engineering. Following that, the study elaborates on the adopted design methodology. It includes static design procedures, pile design based on Cone Penetration Test (CPT) data, and considerations for inertial forces, kinematic interactions, and liquefaction potential assessment. Subsequently, a comprehensive design example is presented, featuring result comparisons, graphical representations, and calculation of critical pile design parameters to validate the methodology. Finally, the study concludes with a summary of key findings, a structured design workflow, and recommendations for future research to enhance pile foundation design in seismic and liquefiable soil conditions.

Key Words— ***Pile Foundation Design, Seismic Loading, Liquefiable Soils, Pile Failure Mechanisms***

I. INTRODUCTION

Pile foundations are commonly used in areas with weak or liquefiable soils to transfer structural loads to deeper, more stable layers. Their effectiveness has been observed during past earthquakes, especially in saturated granular soils prone to liquefaction. However, designing piles in such conditions requires understanding both geotechnical and seismic influences.

This study focuses on analyzing the behavior of single and grouped piles under seismic excitations in liquefiable and non-liquefiable soils. It includes a comparative assessment of pile performance under different soil conditions and emphasizes the impact of inertial and kinematic interactions. Various failure mechanisms, including buckling and bending, are discussed based on changes in soil properties and pile configurations.

Design methodologies, pile classifications (end bearing, friction, compaction, tension), spacing, and group efficiency are reviewed along with relevant codal provisions. The research incorporates MATLAB-based analysis for developing design curves to assist engineers in pile foundation design in seismic zones.

The study ultimately aims to enhance the understanding of pile-soil-structure interaction under earthquake loading and to provide practical insights for safer and more efficient pile foundation systems in liquefiable terrains.

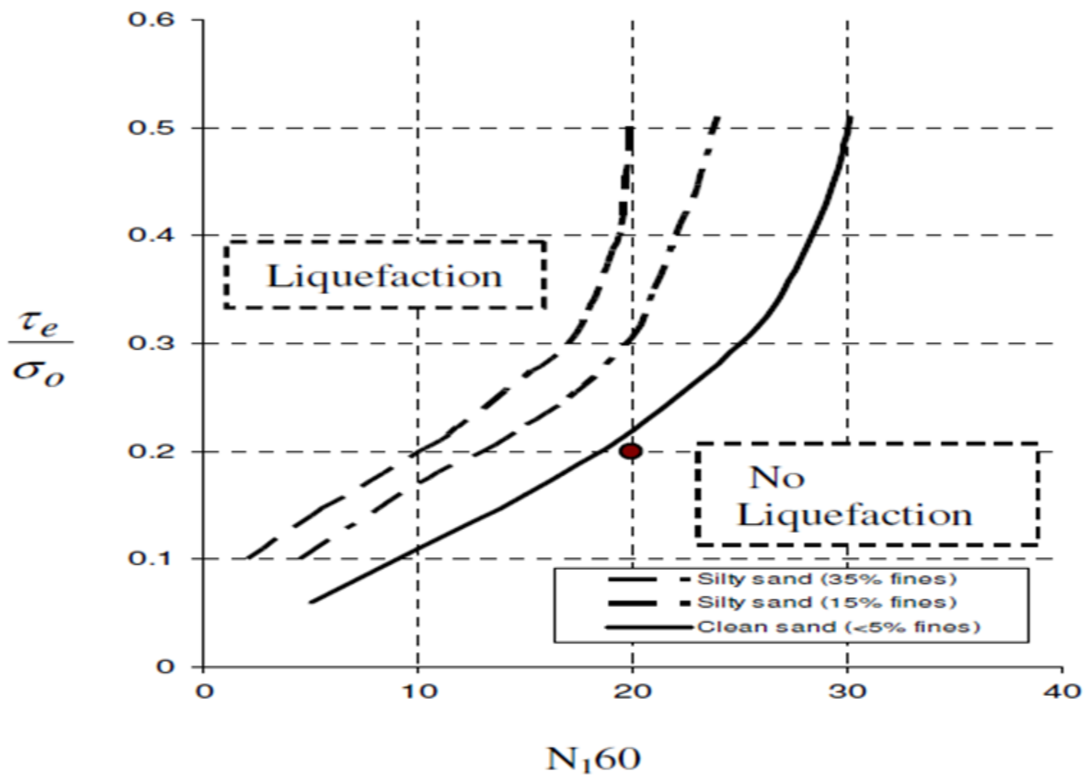

Fig. Liquefaction Potential Charts, Re-plotted Following EC8: Part 5 (2004), Madabhushi et al (2009b)

II. NEED OF STUDY

The design and analysis of piles in both non-liquefiable and liquefiable soils have become paramount in ensuring the safety and stability of structures, particularly in seismic regions. The increasing frequency of extreme weather conditions, urbanization in areas with variable soil conditions, and the growing need for sustainable infrastructure make it essential to develop more refined and reliable methodologies for foundation design. This study addresses the fundamental need for a systematic and robust framework for designing piles, ensuring they can endure both static and dynamic loads under challenging conditions.

In non-liquefiable soils, traditional pile design methods may not always capture the complexities of varying soil properties or seismic-induced forces. By incorporating advanced calculations for axial load capacity, base resistance, and shaft friction, this study contributes to an enhanced understanding of the interactions between soil and pile materials. The use of Cone Penetration Testing (CPT) data is instrumental in refining these calculations, providing more accurate and efficient preliminary designs, ensuring safer and more reliable pile foundations.

Furthermore, the study's exploration of liquefiable soils fills a significant gap in geotechnical engineering. As liquefaction presents a unique challenge by reducing soil strength during seismic events, current methodologies for pile design in liquefiable conditions often lack the sophistication needed to account for complex dynamic soil-pile interactions. This research bridges this gap by developing an approach to accurately estimate liquefaction potential using CSR, CRR, and the Modified Total Stress (MTD) method. The integration of these parameters into the design process will aid in preventing liquefaction-induced failures, a critical advancement in seismic foundation design.

The inclusion of kinematic and inertial loading effects on pile behaviour during earthquakes, and the analysis of soil stiffness and natural frequency, further elevate this study. These dynamic considerations are often overlooked in conventional pile design approaches but are crucial for ensuring the structural integrity of foundations subjected to seismic forces.

In conclusion, this study is a timely and critical contribution to geotechnical engineering, offering a more comprehensive and precise framework for pile design. By addressing both non-liquefiable and liquefiable soils, it provides a valuable resource for engineers and researchers aiming to improve the safety and performance of foundations in regions with challenging soil conditions, ensuring resilience against future seismic events.

III. DESIGN METHODOLOGY

The design methodology for pile foundations in both liquefiable and non-liquefiable soils under seismic loading involves the following key steps:

1. Static Design of Piles
   Initial static load-bearing capacity is determined using standard geotechnical methods, considering factors like soil type, pile material, and size.
2. Cone Penetration Test (CPT)-Based Design
   This method involves interpreting CPT data to assess soil resistance, and it is particularly useful in granular soils prone to liquefaction.
3. Design for Inertial Loading
   Inertial forces due to seismic shaking are considered to determine the dynamic response of piles. This involves calculating the elastic bending of piles based on pile cap stiffness and soil characteristics.
4. Kinematic Interaction and Liquefaction Potential
   Kinematic interactions (soil-pile displacement) are evaluated, especially for liquefiable soils. Liquefaction potential is assessed through seismic soil parameters, including shear wave velocity and liquefaction triggering charts.

Formula for Pile Group Efficiency (Eg)
The efficiency of a pile group is calculated as:
Eg=1−90mn((n−1)m+(m−1)n)·θ
Where:

- EgE_g = Efficiency of pile group
- mm = Number of rows
- nn = Number of columns
- DD = Diameter of pile
- SS = Center-to-center spacing between piles

Table for Minimum Spacing of Piles

Length of Pile	Friction Piles (Sand)	Friction Piles (Clay)	Point Bearing Piles
< 12 m	3D	4D	3D
12 to 24 m	4D	5D	4D
> 24 m	5D	6D	5D

(Where D is the diameter of the pile)
This methodology includes the essential steps and formulas, with emphasis on seismic loading and liquefaction effects on pile design. Let me know if you need further modifications or additional details!

IV CONCLUSION

The research presented outlines the comprehensive methodologies for designing piles in both non-liquefiable and liquefiable soils, with a particular focus on static and dynamic loading conditions. For non-liquefiable soils, the primary consideration for pile design includes axial load carrying capacity, which is determined by calculating base resistance and shaft friction. The use of Cone Penetration Test (CPT) data further refines the base resistance and shaft friction estimates, allowing for more accurate preliminary design. The effects of soil stiffness and natural frequency are also discussed in the context of inertial and kinematic loading, ensuring that the pile design can withstand seismic forces.

In liquefiable soils, the research focuses on determining liquefaction susceptibility through the calculation of cyclic stress ratios (CSR) and cyclic resistance ratios (CRR). It includes methods for estimating the depth of full liquefaction, along with corresponding modifications to the pile design to prevent liquefaction-induced failure. The design methodology emphasizes the need for sufficient safety factors to prevent both bearing failures and excessive settlements due to liquefaction, while considering the effect of liquefied soil on pile response.

The research further integrates inertial loading effects on pile behavior under earthquake conditions, with particular attention to the influence of soil stiffness variation on pile flexibility. The use of flexibility coefficients and the calculation of peak horizontal displacement offer insights into the dynamic behavior of piles during seismic events.

Ultimately, the methodologies outlined in this research enable the design of piles that are both safe and effective under static and dynamic loading conditions in varying soil types. These considerations ensure that piles are adequately designed to resist the axial and lateral forces in non-liquefiable and liquefiable soils, ensuring stability and safety of the structures they support.

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