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

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Abstract- ***Pile foundations are commonly used to support structures in soft or loose soil conditions. However, their performance during major seismic events in liquefiable soils has raised serious concerns among geotechnical and structural engineers. Traditional failure assessments have emphasized flexural failure caused by lateral loads due to seismic ground motion or lateral spreading. Recent studies, however, point toward buckling mechanisms, particularly in long, slender piles subjected to reduced lateral resistance in liquefied soils. This study explores both flexural and buckling failure modes and evaluates their implications on the seismic design of pile foundations. International design guidelines, especially Eurocode 8 – Part I (1997), are reviewed for their applicability in such conditions. The study aims to develop a practical design perspective and provide recommendations for engineers working on pile foundation systems in seismically active, liquefiable areas.***

Although engineering practices have advanced over the years, pile-supported structures built on liquefiable soils still face major risks of damage or collapse during strong earthquakes. The inconsistent performance of such foundations remains a pressing issue in both geotechnical and seismic engineering. This study investigates how soil liquefaction influences pile foundation design, comparing two major failure mechanisms: flexural bending and buckling instability.

The study begins by outlining the basics of pile foundations—their types, group configurations, and behavior under earthquake conditions. It also reviews observed failure patterns in individual and grouped piles during seismic events. The literature review summarizes past work in this field and assesses the current design guidelines widely used in practice.

The research then details the adopted design approach, including static design based on Cone Penetration Test (CPT) data, and factors in inertial forces, kinematic effects, and soil liquefaction potential. A design case study is also included, with calculations, charts, and comparisons to validate the methodology. The thesis concludes by highlighting the major findings, proposing a structured design process, and offering recommendations to further improve the design of pile foundations in earthquake-prone and liquefiable regions.

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.

II. NEED OF STUDY

The structural integrity and seismic resilience of buildings are critically dependent on the robust design and analysis of pile foundations, particularly in regions characterized by both liquefiable and non-liquefiable soils. Given the rising incidence of extreme environmental events, rapid urban expansion into geotechnically complex areas, and the global emphasis on sustainable and resilient infrastructure, there is an urgent demand for advanced and dependable foundation design methodologies. This study seeks to establish a systematic and rigorous framework for pile foundation design capable of withstanding both static and dynamic loading in diverse and challenging subsurface conditions.

In the context of non-liquefiable soils, conventional design approaches often fall short in capturing the nuanced variability of soil behavior and seismic force transmission. To address these limitations, this research integrates refined analytical models that account for axial load capacity, end-bearing resistance, and shaft friction. The application of Cone Penetration Testing (CPT) data further enhances the precision of these evaluations, enabling more informed preliminary designs and contributing to the development of safer and more reliable deep foundation systems.

The investigation extends into the domain of liquefiable soils, an area that continues to pose significant challenges within geotechnical practice. Liquefaction-induced loss of soil strength during seismic events severely compromises foundation performance. Existing design methodologies often do not adequately reflect the complex dynamic interactions between soil and piles under such conditions. This study addresses this gap by incorporating a comprehensive assessment of liquefaction potential using Cyclic Stress Ratio (CSR), Cyclic Resistance Ratio (CRR), and the Modified Total Stress (MTD) method. The integration of these parameters into the pile design process marks a substantial advancement in seismic design protocols, enhancing the ability to mitigate liquefaction-related failure risks.

Moreover, this research incorporates critical dynamic parameters—including kinematic and inertial loading effects, variations in soil stiffness, and structural natural frequency—into the design paradigm. These considerations, frequently neglected in traditional design practices, are shown to be essential for ensuring the structural reliability of pile-supported systems under seismic excitation.

In summary, this study makes a timely and significant contribution to the field of geotechnical engineering by proposing a holistic and technically robust framework for the design of pile foundations. By addressing the distinct challenges associated with both liquefiable and non-liquefiable soils, it provides a valuable reference for engineering professionals and researchers striving to enhance foundation performance and resilience in seismically vulnerable environments.

III. DESIGN METHODOLOGY

The design approach for pile foundations subjected to seismic loading in both liquefiable and non-liquefiable soils includes the following essential steps:

1. Static Pile Design
   The initial static bearing capacity of piles is calculated using established geotechnical techniques, taking into account soil properties, pile dimensions, and material characteristics.
2. CPT-Based Soil Assessment
   Cone Penetration Test data is analyzed to evaluate soil resistance, which is especially effective for granular soils susceptible to liquefaction.
3. Consideration of Inertial Loads
   The impact of seismic-induced inertial forces on piles is assessed by determining the dynamic bending response, incorporating pile cap stiffness and soil parameters.
4. Evaluation of Kinematic Effects and Liquefaction Risk
   Soil-pile relative displacements (kinematic interactions) are examined, with a focus on liquefiable soils. Liquefaction susceptibility is evaluated using seismic soil parameters such as shear wave velocity and triggering criteria from liquefaction charts.

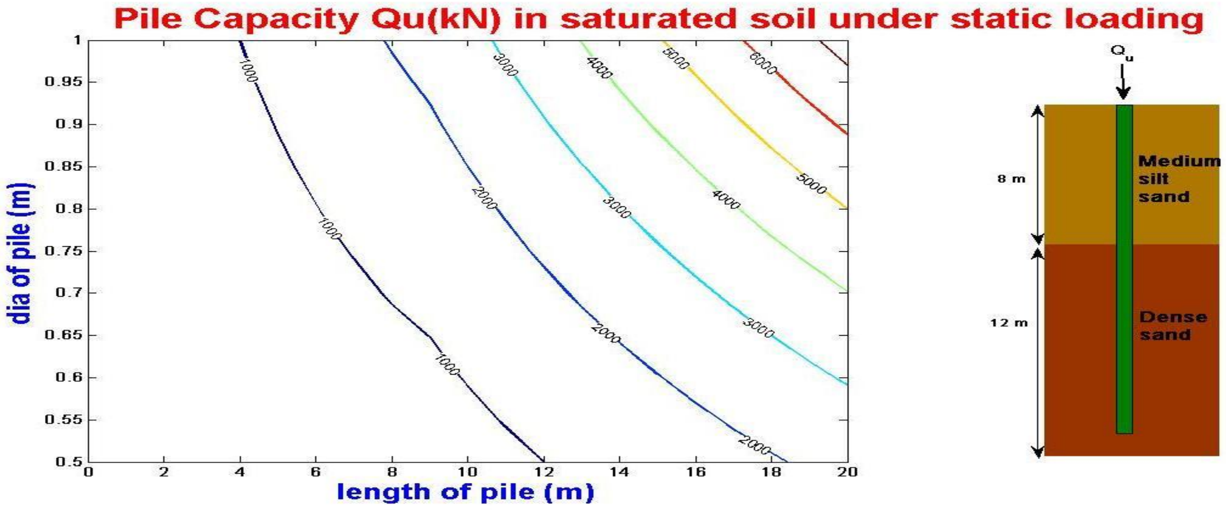

Figure : Pile capacity curve for static loading in saturated soil

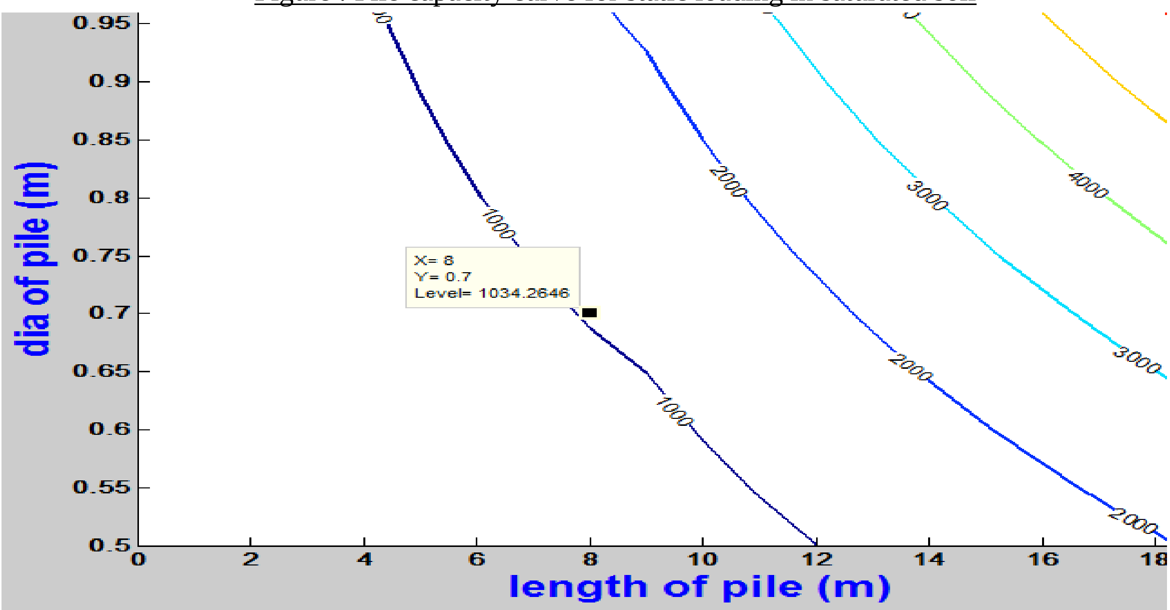

Figure: Data representation of static pile capacity curve

Results:

Corrected Young’s modulus of pile (Ep_corrected) = 25.61 GPa

Effective mean confining stress at the depth of diameter of pile (p’) = 3.3 kPa

Small – strain shear modulus (G0) = 14.26 MPa

Degraded shear modulus of soil (Gs) = 2.3248 MPa

Young’s modulus of soil at depth of diameter of pile (EsD) = 6.97 MPa

Effective length of pile (Lad) = 9.12 m

Minimum Elastic length of pile (ZL_min) = 4.378 m

Maximum Elastic length of pile (ZL_max) = 6.938 m

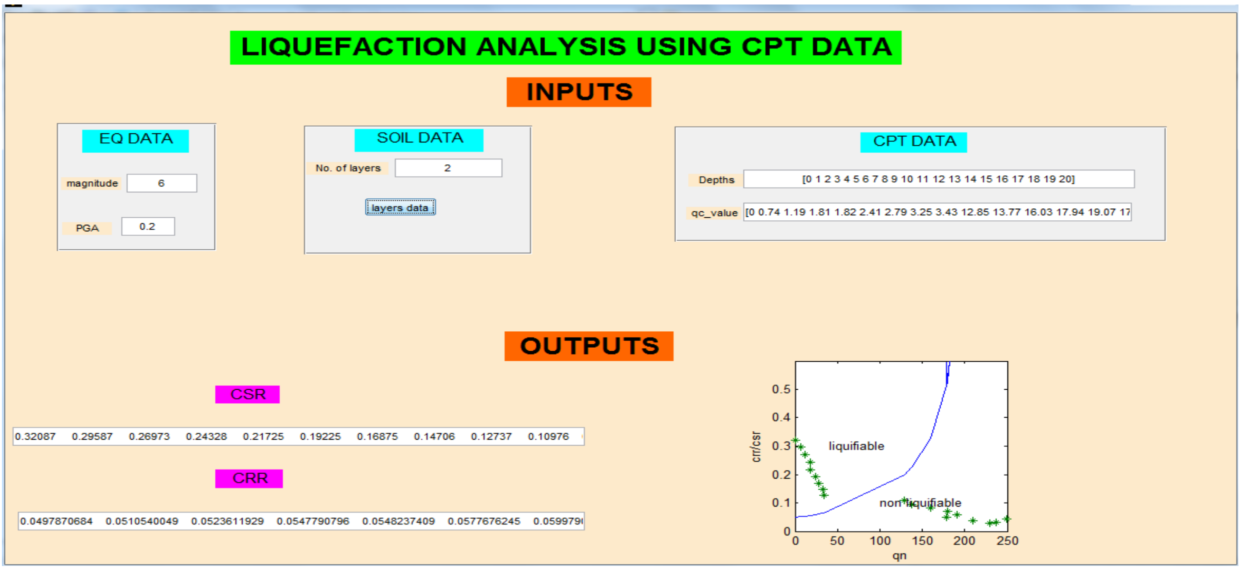

Figure : Results from GUI for liquefaction susceptibility analysis

IV CONCLUSION

This study presents an in-depth framework for designing pile foundations in both stable (non-liquefiable) and unstable (liquefiable) soil environments, emphasizing their performance under static and seismic loads. In non-liquefiable soils, the design primarily revolves around evaluating the pile's axial capacity by accurately estimating the base bearing resistance and shaft friction. Incorporating Cone Penetration Test (CPT) data enhances the precision of these estimates, leading to more reliable initial designs. Additionally, the study addresses the influence of soil stiffness and natural vibration frequencies on pile response, particularly in the presence of inertial and kinematic seismic forces, ensuring the foundation's resilience to earthquake loading.

For soils prone to liquefaction, the focus shifts to assessing the risk of liquefaction through calculations of cyclic stress ratio (CSR) and cyclic resistance ratio (CRR). The methodology includes predicting the depth and extent of soil liquefaction and adapting the pile design to mitigate failure modes related to loss of soil strength. Special attention is given to maintaining appropriate safety margins to prevent foundation bearing failure and excessive settlements triggered by liquefaction, while accounting for altered pile-soil interaction in weakened soil conditions.

Furthermore, the research incorporates the effects of dynamic inertial loads on pile behavior during seismic events, highlighting how changes in soil stiffness affect pile flexibility. The analysis includes the use of flexibility factors and peak horizontal displacement calculations, providing deeper insight into the dynamic response of pile foundations under earthquake forces.

In summary, this comprehensive approach enables the design of pile foundations that effectively resist both vertical and lateral loads across diverse soil conditions. The strategies developed ensure structural stability and safety by addressing the complex challenges posed by seismic activity in both liquefiable and non-liquefiable ground.

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