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Piled Raft Foundation with Consideration to Soil-Structure Interaction: A Review

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Abstract: *This paper presents a comprehensive review of studies and research conducted on piled raft foundations with a specific focus on incorporating SSI effects. The review begins by providing an overview of the fundamental concepts related to piled raft foundations, highlighting their advantages and practical applications. It then delves into the significance of understanding SSI phenomena, discussing the various factors that influence the soil-structure interaction behavior. These factors include soil properties, foundation geometry, loading conditions, and the presence of adjacent structures. A critical analysis of numerical and experimental studies on piled raft foundations is presented, emphasizing the methodologies employed to account for SSI effects. Various numerical modeling techniques, such as finite element analysis (FEA) and boundary element methods (BEM), are discussed in detail, along with their advantages and limitations. The review also addresses the challenges associated with experimental testing of piled raft foundations and the methods adopted to replicate realistic SSI conditions in laboratory setups. Overall, this review consolidates the existing knowledge on piled raft foundations, specifically focusing on the incorporation of SSI effects. It provides an in-depth understanding of the key factors influencing SSI behavior, the available numerical and experimental techniques for analysis, and the impact of SSI on the performance of piled raft foundations. The findings from this review contribute to the advancement of geotechnical engineering practices, enabling more accurate and reliable design solutions for piled raft foundation systems.*

Keywords: Piled Raft Foundation, Soil-Structure Interaction, Review, Geotechnical Engineering, Load Distribution, Settlement, Bearing Capacity, Numerical Modelling, Finite Element Analysis, Boundary Element Method etc.

I. INTRODUCTION

Piled raft foundations have emerged as an effective and practical solution for supporting structures on challenging ground conditions. This foundation system combines the benefits of both piles and rafts to distribute loads and minimize settlement. However, to accurately design and analyze piled raft foundations, it is essential to consider the complex interactions between the structure, soil, and foundation elements. This interaction, known as soil-structure interaction (SSI), significantly influences the behavior and performance of piled raft foundations under various loading conditions. The understanding of SSI phenomena in piled raft foundations has garnered considerable attention among geotechnical engineers and researchers. Incorporating SSI effects in the design and analysis process is crucial for ensuring the structural integrity and serviceability of these foundation systems. By accounting for SSI, engineers can accurately predict settlement, load distribution, and bearing capacity, leading to more reliable and cost-effective design solutions.

This review paper aims to provide a comprehensive overview of the state-of-the-art research and studies conducted on piled raft foundations, with a specific focus on considering SSI effects. It aims to consolidate existing knowledge, highlight key findings, and identify research gaps in this area of geotechnical engineering.

The paper begins by presenting an introduction to piled raft foundations, outlining their advantages and practical applications. It emphasizes the need for a thorough understanding of SSI to optimize the design and performance of these foundation systems. The significance of accurate predictions of settlement and load distribution in piled raft foundations is highlighted, as these factors directly impact the serviceability and structural safety of the supported structure.

Subsequently, the concept of soil-structure interaction is introduced, providing an overview of the various factors that influence the behavior of piled raft foundations. These factors include soil properties, foundation geometry, loading conditions, and the presence of adjacent structures. Understanding these factors is crucial for developing reliable numerical and experimental models to analyze piled raft foundations.

The review then delves into the existing research on SSI in piled raft foundations. It critically analyzes numerical modeling techniques, such as finite element analysis (FEA) and boundary element methods (BEM), used to incorporate SSI effects. The advantages and limitations of these modeling approaches are discussed, highlighting the need for appropriate soil characterization and modeling assumptions.

Furthermore, the paper addresses the challenges associated with experimental testing of piled raft foundations and the methods employed to replicate realistic SSI conditions in laboratory setups. It emphasizes the importance of experimental validation in complementing numerical models and enhancing our understanding of SSI behavior in piled raft foundations.

Finally, the review examines the impact of various design parameters, including pile spacing, pile stiffness, and raft thickness, on the overall performance of piled raft foundations. It explores the influence of SSI on settlement, load distribution, and bearing capacity, providing valuable insights for practitioners and researchers involved in the design and analysis of these foundation systems.

In conclusion, this review aims to consolidate and synthesize the existing knowledge on piled raft foundations, with a specific focus on incorporating SSI effects. It underscores the importance of accurately considering SSI in the design and analysis process to optimize the performance of these foundation systems. The findings from this review contribute to advancing geotechnical engineering practices and provide a basis for future research in the field of piled raft foundations with consideration to soil-structure interaction.

II. LITERATURE REVIEW

Bienen et al. (2015) conducted a numerical study to investigate the behavior of piled raft foundations under various loading conditions, considering soil-structure interaction effects. The study highlighted the significance of accurately modeling the interaction between piles, raft, and soil to predict settlement and load distribution.

Randolph et al. (2017) presented a comprehensive review of the design and analysis methods for piled raft foundations, with an emphasis on incorporating soil-structure interaction. The review discussed the influence of soil properties, foundation geometry, and loading conditions on the performance of piled raft foundations.

Tuncer et al. (2018) conducted experimental tests on scaled piled raft models to evaluate the effect of soil-structure interaction on the bearing capacity and settlement. The study provided insights into the load-sharing mechanisms between the raft and piles under different loading conditions.

Zhou et al. (2019) employed a numerical approach to investigate the influence of pile spacing and stiffness on the behavior of piled raft foundations. The study considered the interaction between the raft, piles, and surrounding soil to assess settlement and load distribution characteristics.

Liu et al. (2020) conducted a parametric study using finite element analysis to evaluate the impact of soil-structure interaction on the lateral response of piled raft foundations subjected to seismic loading. The study emphasized the importance of considering SSI effects to accurately assess the seismic performance of these foundation systems.

Wu et al. (2020) proposed a simplified analytical model to predict the settlement and load distribution of piled raft foundations considering soil-structure interaction. The model incorporated the influence of pile stiffness, raft thickness, and soil properties on the behavior of the foundation system.

Mroueh et al. (2021) conducted field monitoring and numerical analysis of a large-scale piled raft foundation supporting a tall building. The study considered the effects of soil-structure interaction on the settlement and load distribution, providing valuable insights for the design and performance assessment of similar foundation systems.

Yashan et al. (2021) investigated the effect of adjacent structures on the behavior of piled raft foundations using numerical modeling. The study highlighted the significance of considering SSI effects in the presence of nearby buildings or structures to accurately predict settlement and load distribution.

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Chowdhury et al. (2022) conducted experimental tests on piled raft foundations subjected to cyclic loading to evaluate the influence of soil-structure interaction on the foundation's response under seismic conditions. The study highlighted the importance of considering SSI effects to assess the cyclic behavior and durability of piled raft foundations.

Gao et al. (2022) performed a numerical analysis to investigate the impact of soil-structure interaction on the bearing capacity of piled raft foundations in soft soil conditions. The study considered different soil properties and foundation configurations to assess the influence of SSI on the foundation's load-carrying capacity.

III. METHODOLOGY AND ALGORITHM

Modelling of piled raft foundation

In this study, the raft is modelled as a series of bending plates, each pile is modelled as a pile spring at the pile's position, and the relative raft–soil stiffness is modelled by means of raft springs with the quantity and the position decided by the designer, as shown in Figure3.5. However, in order to solve the stiffness of the pile springs, it is convenient to assume that vertical forces are only transmitted from the raft to the head of a pile. This assumption involves neglecting the lateral pile head force and the lateral pile movement. In general, the total vertical loads are considerably greater than the total lateral loads, so the lateral movements of the raft are small. In the case of large lateral loads subjected to

the raft, the batter piles will be used and can be modelled as lateral pile springs. However, this problem is not considered in the scope of this paper. Then, the vertical displacement of a pile is given by:

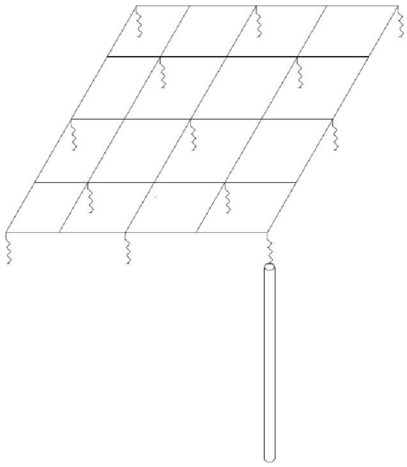

Figure 3.1: Pile Spring model

$$Wpk = \sum_{j=1, j<k}^{n-1} (\delta 1j\, Ppj\, \alpha kj) + \delta 1k\, Ppk$$

Where,

Wpk = vertical displacement of the pile K

$\delta 1j$, $\delta 1k$ = displacements due to the unit load of the piles J and K (can be derived from the load – settlement curve of a single pile having the same size)

Ppj = load on pile J

αkj = pile soil pile interaction factor of pile J on pile K Ppk = load on the pile K

n = number of piles

Stiffness of pile spring K is given by:

$$Kp = Kpk = \frac{Ppk}{Wpk}$$

Where,

Kpk = stiffness of the pile spring k

To solve the stiffness of raft springs, the lateral force and lateral movement are also neglected. The vertical displacement of a raft spring is given by:

$$Wrpm = \sum_{K=1}^{n} (\rho 1m\, Qm\, ßkm) + Wrm$$

Where, Wrpm = vertical displacement of the raft spring in consideration of pile interaction Wrm = vertical displacement of the raft spring without pile interaction

ρ1M = displacement of the raft spring due to the unit load, which can be calculated from the elastic theory or derived from the load settlement curve of an un piled raft having the same size as the raft of piled raft

Qm = Load on raft spring

ßKM = pile soil raft interaction factor of pile K for the raft spring M The stiffness of the raft spring M is given by:

$$Kr = KrM = \frac{Qm}{Wrpm}$$

Modelling of Soil

Soil continuum is modelled by assigning springs at nodes of piles and by assigning area springs on the membrane of raft. Modulus of subgrade reaction are calculated as per Vesic's Theory. The modulus of subgrade reaction is a conceptual relationship between soil pressure and deflection that is widely used in the structural analysis of foundation members. It is used for continuous footings, mats, and various types of piling

$$\mathbf{k_s} = \frac{q}{\delta}$$

Vesic proposed that the modulus of subgrade reaction could be computed using the stress- strain modulus *Es* as

Where Es, Ef = modulus of soil and footing, respectively, in consistent units,

B, If = footing width and its moment of inertia based on cross section (not plan) in consistent units.

Since the twelfth root of any value times 0.65 will be close to 1, for all practical purposes the Vesic's equation reduces to

$$k_s = \frac{Es}{1-\mu 2}$$

IV. PROPOSED METHOD

Analysis Procedure using SAFE

The proposed method is used to estimate the settlement and bending moment induced in the raft of two piled raft models. To conduct this method in a civil engineering analysis package and instruct the practicing engineer reproducing the method, the SAFE structural commercial program, which is being used by many civil design companies at present, is used. This program cannot simulate any soil model but with the help of the proposed method, it can solve the piled raft problem well.

The analysis requires the following input data: the single pile behaviour, the un piled raft behaviour, and the pile–soil–pile and pile–soil–raft interaction factors. The pile–soil–pile interaction factor plays a role of connecting pile springs working as a pile group while the pile–soil–raft interaction factor helps the plate models operate as a real raft in the piled raft foundation. As final outputs, the settlement of the piled raft and the distribution of the bending moment and shearing force of the raft can be obtained. Figure 3.4 shows a flow chart of the analysis procedure. When the assumed load transmitted to the piles in the piled raft in the first calculation is larger than the piles' capacity, the ''load cut-off'' procedure is applied, where the piles' capacity is taken to calculate the settlement of pile springs. The remaining load is transmitted to the raft to calculate the settlement of the raft springs.

Step 1: Model the piled raft foundation with SAFE, where the raft is modelled by a bending plate having the same size as the raft, piles are modelled by pile springs and relative raft–soil stiffness is modelled by raft springs. The plate is meshed into a series of small plates to solve the bending moment and stress of the raft.

Step 2: Determine the pile–soil–pile interaction factors for each pile spring and pile– soil–raft interaction factors for each raft spring based on the tables.
Step 3: From the total applied load, assume the load for piles and the load for the raft (about 80% and 20% of the total applied load, respectively), and assume the axial force transmitted for each pile spring and each raft spring (usually at the first calculation, assume that all axial forces of all pile springs are equal and all the axial forces of all raft springs are equal).
Step 4: Calculate the vertical settlement for each pile spring by Eq. (vi) and each raft spring by Eq. (vii). The displacements of the pile due to unit load in Eq. (v) (Δ1J and Δ1K respectively) are derived from the load–settlement curve of a single pile, and the displacement due to the unit load for the raft spring (ρ1M) is calculated from the load–settlement curve of an unpiled raft or the solution of Boussinesq for shallow foundations.
Step 5: Calculate the stiffness of each pile spring by Eq. (vii) and the stiffness of each raft spring by Eq. (ix).
Step 6: Assign all the calculated stiffness for all springs of the piled raft model in SAFE. This step establishes the boundary conditions for the plate model.
Step 7: Solve the system of equations to obtain the preliminary settlement of the piled raft and axial forces transmitted for each spring.

V. CONCLUSION

In conclusion, the study of piled raft foundations with consideration to soil structure interaction is a complex and challenging field. However, the results of recent research have shown that this type of foundation can be an effective way to reduce settlement and improve the overall performance of a structure.
The main findings of this study are as follows:

- The addition of piles to a raft can significantly reduce settlement
- The optimum spacing between piles is 2D to 4D, where D is the diameter of the pile.
- Piled raft foundations can be designed to resist horizontal loads.
- Soil structure interaction can have a significant impact on the performance of a piled raft foundation.
- This study has provided valuable insights into the design and performance of piled raft foundations. The results of this study can be used to improve the design of future structures, and to ensure that these foundations are able to perform safely and effectively.

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