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Nonlinear 3D interactive analysis of superstructure and piled raft foundation

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ABSTRACT

An interactive design method that takes into account the coupling between the stiffness of the superstructure, the piled raft and the soil has been proposed for analyzing the response of building structure. Special attention is given to consideration of interaction between the superstructure and the piled raft. And a series of numerical analysis is performed to validate the interactive analysis routine in comparison to the unified analysis method. Through the comparative studies, it is found that the iterative and interactive analysis gave similar results of settlement and raft bending moment compared with finite element analysis. And it is also found that the proposed design method considering interaction between superstructure and foundation is capable of predicting reasonably well the behavior of building structures. It can be effectively used to perform the design of a superstructure-piled raft foundation system.
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1. Introduction

All over the world, an increasing need for optimized foundation design of the building structure is becoming an important issue in engineering practice. In the conventional design of pile foundations, the total load transmitted by the superstructure is carried by the piles, with any contribution of the raft (footing) being ignored. The piles are generally located on a regular grid pattern with the same diameter and length. According to most standards of pile design, identical piles must be designed with an adequate safety factor from 2 to 3. This requirement leads to a higher number and larger length of piles. Therefore, the pile foundation is more expensive and the settlement is unnecessarily small. In recent decades, the concept of piled raft has been used extensively in Europe and Asia and an increasing number of structures, especially buildings, have been founded on them [1–4] and piled rafts have proved to be an economical alternative to conventional pile foundations in circumstances in which the soil below the raft can provide significant bearing capacity and stiffness to supplement that of the piles.

In the design of a building structure, the soil-structure interaction problem is an interdisciplinary field which involves structural and geotechnical engineering. In the traditional design practice, the superstructure is typically analyzed without modeling the foundation-subsoil (i.e. fixed boundary or rigid base conditions) and the foundation is designed without considering the effect of the superstructure stiffness. It may result in overestimation of forces, the bending moment, and the settlement of the superstructure and foundation [5,6]. Nevertheless the traditional design approach is still dominant in engineering practice. This is because the analysis process is affected by many factors such as: column and wall geometry, design load, raft and pile group geometry, soil properties, and interaction between different structural elements. Accordingly, there is currently no practical method available to predict behavior of the entire structures due to the difficulty and uncertainty in quantifying these factors.

Much work has been done to study the superstructure-foundation interaction problem by many researchers. In the early 1950s, Mayerhof [7] recognized the importance of superstructure-foundation-soil interaction. From then onwards, numerous studies have been carried out to quantify the effect of soil-structure interaction on the behavior of framed structure. Recently the possible unified structural-geotechnical models for the structure-foundation-soil system are reported. Lee and Brown [8] developed and analysis by treating the structure, foundation and soil system as an integral unit. Fraser and Wardle [9] used the finite element method to analyze a two bay portal frame on a layered cross-anisotropic elastic continuum. Viladkar et al. [10] also presented a new approach for the physical and material

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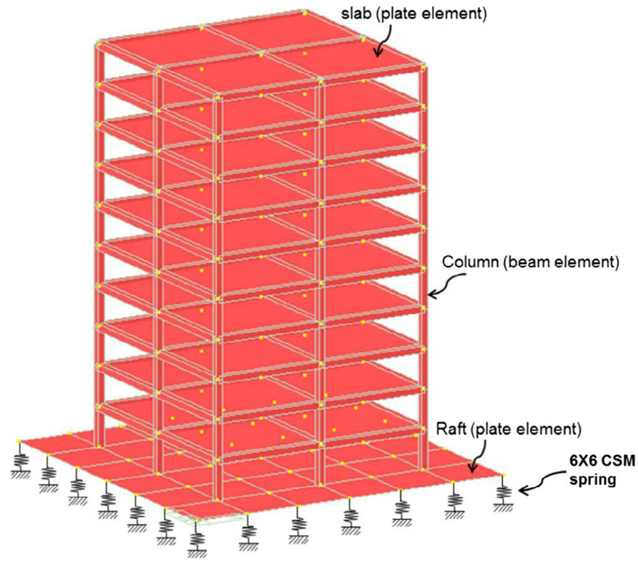
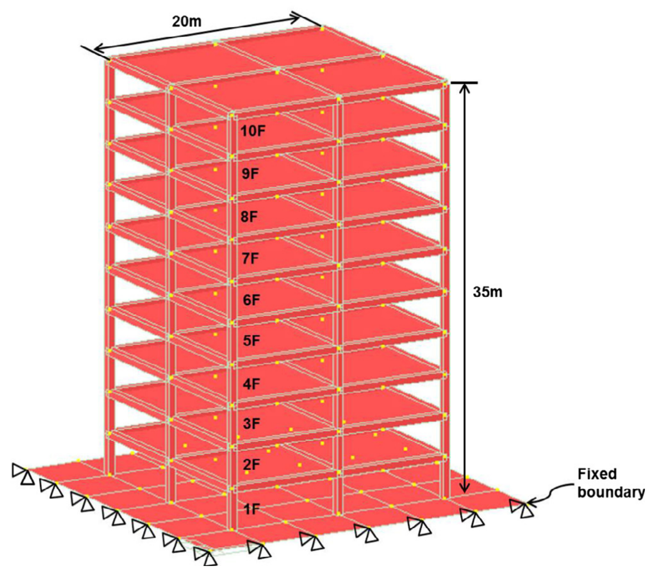
modeling of a space frame-raft-soil system. Hora [11] presented the computational methodology adopted for nonlinear soil-structure interaction analysis of an infilled frame-foundation-soil system. Most of the unified analysis based on the finite element method [12–15] provides versatile tools that are capable of modeling the superstructure, soil continuity, soil nonlinearity, soil-structure interface behavior, and 3-D boundary conditions. Therefore, it considers the structure-foundation-soil interaction automatically, while the traditional design method does not. However, the finite element method remains primarily a research technic due to the effort required in computation and in modeling the problem. Additionally, full 3D FE analyses were almost impossible for large scale of superstructure-foundation-soil systems. This is because it is too complicated and time consuming to simulate a soil-structure interaction problem as the entire building structure. Besides, the amount of results from the 3D FE analysis is huge but only a few data are of interest to the structural engineer. So for a practical design of a building structure, the design methods should be more simple and reliable, especially for cost-effectiveness.

In this study, an interactive design method is proposed for the simplified interaction between the superstructure and a piled raft. It is intermediate in theoretical accuracy between a unified analysis and the conventional design approach. Additionally, the proposed method is necessary for the geotechnical engineer to form an understanding of the load transfer mechanism from the superstructure to the foundation. The overall objective of this study is focused on the application of the interactive design method for predicting behavior of entire building structures, and a series of numerical analysis is performed to validate the interactive analysis routine in comparison to the unified analysis method. For this purpose, the three-dimensional (3D) Finite-Element (FE) analysis has been carried out. For the unified analysis of superstructure and foundation, the numerical analyses were performed via the FE code PLAXIS 3D foundation [16], with column, floor and piled raft foundation systems.



(a) CSM boundary condition (proposed method)



(b) Fixed boundary condition (conventional design)

Fig. 1. Idealized 3D model of superstructure (MIDAS-CIVIL).

2. New design method for piled rafts supported building structures

To determine accurate deformations and internal forces in a building structure, it is necessary to account for the whole system response, including the superstructure, foundation, and soil. Such an accurate determination of the building response is necessary to make design decisions within the performance-based engineering framework. In this study, therefore, a new analysis methodology for superstructure-foundation-soil is proposed by considering coupled stiffness of foundation-soil and structure.

2.1. Idealization of superstructure

Fig. 1(a) and (b) illustrate a numerical model of superstructure used in the proposed and conventional design method. A 3D FEM model to simulate the response of a superstructure under gravity load using MIDAS-CIVIL [17] is presented here. In the most generalized form, superstructure of the building frames may be idealized as three-dimensional space frame using two noded beam elements with six degrees of freedom per node. It is adopted for the beams and columns of superstructure and connections between beams and columns are treated as rigid. A four-node plate element with six degrees of freedom per node was used to model the slabs of the superstructure and the raft supporting the frame structure.

The soil and pile head supporting at various node of the plate element are simulated by a series of equivalent and independent elastic springs with six degrees of freedom. The coupled stiffness matrix (CSM), $[k]_i$, is of order 6×6, representing three spring constants, three rotational constraints, and four coupling between spring and rotational constraints. The equilibrium equation at the pile head and soil in local coordinate system (u, v, w) is represented as follows;

$$\begin{bmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{22} & 0 & 0 & 0 & k_{26} \\ 0 & 0 & k_{33} & 0 & -k_{35} & 0 \\ 0 & 0 & 0 & k_{44} & 0 & 0 \\ 0 & 0 & -k_{53} & 0 & k_{55} & 0 \\ 0 & k_{62} & 0 & 0 & 0 & k_{66} \end{bmatrix}_i \begin{Bmatrix} \delta_u \\ \delta_v \\ \delta_w \\ \alpha_u \\ \alpha_v \\ \alpha_w \end{Bmatrix}_i = \begin{Bmatrix} F_u \\ F_v \\ F_w \\ M_u \\ M_v \\ M_w \end{Bmatrix}_i \tag{1}$$

where $[k]_i$ is the stiffness matrix of pile head and soil, $\{\delta\}_i$ is the vector of displacement, $\{\alpha\}_i$ is the vector of rotation, $\{F\}_i$ is the vector of force, and $\{M\}_i$ is the vector of moment at the ith pile head and soil.

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