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Probabilistic assessment of pile group response considering superstructure stiffness and three-dimensional soil spatial variability

Y.F. Leung*, M.K. Lo

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

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ABSTRACT

This note presents the probabilistic analyses of pile groups considering spatially variable soil properties and superstructure-foundation interaction effects. Condensed stiffness matrices for the superstructure and spatially variable subsurface domain are evaluated individually, and coupled with foundation elements for holistic analyses of the system. Probabilistic assessments are then performed using surrogate modeling method. Parametric studies show that common assumptions of perfect or no spatial correlations in the soil may not represent the critical scenario for pile groups. Two presented foundation case studies also reveal the significance of interactions between superstructure and soil variability, and potentials of foundation tilting due to spatially variable soil properties.

1. Introduction

The designs of large pile groups or piled rafts are often controlled by differential settlements, which may cause distortion or tilting of the structure. However, in previous studies of probabilistic analyses of piles and pile groups [e.g., 1–7], there have been limited discussions on the uncertainties associated with these aspects of piled foundation response, and their inter-relationship with spatial variability of soil properties and influence of superstructure. This may be partly attributed to the complex interaction effects in the system. Simulating all superstructure elements, foundation components and subsurface domain using a single finite element model involves substantial computational demands. The problem is exacerbated for probabilistic assessments that require a large number of analyses for typical Monte Carlo approaches.

This note proposes an efficient approach to circumvent these issues, which enables the impacts of three-dimensional soil variability and superstructure stiffening effects to be considered in probabilistic analyses of large piled foundations. To reduce computational demands, stiffness components of the spatially variable subsurface domain and superstructure are evaluated separately through matrix condensation techniques, and then incorporated with the foundation model. Two piled raft case studies are presented to show that the probabilistic approach may reveal deformation mechanisms in large foundations that cannot be captured by the conventional deterministic approach.

2. Response model for pile groups in spatially variable soils

Fig. 1 illustrates the concept of matrix condensation applied to both the superstructure and foundation soil with spatial variations, which avoids the excessive computational demands associated with modeling the entire system in a single numerical model. The pile group analysis approach is conceptually similar to that by [8], except for the modeling of spatially variable soil domain. The piles and the cap (or raft if in touch with foundation soil) are discretized into segments specified by nodes. In the case of linear-elasticity, the displacements, $\boldsymbol{u}$, is given by:

$$(\mathbf{K}^p + \mathbf{K}^r + \mathbf{K}^s)\boldsymbol{u} = \boldsymbol{p}^w + \boldsymbol{p}^g = \boldsymbol{p}^w - \mathbf{F}^{-1}\boldsymbol{u} \quad (1)$$

where $\mathbf{K}^p$= stiffness matrix of piles modeled as one-dimensional beam elements; $\mathbf{K}^r$= stiffness matrix of pile cap, modeled as four-node thin plate elements; $\mathbf{K}^s$= condensed structure matrix; $\boldsymbol{p}^w$= loading from superstructure; $\boldsymbol{p}^g$= ground reaction forces acting on foundation elements, which are equal and opposite to the pile forces on soil, represented through the soil flexibility matrix $\mathbf{F}$. In this study, only the vertical displacements are considered.

The condensed matrix $\mathbf{K}^s$ represents the rigidity of superstructure against differential displacements at its connections to the foundation, which may be columns or walls modeled as discrete supports. Its components K_{ij}^s can be obtained through a finite element model of the superstructure, where a unit displacement is applied at column j while fixing the other supports, and reaction forces at each support i are then extracted. For a superstructure with n supports, this procedure is

* Corresponding author.
E-mail address: andy.yf.leung@polyu.edu.hk (Y.F. Leung).

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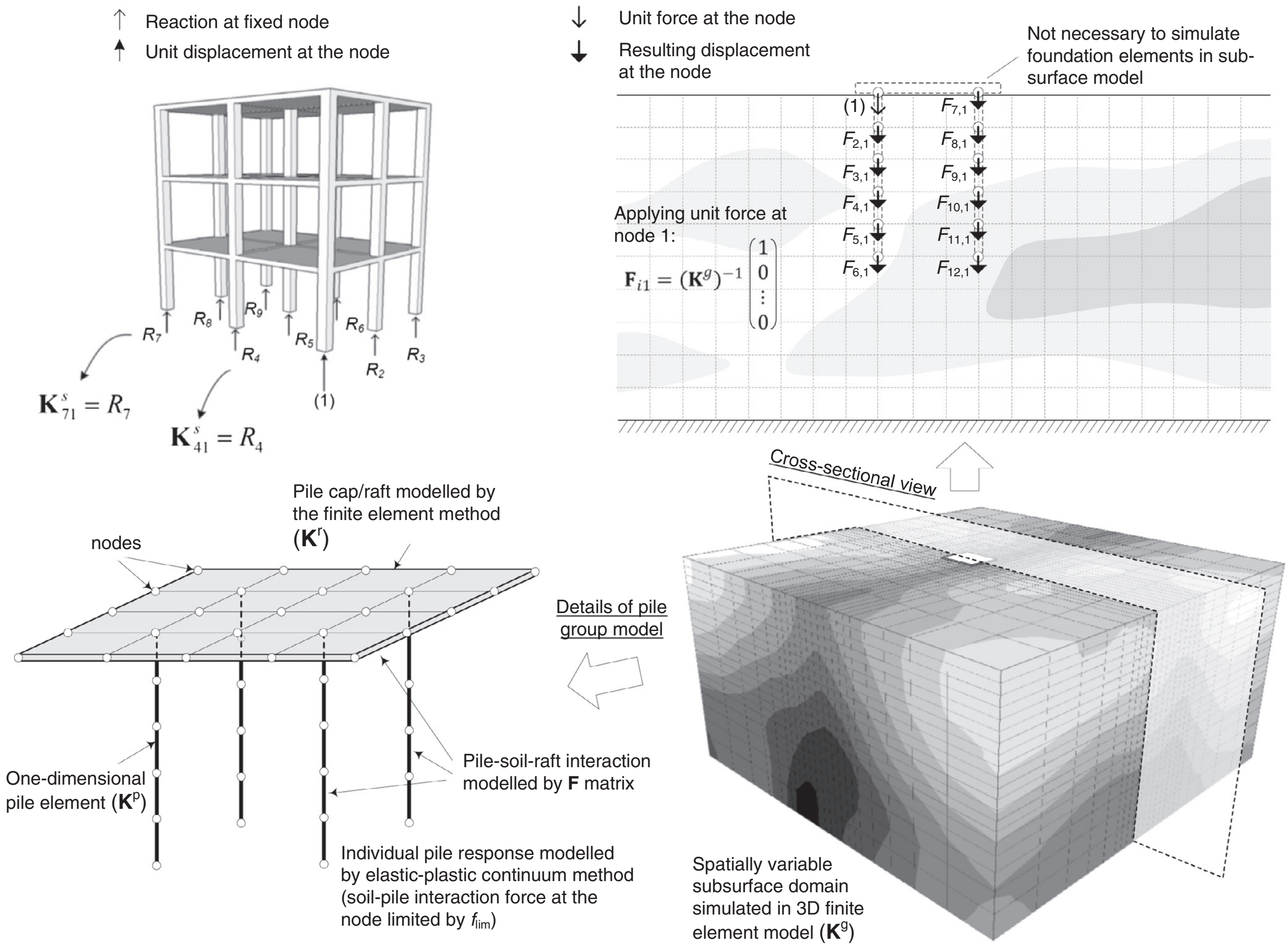

Fig. 1. Formulation of probabilistic pile group analysis approach.

repeated by n times to construct a $n \times n$ matrix [8]. To model soil nonlinearity, $\boldsymbol{u}$ consists of a continuum component and a plastic slip component ($\boldsymbol{u}^{ip}$), in which case Eq. (1) becomes [9,10]:

$$(\mathbf{K}^s + \mathbf{K}^p + \mathbf{K}^r + \mathbf{K}^*)\boldsymbol{u} = \boldsymbol{p}^w + \mathbf{K}^*\mathbf{F}^*\langle \boldsymbol{p}^{in}\rangle + \mathbf{K}^*\boldsymbol{u}^{ip}$$
$$\text{where} \quad \langle \boldsymbol{p}^{in}\rangle_i = \min\{[\boldsymbol{p}^w - (\mathbf{K}^s + \mathbf{K}^p + \mathbf{K}^r)\boldsymbol{u}]_i, f_{lim}\} \tag{2}$$

and $\mathbf{K}^*$= local soil stiffness matrix and is diagonal ($K^*_{ii} = 1/F_{ii}$), $\mathbf{F}^*$= soil flexibility matrix without the main diagonal, and f_{lim}= limit force at the nodes, evaluated based on the raft bearing capacity or pile shaft or base resistance; $\boldsymbol{u}^{ip}$= plastic displacements when the soil-pile interface force exceeds f_{lim}, and Eq. (2) can be solved by an iterative process [10]. Derivation from Eq. (1) to Eq. (2), and its validation for deterministic analysis are presented in [8].

The objective of this study is to incorporate spatial variability of soil properties into analyses of large pile groups. For this purpose, formulation of soil flexibility matrix, $\mathbf{F}$, is modified here. This matrix represents the pile-soil-pile interaction effects and is often evaluated using elastic solutions [11,12]. There is, however, no closed-form solution for three-dimensional random fields of spatially variable modulus. The finite element method is therefore adopted. The procedure is essentially a matrix condensation technique: when a unit force is applied at pile node location j, displacements at other pile node locations are extracted as a vector , and this is repeated at all pile nodes to obtain the complete $\mathbf{F}$ matrix. In a probabilistic assessment, each random field realization is associated with a different $\mathbf{F}$ matrix.

In the proposed approach (Fig. 1), the superstructure stiffness ($\mathbf{K}^s$) and subsurface soil flexibility ($\mathbf{F}$) matrices are evaluated separately by matrix condensation technique, and then coupled to the stiffness of foundation elements through Eq. (2). Therefore, it is not necessary to simulate the piles or raft in the three-dimensional subsurface model, which is streamlined to evaluate only the pile-to-pile and pile-to-raft interaction effects. A finite element program is written in this study for such purpose, adopting eight-node hexahedral elements with two Gauss points in each direction, i.e., 8 Gauss points per element. Each element involves a different stiffness matrix, $\mathbf{K}^e$, due to differences in both element geometries and deformation moduli. The global subsurface stiffness matrix, $\mathbf{K}^g$, is then assembled for evaluation of $\mathbf{F}$. As discussed, nonlinearity of pile behavior is modeled through the slip displacement $\boldsymbol{u}^{ip}$, by limiting f_{lim} at soil-pile interface, while interaction effects between the piles are modeled as linear-elastic. This is consistent with [13], who stated that soil nonlinearity is confined to a narrow zone around the pile, and soil response remains essentially elastic outside this zone. This phenomenon is further discussed in [9,14–17].

3. Probabilistic analyses of pile groups with rigid or flexible caps

In this study, the soil properties are represented as a combination of the trend ($\boldsymbol{t}$) and residuals ($\boldsymbol{e}$). The residuals (or deviations from trend) are often observed to be correlated spatially [18,19], with their uncertainties represented by the spatial covariance matrix $\mathbf{V}$, which can be factored as $\mathbf{V} = \sigma^2\mathbf{R}$, where σ^2 = variance of $\boldsymbol{e}$ across the domain; $\mathbf{R}$ = spatial correlation matrix, with components R_{ij} represented by a squared exponential function describing correlation of parameters at various locations: