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Influence of Pile Cap Flexibility on Cap-Pile-Soil System

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The load deformation behavior of the cap-pile-soil system is investigated, based on numerical analysis. Special attention is given to consideration of pile cap flexibility. Rigid pile cap analysis and flexible cap analysis were conducted for comparison. A numerical method that takes into account the coupling between the rigidities of the piles, the cap and the column has been introduced to analyze the response of pile group-supported columns. The prediction of the lateral loads and bending moments in the pile cap is much more conservative for a flexible cap than for a rigid cap.

INTRODUCTION

Piles are often used in groups for the support of bridge structures. There are numerous analytical and numerical methods for designing pile groups. These methods can generally be classified into 3 different types:

(1) the equivalent single pile method (Bogard and Matlock, 1983; Brown et al., 1988; Ooi et al., 2004),

(2) the elasticity method (Poulos, 1971; Banerjee and Driscoll, 1976; Randolph, 1980), and

(3) the general 3-dimensional load transfer method (Reese et al., 1970; Chow, 1987; Hoit et al., 1996; Kitiyodom and Matsumoto, 2002).

An essential element of pile foundation design is the effort required to define the stiffness of the cap-pile-soil system confidently. According to the U.S. Army Manual (1991), knowing the correct relationship between the stiffness of the pile and cap is extremely important so as to design pile groups accurately for use in flexible base structures. Two kinds of methods are available for calculating the pile–cap interaction: the stiffness method and the finite element method.

The stiffness method was suggested by Hrennikoff (1950) and has been extended into a general 3-D method by Saul (1968) and Reese et al. (1970). Group 6.0 (2004), a commercial package which has been used for practical design, is based on this stiffness method. This method can consider the pile–cap interaction, the nonlinear behavior of individual piles, and the pile–soil–pile interaction, but has limitations in that it cannot consider the coupling of the rigidities of the pile cap to each other and to the column, since this method assumes a pile cap to be a rigid body. To consider these coupled pile cap rigidities, a pile cap needs to be modeled by finite elements such as beams, frames, plates and flat-shell elements.

The overall objective of this study is to investigate the effect of changes in the pile cap stiffness. A numerical method that considers coupled cap rigidities has been introduced to overcome the restrictions associated with the conventional stiffness method. Rigid pile cap analysis and flexible cap analysis have been conducted to examine the effect of changes in the pile cap stiffness. A series of parametric studies has been carried out, and the results of a numerical analysis are highlighted.

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KEY WORDS: Cap-pile-soil, cap flexibility, numerical analysis, bending moment, pile group.

METHOD OF ANALYSIS FOR STRUCTURE–PILE–SOIL SYSTEM

Modeling of Pile Group

Fig. 1 presents a schematic diagram of a typical pile group-supported column (a piled pier) and the associated numerical model used in this study. The pile group consists of 4 piles and a flexible pile cap, which is not in direct contact with the soil. Here, the individual piles are modeled using beam–column elements. The soil around the individual piles is represented by a set of load–transfer curves, and the interaction between piles is represented by a p-multiplier. For the modeling of the flexible pile cap and the column, 3-D finite elements, such as 4-node flat-shell elements for the pile cap and 3-D beam elements for the column, were used.

The equation for equilibrium at the pile head in the local coordinate system (u, v, w) is as follows:

$$\{F\}_i = \begin{Bmatrix} F_u \\ F_v \\ F_w \\ M_u \\ M_v \\ M_w \end{Bmatrix}_i = \begin{bmatrix} k_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{22} & 0 & 0 & 0 & k_{26} \\ 0 & 0 & k_{33} & 0 & -k_{35} & 0 \\ 0 & 0 & 0 & k_{44} & 0 & 0 \\ 0 & 0 & -k_{53} & 0 & k_{55} & 0 \\ 0 & k_{62} & 0 & 0 & 0 & k_{66} \end{bmatrix}_i \begin{Bmatrix} \delta_u \\ \delta_v \\ \delta_w \\ \alpha_u \\ \alpha_v \\ \alpha_w \end{Bmatrix}_i = [K_E^p]_i \{\delta\}_i \quad (1)$$

where $[K_E^p]_i$ is the stiffness matrix of the pile head, $\{\delta\}_i$ the displacement vector at the pile head, and $\{F\}_i$ the vector of the force at the ith pile head. The pile head stiffness matrix $[K_E^p]_i$ is of order 6×6, representing 3 displacement constants, 3 rotational constraints, and 4 couplings between the displacement and rotational constraints.

In this study, the individual piles were analyzed one by one to retain all of the load–displacement relationships for each pile head in the first instance. The stiffness matrices $[K_E^p]$ of the individual piles which were incorporated into the structural analysis were derived from the load–displacement curves of the individual piles.

Modeling of Flexible Pile Cap

The stiffness method (Hrennikoff, 1950) can consider neither coupling between the pile group and the column, nor flexibility of the pile cap because the pile cap is assumed to be a rigid body.