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A numerical solution and evaluation of dynamic stiffness of pile groups and comparison to experimental results

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ABSTRACT

A number of solutions and computer programs are already available to determine the dynamic stiffness of complete pile foundations, assuming linear elastic soil behavior and perfect bonding between the piles and the surrounding soil. These are assumptions that would be generally valid for properly designed machine foundations where very small strains should be expected. A number of approximate formulations have also been developed. Among these the most commonly used one is that proposed by Poulos (1971) [1,2] for the static case, computing interaction coefficients between the heads of two piles considered by themselves, then forming a matrix of these coefficients to obtain the interaction between the heads of all the piles in the group. Additional approximations have been suggested, particularly for the computation of the interaction coefficients, using closed form expressions. In this paper, a semi-analytical-semi-numerical formulation has been adopted to calculate the static and dynamic stiffness of pile foundations in the frequency domain, and some approximate expressions are suggested. They are intended for pile groups with pile spacing of the order of two to four diameters, typical range of the modulus of elasticity of the piles over that of the soil between 100 and 1000, and very small amplitude vibrations.

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1. Introduction

The dynamic stiffness of pile groups was studied by Gomez [3], Kaynia [4], Dai [5,8] and Dai and Roesset [6,7] using an Elasto-Dynamics formulation and assuming linear elastic behavior of piles & soil and perfect bonding between them. They studied groups of 2 by 2, 3 by 3 and 4 by 4 piles, accounting for the complete interaction between all piles and enforcing perfect bonding between the piles and the surrounding soil over the complete lengths of all piles, considering only the pile head interactions. Some other researchers, e.g. Kouroussis [9], instead, employed a three-dimensional finite element method to calculate dynamic stiffness of pile groups in time domain considering nonlinear effect.

In this study, a numerical formulation has been adopted to calculate static and dynamic stiffness of the pile foundations, which is a semi-analytical solution in the frequency domain and also assumes linear elastic behavior and perfect soil-pile bonding, while incorporating the Poulos' approximation instead of complete interaction between all piles. Results show very little differences to those with complete interaction. The analysis consists then of the following steps:

1. Determination of the dynamic stiffness matrix of one cylindrical cavity (to be filled by a pile) in a horizontally layered soil deposit extending to infinity in the horizontal directions for any frequency of interest. This step is carried out using a semi-analytical-semi-numerical formulation developed by Kausel [10]. The formulation uses an analytical solution in the horizontal directions extending to infinity, while the soil deposit is discretized vertically enabling a numerical method. Below the horizontally layered soil deposit, bed rock or very stiff soils are assumed in this study. One can also consider a uniform half space underneath the layered soil deposit with small modifications to the computer program. The dynamic stiffness matrix of the cylindrical cavity is then combined with that of a single pile, which is modeled using beam theory, to obtain the dynamic

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stiffness matrix of the pile-surrounding soil system, $[K_F]$. This matrix would provide the solution to the dynamic analysis of a single pile.

2. Using $[K_F]$ and Poulos' assumption, which considers only one pile at a time and neglects the existence of all other piles, and applying a unit horizontal load at the pile head, one can calculate the horizontal dynamic displacement at the pile head, $u_{1,1}$, and the displacement at the position supposed to be occupied by the other pile, $u_{2,1}$, in the frequency domain, although Poulos' assumption was originally used only for static cases. Using the same approach, one can calculate $u_{1,2}$ and $u_{2,2}$. The resulting expressions for displacements of the two pile heads with forces P_1 and P_2 applied at each one would be

$$\begin{cases} u_1 = u_{1,1}P_1 + u_{1,2}P_2 = u_{1,1}(P_1 + \alpha_{1,2}P_2) \\ u_2 = u_{2,1}P_1 + u_{2,2}P_2 = u_{2,2}(\alpha_{2,1}P_1 + P_2) \end{cases}$$

$\alpha 1,2 = u1,2/u1,1$ and $\alpha 2,2 = u2,1/u2,2$ are the pile head interaction coefficients. If the heads of the two piles are connected by a rigid cap and a total force P is applied to the cap, writing $\boldsymbol{I} = \pi r^2\{1,1\}^T$, $P = P_1 + P_2 = \boldsymbol{I}^T\{P_1, P_2\}^T$, $\boldsymbol{U} = \{u_1, u_2\}^T$, and defining $\boldsymbol{A} = \begin{Bmatrix} 1 & \alpha_{1,2} \\ \alpha_{2,1} & 1 \end{Bmatrix}$, $\boldsymbol{K} = \begin{Bmatrix} 1/u_{1,1} & 1 \\ 1 & 1/u_{2,2} \end{Bmatrix}$, $\boldsymbol{U} = \boldsymbol{K}^{-1}\boldsymbol{A}\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix}$ or $\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} = \boldsymbol{A}^{-1}\boldsymbol{KU}$, and $P = \boldsymbol{I}^T\boldsymbol{A}^{-1}\boldsymbol{KU}$, the dynamic stiffness of the group of two piles is $K_G = \boldsymbol{I}^T\boldsymbol{A}^{-1}\boldsymbol{KI}$. All matrices and vectors are denoted in bold throughout this paper unless notified otherwise. It is also assumed that the two piles have the same horizontal pile head displacements due to the existence of a rigid cap or $u_1 = u_2$, and the cap is fixed against rotation or rocking. This would provide the solution for the case of two piles.

3. For a group of N by N piles considering every combination of two piles i, j from the complete pile foundation, and obtaining the corresponding interaction factors $\alpha_{i,j}$ and $\alpha_{j,i}$, an interaction matrix A of size N by N can be formed in a similar manner. Defining $K_{i,j} = diagonal(1/u_{i,j})$, the pile group stiffness would still be given by $K_G = \boldsymbol{I}^T\boldsymbol{A}^{-1}\boldsymbol{KI}$.

Computer programs were developed implementing the above formulation. Results were then obtained for pile groups of a single pile, 2 by 2, 4 by 4, 6 by 6, 8 by 8 and 10 by 10 piles. The soil used for the study had a shear wave velocity of 100 m/s, a Poisson's ratio of 0.25, a mass density of 2000 kg/m^3 and internal (material) damping of 5%. The piles were assumed to have a radius of 0.5 m, pile spacing of 3 m as the base case, a mass density of 2500 kg/m^3 and 5% material damping. The modulus of elasticity of the piles was changed to investigate the effect of the E_P/E_S ratio and sensitivity studies were also conducted for pile spacing of 2–4 m. The depth of the soil deposit was assumed to be 50 m for the base case unless specified otherwise. End bearing and floating piles were considered. The end bearing piles had a length of 50 m, the same as the soil deposit, while the floating piles were 25 m long. Sensitivity studies were also conducted for depth of soil deposit, pile spacing, Poisson's ratio and soil material damping.

2. Results

The horizontal stiffness of the pile groups was calculated accounting for the full interaction coefficients computed from the elastic analyses. A limited number of field tests have suggested that no interaction takes place beyond a certain distance. As a result, some authors have recommended using a limiting distance of 10 or even 5 diameters, beyond which the interaction between piles is ignored. The differences in results using a limiting distance or not were discussed in an earlier paper (Dai and Roesset [6]) and can be significant. Unfortunately, there is a scarcity of experimental data for very small amplitude vibrations to ascertain which of the two approaches is more realistic. Among the experimental studies, the best one is probably the one carried by Sharnouby and Novak [11]. The results of this study will be compared to theirs.

The horizontal dynamic stiffness of the foundations can be written as

$$K_{dynamic} = K_{real} + iK_{imaginary} = K_{real} + i\Omega C_{eq} = K_{static}\left(k_1 + i\frac{\Omega R_{eq}}{c_S}c_1\right)$$

in which Ω is the frequency of vibration, C_{eq} is the constant of an equivalent viscous dashpot, $R_{eq} = \sqrt{Ar/\pi} = Ns/\sqrt{\pi}$ is an equivalent radius of the pile group, $Ar = N^2s^2$ is the foundation area as defined by Fig. 1, s is the pile spacing, c_s is the shear wave velocity of the soil deposit, and k_1 and c_1 are dynamic stiffness coefficients.

The objective of this study was to compute values of the stiffness at zero frequency (static stiffness) and the dynamic coefficients k_1 and c_1, or the equivalent dashpot, for the frequencies of interest.

2.1. Static stiffness

Blaney et al. [12] expressed the lateral static stiffness of a single solid circular pile with the head fixed against rotation as

$$K = \alpha\frac{E_P I_P}{R^3}\left(\frac{E_S}{E_P}\right)^{\beta},$$

where E_P, E_S are the Young's moduli of the pile and the soil, respectively, R is the radius of the pile and I_P its moment of inertia. Sanchez Salinero [13] conducted an extensive set of comparisons for the static stiffness of a single pile using the formulations and results presented by Poulos [1,2,14], Kuhlemeyer [15], Novak and Nogami [16] and Blaney et al. [12]. The values of the coefficients varied from 2.38 and 0.80, to 4.6 and 0.83. Using Blaney's formulation [12], Sanchez-Salinero [13] recommended values of $\alpha = 3.34$, $\beta = 0.81$. Results from this study recommend $\alpha = 6.09$ and $\beta = 0.786$. It is worth nothing that static stiffness of a single pile obtained in this study is only a result of Kausel formulation before introducing Poulos' assumption.

The static group factors for end bearing piles with spacing of 3 diameters are presented in Fig. 2. The group factor is defined as the ratio of the group stiffness to that of a single pile multiplied by the

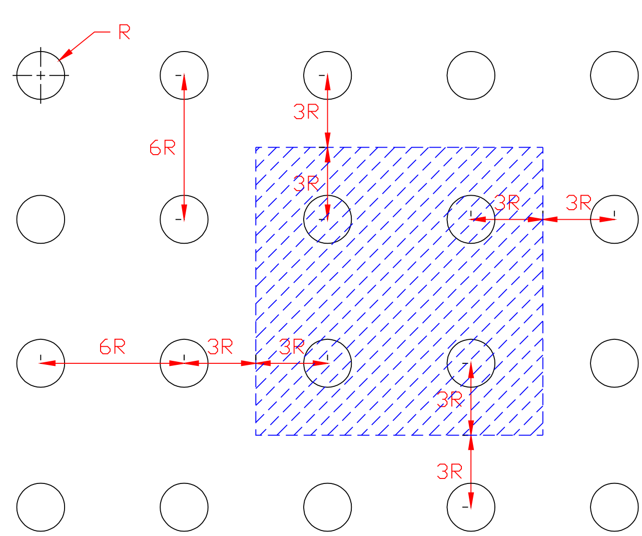

Fig. 1. Definition of equivalent area (shaded area) for pile groups.

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