Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

5-3-4

CHARACTERISTICS OF THE DYNAMIC RESPONSE OF PILE GROUPS IN HOMOGENEOUS AND NONHOMOGENEOUS MEDIA

Amir M. KAYNIA

Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran

SUMMARY

In this paper a boundary element formulation is used to evaluate the dynamic response of pile groups embedded in homogeneous and nonhomogeneous soil media. To obtain the Green's functions for semi-infinite media the equations of wave propagation are solved by Fourier and Hankel transforms. The results of the analysis are presented in nondimensional form to demonstrate the basic features of dynamic stiffnesses and seismic response of pile groups in different soil media.

INTRODUCTION

Early studies on pile groups have primarily focussed on static pile behavior (Refs. 1,2). In these studies Mindlin's fundamental solution (Ref. 3) for the displacement field within a semi-infinite medium was used to couple the flexibility matrices of piles and the soil medium through boundary element techniques. Although these studies were unable to provide any qualitative information on dynamic aspects of the problem their methodology was used later for dynamic analyses. Earlier contributions to this subject (Refs. 4,5) revealed that the dynamic behavior of pile groups was strongly frequency-dependent. This stimulated extensive research on this subject. Most of these studies were based on the boundary element method. The Green's functions in these studies were obtained either numerically by axisymmetric finite element methods (Ref. 4,6) or by numerical solution of the three dimensional wave propagation equations (Refs. 7,8,9,10). In addition, a number of approximate methods have been developed for dynamic analyses of pile groups (Refs. 11,12,13,14).

The objective of this paper is to study the characteristics of the horizontal and vertical dynamic stiffnesses and seismic response of pile groups in homogeneous and nonhomogeneous media. Fig.1 shows the problem under consideration. The nonhomogeneous medium in this study is a semi-infinite medium in which the elasticity modulus increases linearly with depth up to the pile tips and remains constant beyond (Fig.1-b). The homogeneous medium, on the other hand, is a visco-elastic half-space with an elasticity modulus equal to the constant modulus of the nonhomogeneous medium (Fig.1-c).

FORMULATION

The surface tractions that develop at the pile-soil interface can be considered to consist of lateral and frictional components. Fig.2 shows the distribution of lateral tractions on one of the piles in a group (other components of surface tractions have similar distributions). The pile-soil interface is discretized into a number of cylindrical boundary elements and the actual distribution of surface tractions is replaced by a piecewise-constant distribution over boundary elements. If U denotes the vector of nodal displacements and P denotes the vector of force resultants on boundary elements then, considering the equilibrium of the soil mass, one can write

$$U = F_S P \tag{1}$$

in which F_S denotes the frequency-dependent "flexibility matrix" of the soil medium, relating piecewise-constant harmonic loads to the steady-state average displacements of the boundary elements. (In this formulation, quantities such as U and P are complex; their variation with time is given by the factor $\exp(i\omega t)$, where ω is the frequency of harmonic vibration). Similarly considering the equilibrium of piles one can write

$$\begin{aligned} U &= \Psi U_\circ - F_p P \\ P_\circ &= K_p U_\circ + \Psi^T P \end{aligned} \tag{2}$$

in which $U_\circ$ is the vector containing the displacements of pile ends and $P_\circ$ is the associated force vector, Ψ is a matrix relating the three components of displacements at the nodes of boundary elements to the displacements of pile ends, F_S is the dynamic flexibility matrix of piles with clamped ends, and K_p is the dynamic stiffness matrix of piles.

Combining Eqs.(1) and (2) one gets

$$P_\circ = \{K_p + \Psi^T (F_S + F_p)^{-1} \Psi\} U_\circ = K_\circ U_\circ \tag{3}$$

$K_\circ$ is a matrix which relates only the five components of forces at each end of piles to the corresponding displacements.

To obtain expressions for K_p, F_p and Ψ one has to solve the dynamic beam equations with the appropriate boundary conditions at the two ends (Ref. 7). To calculate F_S, one needs to evaluate Green's functions for buried uniform ring loads (distributed over the surface of cylindrical boundary elements). for this purpose, the three dimensional equations of wave propagation were solved numerically by means of Fourier and Hankel transforms (Ref. 7). It should be noted, however, that the matrix thus obtained corresponds to soil mass without cavities (the spaces occupied by piles). It has been shown that (Ref. 7) the effect of cavities can be approximately accounted for by subtracting the mass density and elasticity modulus of the soil from those of the pile .

In order to obtain dynamic stiffnesses of a rigid foundation (pile cap) to which the piles are connected one needs to impose the appropriate geometric and force boundary conditions at the pile heads and pile tips.

To extend this formulation to seismic analyses one only needs to express the displacements U as the summation of free-field displacements $\bar{U}$ and the displacements caused by pile-soil interface forces P; that is

$$U = \bar{U} + F_S P \tag{4}$$

Combining Eqs.(2) and (4) one gets

$$P_\circ = K_\circ U_\circ + \bar{P}_e = K_\circ U_\circ - \Psi^T (F_S + F_p)^{-1} \bar{U} \tag{5}$$

where $\bar{P}_e$ defines consistent fictitious forces at pile ends which reproduce the seismic effects. Again, one has to impose the appropriate boundary conditions at pile ends to obtain the transfer functions from the ground motion to pile cap. Free-field displacements and Green's functions can be obtained by a discrete layer matrix formulation (Ref. 7), In which a nonhomogeneous medium should be replaced by a set of homogeneous layers.

RESULTS

In this study, the elasticity modulus, mass density, Poisson's ratio and material damping ratio of the soil are denoted by E_s, ρ_s, ν_s and β_s, respectively, and the corresponding quantities for the piles are denoted by E_p, ρ_p, ν_p and β_p. In addition L and d define the length and diameter of piles, and s denotes the distance between adjacent piles. Finally $a_o = \omega d/C_s$ defines the nondimensional frequency, in which ω is the frequency of harmonic vibration and C_s is the largest shear wave velocity of the soil profile.

The quantities of interest in this study are the dynamic stiffnesses and the seismic response of pile groups. The stiffness functions are complex quantities which can be expressed as

$$K^G = k^G + i\, a_o c^G \tag{6}$$

In the results presented in this paper the dynamic stiffnesses are normalized with respect to the associated static stiffness of a single pile in the group $(k^s(0))$. The seismic motion, in the present study, is assumed to be due to vertically propagating shear waves in the soil medium that produce a free-field ground surface displacement u_g. These waves induce both a translation and a rotation in the pile cap. The transfer functions for these quantities are complex-valued functions and will be presented in terms of their absolute values.

For the results presented here it has been assumed that $\beta_s = 0.05$, $\nu_s = 0.4$, $\beta_p = 0.0$, $\nu_p = 0.25$, $L/d = 20$, $\rho_s/\rho_p = 0.7$ and $E_s/E_p = 10^{-2}$ (note that for the nonhomogeneous medium E_s represents the maximum value of elasticity modulus in the soil profile (Fig.1-b). The quantities of interest have been evaluated for 3×3 square groups with two different pile spacings ($s/d = 2.5$ and 5).

Figs.3 and 4 show the normalized horizontal and vertical dynamic stiffnesses (k^G and c^G in Eg. 6) of a 3×3 pile group with a colse pile spacing ($s/d = 2.5$) in the homogeneous and nonhomogeneous media, described earlier in this paper (Fig.1). Figs.5 and 6 show the same quantities for a 3×3 group with a wider pile spacing ($s/d = 5$) . These results suggest that the response of pile groups in the nonhomogeneous medium is more frequency-dependent than the response in the homogeneous medium. In other words, the interaction effects, which are characterized by sharp peaks in stiffness functions are more pronounced in the nonhomogeneous medium. The fact that the behavior of piles (especially for horizontal vibration) is essentially governed by the near surface soil properties and that interaction effects in softer soil media are stronger than in stiffer media are (Ref. 7) help one to understand these observations.

Figs.7 and 8 display the normalized dynamic stiffnesses of the same pile groups in the nonhomogeneous medium of Figs.3 and 4 but computed by the conventional superposition technique. In this technique, which was originally proposed for static analyses of pile groups (Ref. 1), and was later extended to dynamic analyses (Refs. 7,8), only two piles are considered at a time in the formation of the global flexibility matrix. Comparison of the results of superposition method and those of the three-dimensional method (dotted curves in Figs.7 and 8) suggests that for very close pile spacings this technique is not capable of providing accurate results. However, the accuracy of this method improves as the pile spacing increases. This is verified by Figs.9 and 10, where the results obtained by the superposition method for dynamic stiffnesses of the same pile groups in the nonhomogeneous medium of Fig.5 and 6 are compared with the associated three-dimensional results.

Finally Figs.11 and 12 display the absolute value of the transfer function from ground surface horizontal displacement, u_g, to the pile cap displacement for the same pile groups for which stiffness characteristics were studied in Figs.3 to

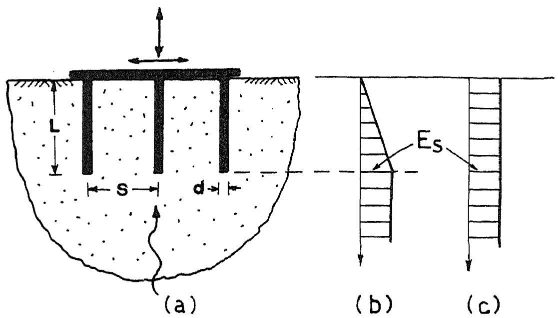

Fig.1 Nonhomogeneous and homogeneous media

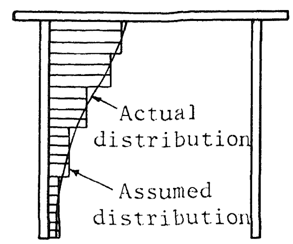

Fig.2 Distribution of tractions

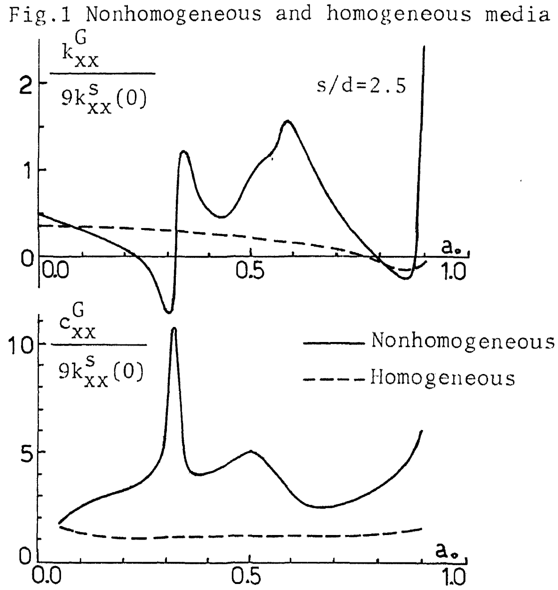

Fig.3 Horizontal dynamic stiffness

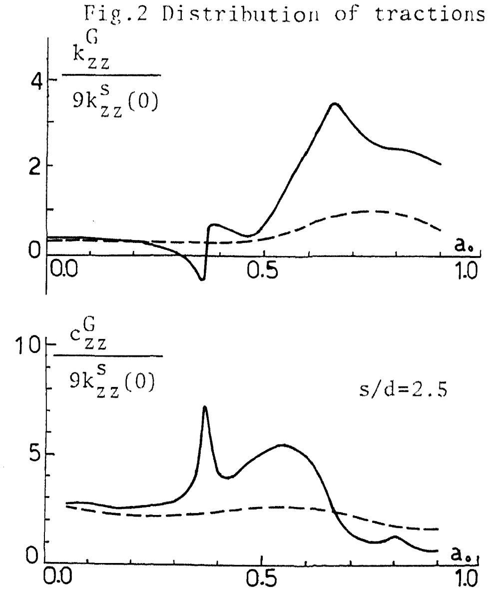

Fig.4 Vertical dynamic stiffness

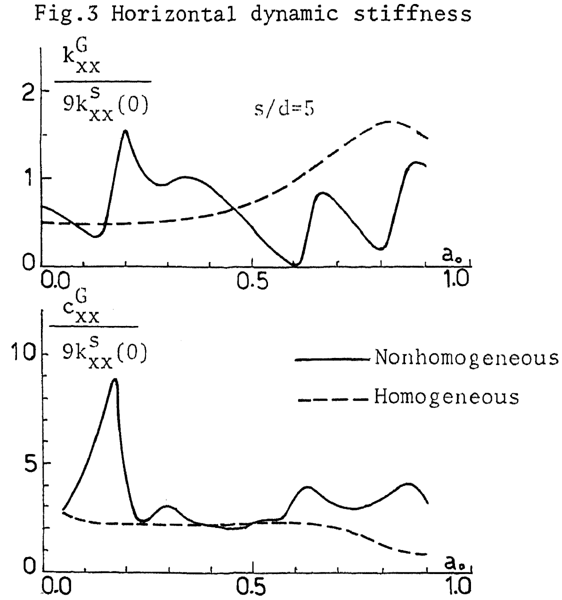

Fig.5 Horizontal dynamic stiffness

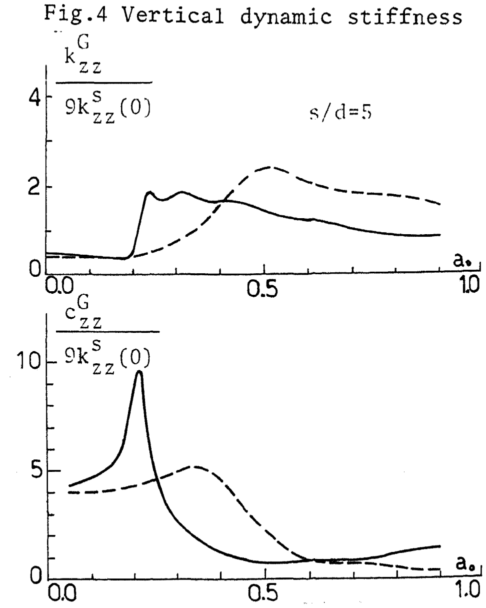

Fig.6 Vertical dynamic stiffness

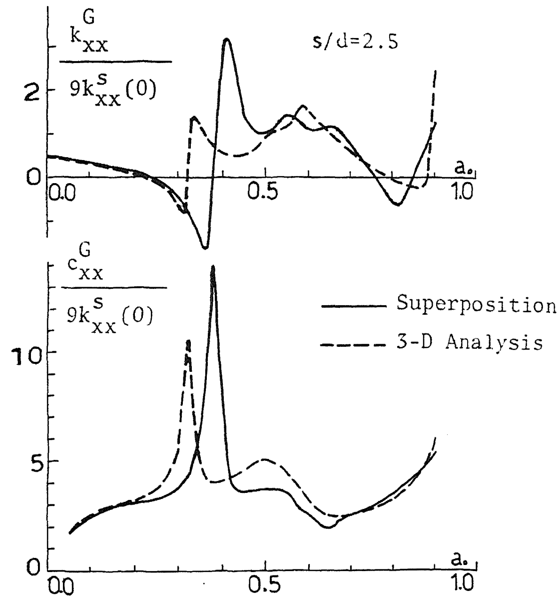

Fig.7 Horizontal dynamic stiffness

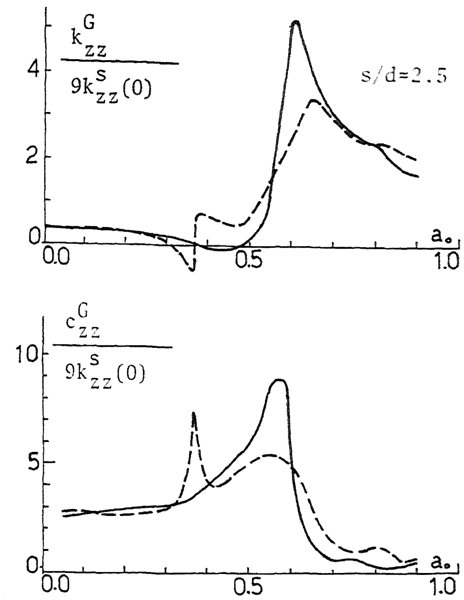

Fig.8 Vertical dynamic stiffness

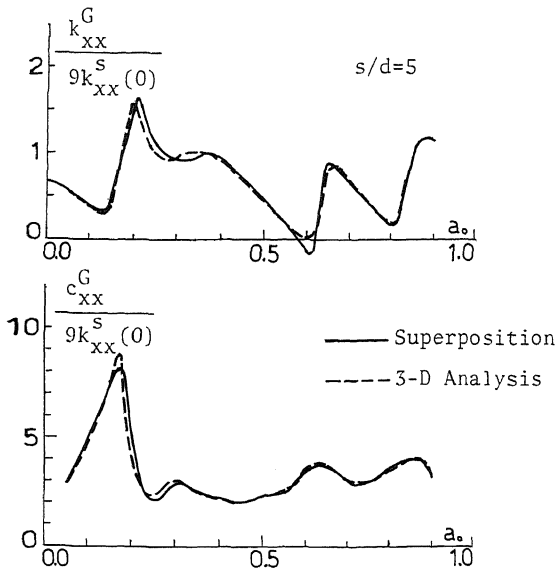

Fig.9 Horizontal dynamic stiffness

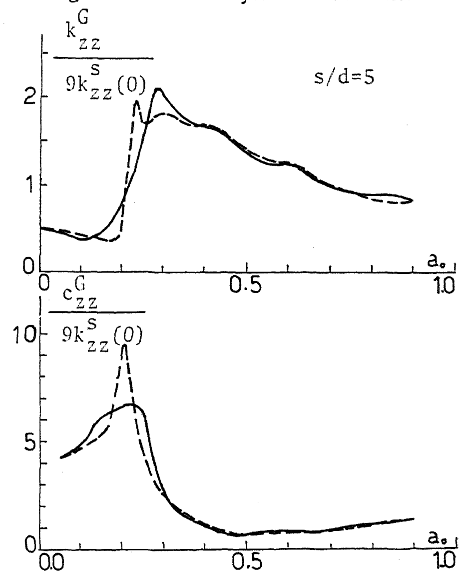

Fig.10 Vertical dynamic stiffness

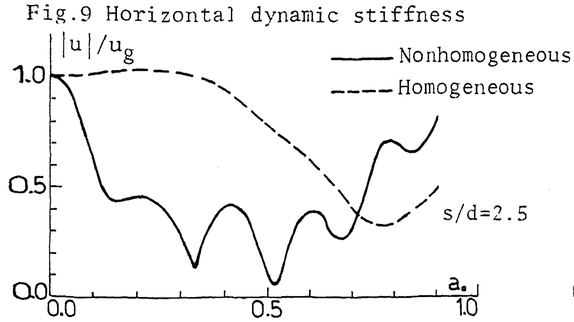

Fig.11 Horizontal transfer function

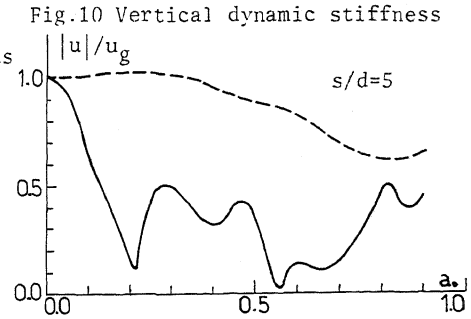

Fig.12 Horizontal transfer function

6. These results indicate that pile groups in the nonhomogeneous medium filter out, to a greater extent, the high frequency components of the ground motion.

CONCLUSIONS

The results of this study indicate that the horizontal response of pile groups is primarily governed by near surface soil properties, whereas the vertical response is mainly influenced by the characteristics of deeper layers. In addition, the interaction effects, which stem from pile-soil-pile interactions, are stronger in the nonhomogeneous medium than in the homogeneous medium.

ACKNOWLEDGEMENTS

The analyses presented in this paper were carried out at the computer center of the Plan and Budget Ministry of Iran. This support is gratefully acknowledged.

REFERENCES

1. Poulos, H. G. and Davis, E. H., Pile Foundation Analysis and Design, John Wiley and Sons, (1980)
2. Banerjee, P. K., "Analysis of Axially and Laterally Loaded pile Groups," in Developments in Soil Mechanics, (C. R. Scott, Ed.), Applied Science Publishers, (1978)
3. Mindlin, R. D., "Force at a Point in the Interior of a Semi-Infinite Solid," Physics, 7, 195-202, (1936)
4. Wolf, J. P. and Von Arx, G. A., "Impedance Functions of a Group of Vertical Piles," Proc. ASCE Specialty conf. Earthquake Eng. Soil Dyn., Pasadena, CA, 2, 1024-1041, (1978)
5. Nogami, T., "Dynamic Group Effect of Multiple Piles under Vertical Vibration," Proc. ASCE Eng. Mech. Div. Specialty Conf., Austin, TX, PP. 750-754, (1979)
6. Waas, G. and Hartman, H. G., "Analysis of Pile Foundations under Dynamic Loads," SMIRT Conf., Paris, (1981)
7. Kaynia, A. M., "Dynamic Stiffness and Seismic Response of Pile Groups," Dept. Civil Eng. Research Report R82-03, M.I.T., Cambridge, Mass., (1982)
8. Kaynia, A. M. and Kausel, E., "Dynamic Behavior of Pile Groups," 2nd Int. Conf. Numer. Methods Offshore Piling, Austin, TX, (1982)
9. Sen, R., Davies, T. G., and Banerjee, P. K., "Dynamic Analysis of Piles and Pile Groups Embedded in Homogeneous Soil," Earthquake Eng. Struct. Dyn., 13, 53-65, (1985)
10. Davies, T. G., Sen, R., and Banerjee, P. K., "Dynamic Behavior of pile Groups In Inhomogeneous Soil," J. Geotech. Eng. Div., ASCE, 111, No. 12, 1365-1379, (1985)
11. Nogami, T., "Dynamic Stiffness and Damping of Pile Groups in Inhomogeneous Soil, " ASCE Special Technical Publication on Dynamic Response of Pile Foundation, 31-52, (1980)
12. Sheta, M. and Novak, M., "Vertical Vibration of Pile Groups," J. Geotech. Eng. Div., ASCE, 108, 570-590, (1982)
13. Nogami, T., "Flexural Responses of Grouped Piles under Dynamic Loading," Earthquake Eng. Struct. Dynamics, 13, 321-336, (1985)
14. Novak, M. and El Sharnouby, B., "Evaluation of Dynamic Experiments on pile Groups," J. Geotech. Eng. Div., 110, 738-756, (1984)