Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Seismic response analysis of grouped pile embedded foundation by substructure method

Shin-ichiro Takano, Yuzuru Yasui & Hitoshi Maeno
Obayashi Corporation, Tokyo, Japan

ABSTRACT: Many structures constructed on soft soil are founded on grouped pile embedded foundation. For these structures, it is important to take structure-pile-soil interaction into account. The object of this paper is to analyse three dimensional structure-pile-soil interaction problem by substructure procedure. Frequency dependent impedances (sliding, vertical and rocking) and foundation input motions are calculated to evaluate the effect of foundation embedment and grouped pile.

1. INTRODUCTION

Many important structures founded on soft soil are supported on grouped pile embedded foundation. Dynamic structure-pile-soil interaction must be taken into account for this type of foundation. Some results have already been presented for structure-pile-soil interaction effects such as Waas-Hartmann[1]. The calculation method presented here is almost same as the one of Waas-Hartmann except for using the alternative substructure procedure. The total system is separated into structure sybsystem and pile-soil subsystem. The pile-soil subsystem is estimated as the frequency dependent impedance matrix, and seismic input to the structure is evaluated as the frequency dependent foundation input motion. This method can not only evaluate soil-pile interaction but also take the embedment of the foundation into account. Adopting thin layer element method, layered soil can also be taken into account.
Symmetric property is adopted to reduce the requied storage and computational effort.

2. SUBSTRUCURE PROCEDURE

The total structure-pile-soil system can be separated to three subsystems, that are structure subsystem, pile subsystem and soil subsystem(Fig.1). Each subsystem is evaluated by the following equilibrium equations.

$$\begin{bmatrix} K^B_{aa} & K^B_{ae} & K^B_{ah} \\ K^B_{ea} & K^B_{ee} & K^B_{eh} \\ K^B_{ha} & K^B_{he} & K^B_{hh} \end{bmatrix} \begin{Bmatrix} U_a \\ U_e \\ U_h \end{Bmatrix} = \begin{Bmatrix} 0 \\ -P_e \\ -P_h \end{Bmatrix} \tag{1}$$

$$\begin{bmatrix} K^P_{hh} & K^P_{hi} \\ K^P_{ih} & K^P_{hh} \end{bmatrix} \begin{Bmatrix} U_h \\ U_i \end{Bmatrix} = \begin{Bmatrix} P^p_h \\ -P_i \end{Bmatrix} \tag{2}$$

$$\begin{bmatrix} K^S_{ee} & K^S_{eh} & K^S_{ei} \\ K^S_{he} & K^S_{hh} & K^S_{hi} \\ K^S_{ie} & K^S_{ih} & K^S_{ii} \end{bmatrix} \begin{Bmatrix} U_e-U^0_e \\ U_h-U^0_h \\ U_i-U^0_i \end{Bmatrix} = \begin{Bmatrix} P_e-P^0_e \\ P^s_h-P^0_h \\ P_i-P^0_i \end{Bmatrix} \tag{3}$$

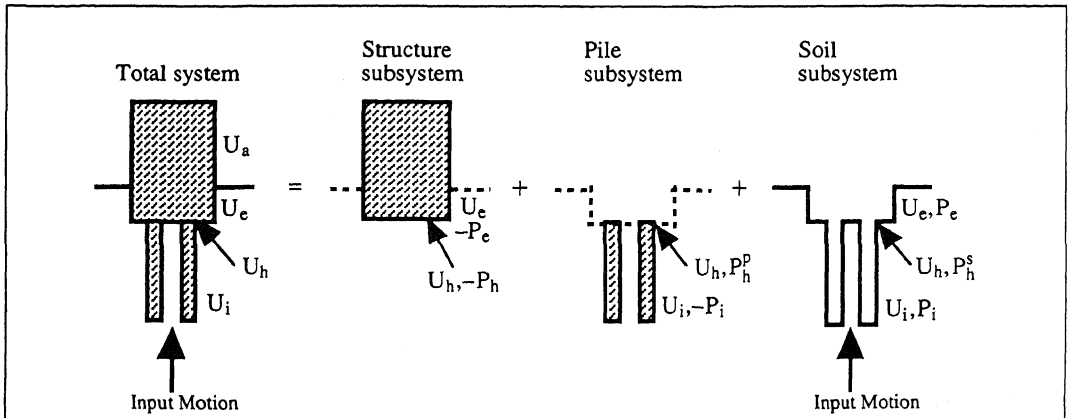


Fig.1 Substructure procedure

Where K^B_{xy}, K^P_{xy} and K^S_{xy} (x, y = a, e, h, i) are stiffness matrices of structure, pile and soil, respectively. The suffices a, e, h and i present the degrees-of-freedom of structure, structure-soil-interface, pile-caps and piles(without pile-caps), respectively. U_x (x=a,e,h,i) is the displacement vector of each node. P_x (x=e,h,i) is the action and reaction force vector generated by separation. Following three forces are balanced at the pile-cap.

$$P_h = P^p_h + P^s_h \tag{4}$$

In eq(3), U^0_x (x=e,h,i) and P^0_x (x=e,h,i) are the displacement vector and the force vector of free field subjected to seismic wave. Adding eq(2) and eq(3), the equation of pile-soil subsystem is derived as follows.

$$\begin{Bmatrix} P_e \\ P_h \\ 0 \end{Bmatrix} = \begin{bmatrix} K^S_{ee} & K^S_{eh} & K^S_{ei} \\ K^S_{he} & K^{S+P}_{hh} & K^{S+P}_{hi} \\ K^S_{ie} & K^{S+P}_{ih} & K^{S+P}_{ii} \end{bmatrix} \begin{Bmatrix} U_e \\ U_h \\ U_i \end{Bmatrix} - \begin{Bmatrix} P^g_e \\ P^g_h \\ P^g_i \end{Bmatrix} \tag{5}$$

where

$$K^{S+P}_{xy} = K^S_{xy} + K^P_{xy} \quad (x,y=e,h,i) \tag{6}$$

$$\begin{Bmatrix} P^g_e \\ P^g_h \\ P^g_i \end{Bmatrix} = \begin{Bmatrix} P^0_e \\ P^0_h \\ P^0_i \end{Bmatrix} - \begin{bmatrix} K^S_{ee} & K^S_{eh} & K^S_{ei} \\ K^S_{he} & K^S_{hh} & K^S_{hi} \\ K^S_{ie} & K^S_{ih} & K^S_{ii} \end{bmatrix} \begin{Bmatrix} U^0_e \\ U^0_h \\ U^0_i \end{Bmatrix} \tag{7}$$

We define new suffix E as the degrees-of-freedom of both structure-soil-interface and pile-cap. then eq(1) and eq(5) are described as follows.

$$\begin{Bmatrix} P_E \\ 0 \end{Bmatrix} = \begin{bmatrix} K^{S+P}_{EE} & K^{S+P}_{Ei} \\ K^{S+P}_{iE} & K^{S+P}_{ii} \end{bmatrix} \begin{Bmatrix} U_E \\ U_i \end{Bmatrix} - \begin{Bmatrix} P^g_E \\ P^g_i \end{Bmatrix} \tag{8}$$

$$\begin{Bmatrix} 0 \\ -P_E \end{Bmatrix} = \begin{bmatrix} K^B_{aa} & K^B_{aE} \\ K^B_{Ea} & K^B_{EE} \end{bmatrix} \begin{Bmatrix} U_a \\ U_E \end{Bmatrix} \tag{9}$$

where

$$K^{S+P}_{EE} = \begin{bmatrix} K^S_{ee} & K^S_{eh} \\ K^S_{he} & K^{S+P}_{hh} \end{bmatrix} \qquad K^{S+P}_{Ei} = \begin{bmatrix} K^S_{ei} \\ K^{S+P}_{hi} \end{bmatrix}$$
$$K^{S+P}_{iE} = \begin{bmatrix} K^S_{ie} & K^{S+P}_{ih} \end{bmatrix} \tag{10}$$

In eq(8), the displacement vector of piles (without pile-caps) U_i can be eliminated, and the stiffness matrix to be condensed.

$$P_E = K^X_{EE} U_E - P^X_E \tag{11}$$

where

$$K^X_{EE} = K^{S+P}_{EE} - K^{S+P}_{Ei}(K^{S+P}_{ii})^{-1} K^{S+P}_{iE} \tag{12}$$

$$P^X_E = P^g_E - K^{S+P}_{Ei}(K^{S+P}_{ii})^{-1} P^g_i \tag{13}$$

Substituting eq(11) for eq(9), the motion-equation of the structure considering pile-soil interaction is derived as follows.

$$\begin{bmatrix} K^B_{aa} & K^B_{aE} \\ K^B_{Ea} & K^B_{EE}+K^X_{EE} \end{bmatrix} \begin{Bmatrix} U_a \\ U_E \end{Bmatrix} = \begin{Bmatrix} 0 \\ P^X_E \end{Bmatrix} \tag{14}$$

where K^X_{EE} presents the stiffness matrix of pile-soil subsystem, and P^X_E presents the driving force vector. When the foundation can be considered rigid, the impedance matrix K_f and foundation input motion U^*_0 are defined as follows.

$$K_f = T^T K^X_{EE} T \tag{15}$$

$$U^*_0 = T^T \left(K^X_{EE}\right)^{-1} P^X_E \tag{16}$$

where T is rigid-body-motion influence matrix, and T^T is transposed matrix of T.

3. CALCULATION OF STIFFNESS MATRIX

The stiffness matrix of each element is calculated as follows. The pile stiffness is estimated by Timoshenko beam theory. The stiffness matrix of the embedded soil is calculated by subtracting the stiffness matrix of the excavated soil evaluated by finite element method from the stiffness matrix of free field (not excavated) soil evaluated by thin layer element method(Fig.2). The fundamental solutions (displacements derived by unit load) used in thin layer element method are summarized in Fig.3. Each solutions are derived by Waas et al[2] and Kausel et al[3].

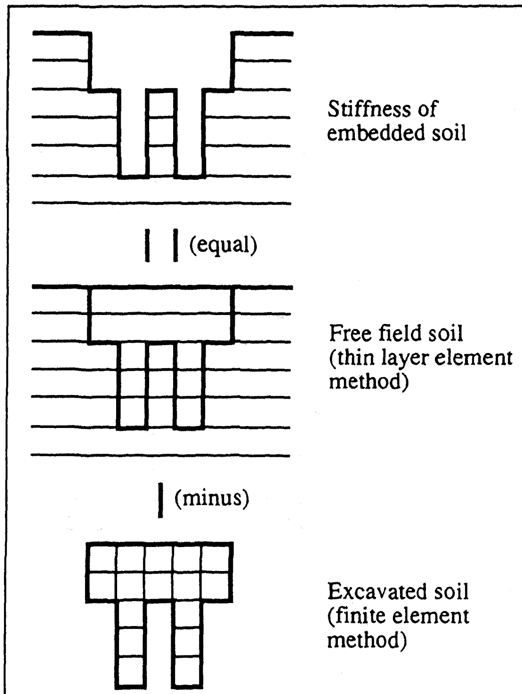


Fig.2 Stiffness of embedded soil

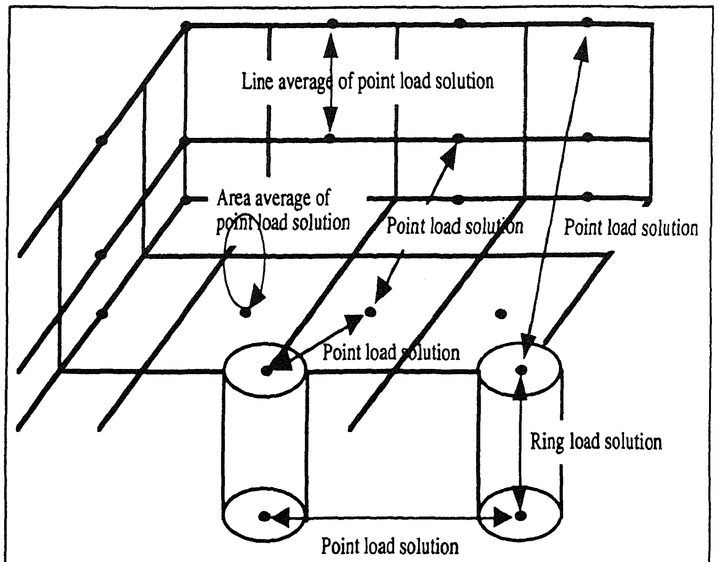


Fig.3 Fundamental solution between two nodes

4. RESULTS

Fig.4 shows the model cases of grouped pile foundation on the uniform soil. Case1, 2 and 3 are grouped pile foundations, and Case4 has no piles. Case1 and Case4 are embedded foundations, Case2 and Case3 are surface foundations, contacted and separated to soil, respectively. S-wave velocity, Poisson ratio and unit mass of soil are 300m/s, 0.45 and 2.0t/m^3, respectively. Shear modulus, Young coefficient and unit mass of piles are 1.087x10^{6}t/m^2, 2.5x10^{6}t/m^2 and 2.5t/m^3, respectively. Fig.5, Fig6 and Fig7 shows sliding impedance, vertical impedance and rocking impedance of the foundation, respectively. In sliding impedance case, the embedment effect of the foundation is larger than the grouped pile effect. On the other hand, in vertical and rocking impedance case, the grouped pile effect is larger than embedment effect of foundation. In every case, each impedance depends greatly on the frequency, that are remarkable in grouped pile foundation case.

Fig.8 and Fig.9 are sliding input motion and rotational input motion (absolute value) in case that the foundation is subjected to vertically incident SV-wave. Sliding input motions are decreasing and rotational input motions are increasing as frequency is increasing. This is the embedment effect of foundation and grouped pile effect. Embedment of the foundation is more effective for the reduction of sliding input motion than grouped pile.

5. CONCLUSIONS

A substructure procedure to analyze the structure-pile-soil interaction problem was presented. Sliding, vertical and rocking impedance of grouped pile embedded foundation can be evaluated in this procedure. Also sliding and rotational input motion in case that the foundation is subjected to vertically incident SV-wave can be calculated in this procedure.

6. REFERENCES

1. G.Waas and H.G.Hartmann,"Analysis of Pile Foundations Under Dynamic Loads",Proceedings of 6th SMIRT(1981)
2. G.Waas, H.R.Riggs and H.Werkle,"Displacement Solutions for Dynamic Loads in Transversely-isotropic Stratified Media",Earthquake eng. struct. dyn. 13, 173-193(1985)
3. E.Kausel and R.Peek,"Boundary Integral Method for Stratified Soils",Report R82-50, Department of Civil Engineering, MIT, 1982

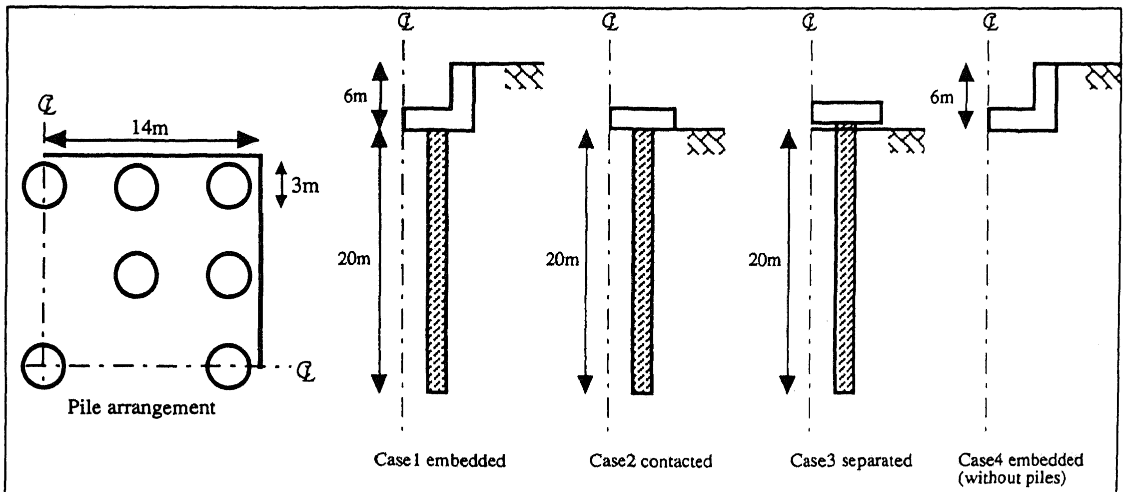
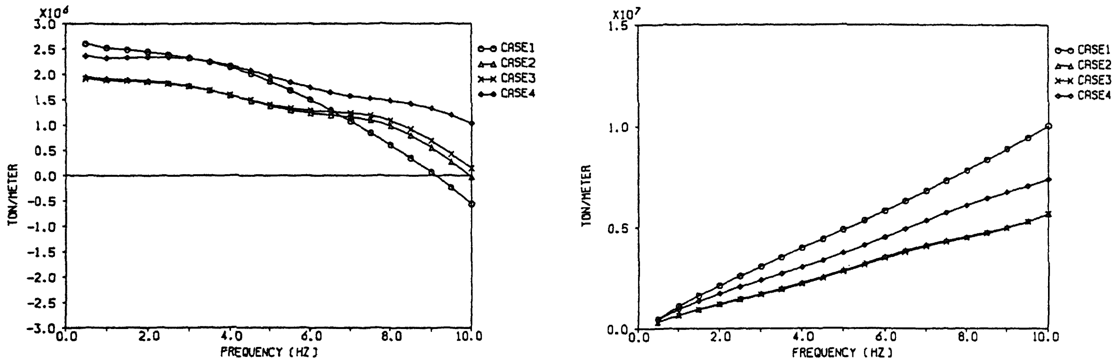


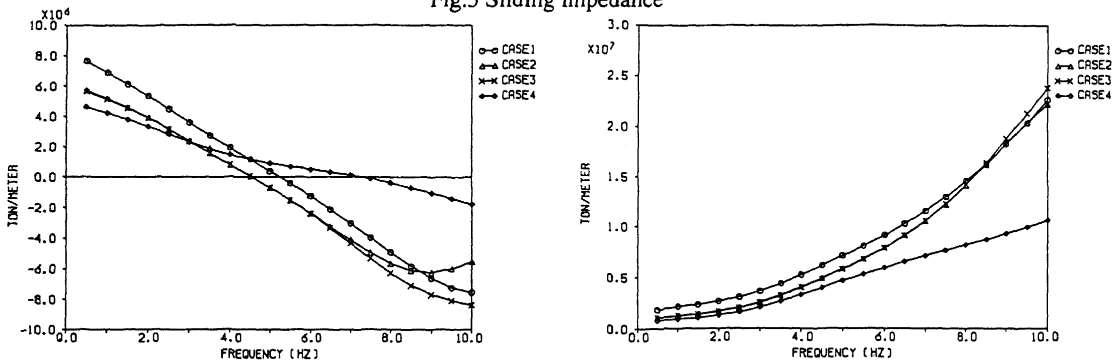
Fig.4 Models for calculation



(a) Real part

Fig.5 Sliding impedance

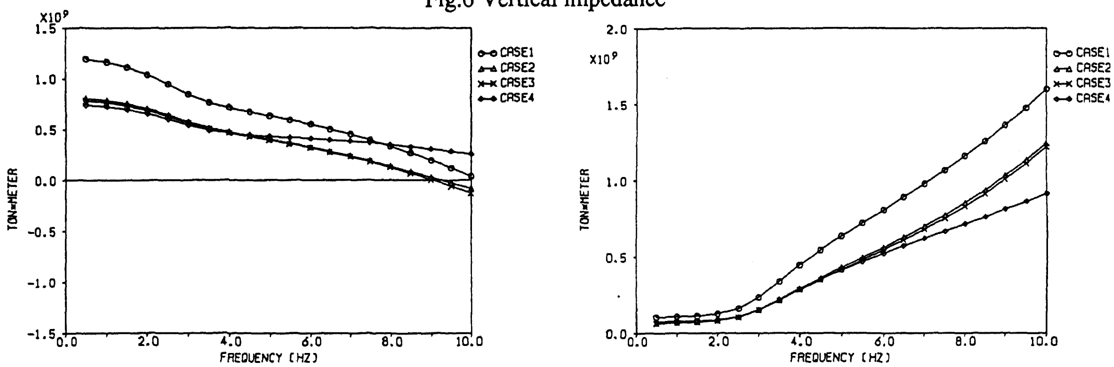
(b) Imaginary part



(a) Real part

Fig.6 Vertical impedance

(b) Imaginary part



(a) Real part

Fig.7 Rocking impedance

(b) Imaginary part

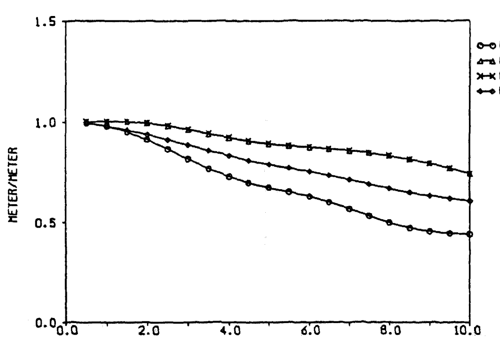


Fig.8 Sliding input motion (absolute value)

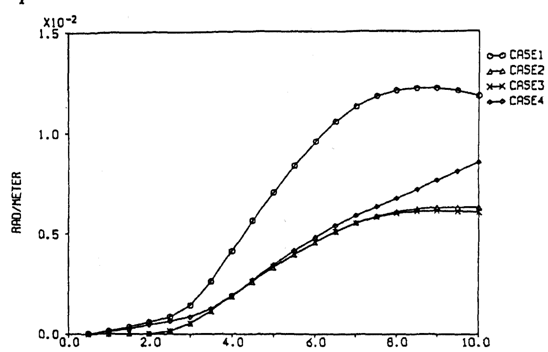


Fig.9 Rotational input motion (absolute value)