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A Study on Pile Forces of a Pile Group in Layered Soil Under Seismic Loadings

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SYNOPSIS : Characteristics of pile forces under seismic loadings are discussed from view points of the inertial interaction due to the mass effect of a superstructure and the kinematic interaction due to the resistance effect of piles against soil motions. A typical building supported on a pile group embedded in a layered soil, which has two- and four-layer profiles, is chosen for studying the pile forces which imply the shearing force and bending moment. The earthquake response analysis is performed in accordance with the substructure method, in which the group effect of piles in the layered soil is appropriately included by using the Green's function derived from the thin layer formulation. The resulting pile forces are compared with those by the static analysis of a single pile applying the base shear force at the pile head. These numerical examples indicate that the kinematic interaction effect on pile forces should be properly considered in the seismic design of pile foundations.

INTRODUCTION

Over a decade has passed since the excellent state of the art report on "Seismic effects on piles", which is intended to throw the light on the important features of this problem, was presented by Tajimi (1977). Since then, many earthquake observations of structures supported on piles and many dynamic tests of model piles and field piles have been carried out. At the same time, dynamic response analyses of the structure-pile-soil system have been made to be compared with the test results. However, the theoretical and empirical knowledge on the dynamic behavior of pile foundations is none the less limited. This seems to be the reason why the group effect of piles based on the pile-soil-pile interaction is intricate on evaluating the dynamic behavior of pile foundations. To clarify the effects, computational methods for the dynamic response analysis of a pile group have been developed in recent years, by Wolf and von Arx (1978), Waas and Hartmann (1981), Kaynia and Kausel (1982), Tyson and Kausel (1983), Sen et al (1985), and Hasegawa and Nakai (1986). All these methods are based on the Green function method, in which the pile-soil-pile interaction is included in a rigorous manner by using the fundamental solutions of the governing equation for point and/or ring loads. These may be the advanced and effective tools for investigating the dynamic behavior of pile foundations, at this stage.

The interest in this topic seems to be the characteristics of pile forces under seismic loadings, because the piles are so weak when strained horizontally that the pile forces are critical in the seismic design of a pile-supported structure. The pile forces during earthquakes are generally originated from both inertia forces of the superstructure and earth pressures caused by the soil motion. The former relates to the so-called inertial interaction which is the interaction due to the mass effect of the structure and the pile cap. The pile forces due to the effect are developed by the base shear and overturning moment of the structure acting on the pile cap. On the other hand, the latter relates to the so-called kinematic interaction which denotes the interaction due to the resistance effect of piles against the soil motion caused by incident waves. The pile forces due to the effect are induced by the soil motion directly carrying to the piles. The present procedure for the seismic design of pile foundations is mainly based on the static method. In the designing procedure, the inertial interaction effect on pile forces is considered by applying the static base shear and overturning moment at the pile head, and the allowable stress and displacement of the piles are checked. However, the kinematic interaction effect is not well considered in the designing procedure, because the soil motion during earthquakes is complicated, especially in a layered soil. Mizuno (1987) pointed out in his technical literature that there are quite a few cases of damage to pile foundations due to the effect of the soil motion, even in moderate earthquakes. Some knowledge on the effect of the kinematic interaction should be provided into the seismic design of pile foundations, in the future.

In this paper, the computational method for the dynamic response analysis of a structure supported on a group of piles is presented. The substructure technique is effectively utilized for the proposed method in which the group effect of piles embedded in a layered soil is appropriately included by using the Green's function derived from the thin layer formulation. The earthquake response analysis of a typical building supported on piles embedded in the different types of layered soils is carried out, and the characteristics of pile forces which herein imply the shearing force and bending moment of the piles are investigated. First, the group effect on pile forces is summarized; and next the pile forces are studied from a view point of both the inertial interaction effect and the kinematic interaction effect. Furthermore, the resulting pile forces obtained from the dynamic analysis are compared with those by the static analysis, and the dynamic effects on pile forces are discussed.

METHOD OF ANALYSIS

The method presented here for the earthquake response analysis of a structure supported on a group of piles is formulated in accordance with the substructure approach. The fundamental procedure of the method is schematically illustrated in Fig. 1. Let us consider the structure-pile-soil system subjected to an external load as a seismic excitation. Assuming linearity in the system and applying the superposition principle based on the flexible volume method (Lysmer, 1973) as shown in Fig. 2, the equation of motion of the total system can be separated into the following equations of motion of the structure-pile system and the soil system, respectively:

$$\left(\begin{bmatrix} [K_{SS}] & [K_{SP}] \\ [K_{PS}] & [K_{PP}]-[K_{PP}^{G}] \end{bmatrix} - \omega^2 \begin{bmatrix} [M_S] & \\ & [M_P]-[M_P^G] \end{bmatrix}\right) \begin{Bmatrix} \{u_S\} \\ \{u_P\} \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ \{F_P\} \end{Bmatrix} \tag{1}$$

$$\left(\begin{bmatrix} [K_{PP}^{G}] & [K_{PG}] \\ [K_{GP}] & [K_{GG}] \end{bmatrix} - \omega^2 \begin{bmatrix} [M_P^G] & \\ & [M_G] \end{bmatrix}\right) \begin{Bmatrix} \{u_P\} \\ \{u_G\} \end{Bmatrix} = \begin{Bmatrix} \{F_G\} \\ \{0\} \end{Bmatrix} \tag{2}$$

where $[M]$ and $[K]$ are the mass and stiffness matrices; subscripts and superscripts of these matrices denote the subsystems of the structure-pile-soil system, as shown in Fig. 1(a). In particular, $[M_P{}^G]$ and $[K_{PP}{}^G]$ are the mass and stiffness matrices of the soil column equal to the volume of pile body, as indicated in Fig. 2. The damping of the system is included in the stiffness as complex modulus representation independently for a given circular frequency ω. $\{u\}$ is the total displacement vector of the respective system, which can be written in the following form when the displacement vector relative to the free field displacement vector $\{u_F\}$ of the soil motion is defined as $\{v\}$:

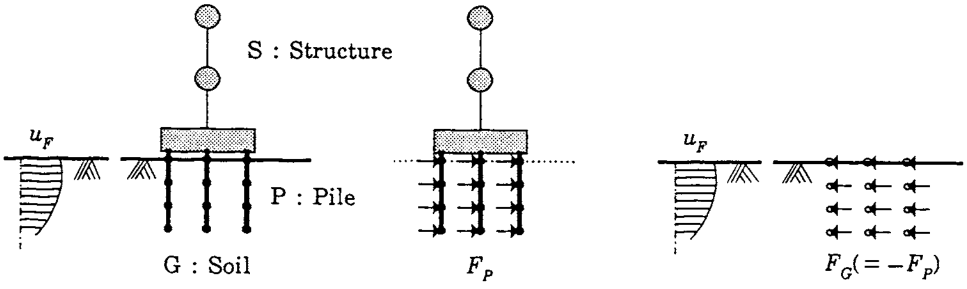
$$\{u\}=\{v\}+\{u_F\} \tag{3}$$

Both $\{F_P\}$ in Eq. (1) and $\{F_G\}$ in Eq. (2) are the interaction force vectors produced by the separation at the common nodes of the piles and the soil, as shown in Fig. 1(b), (c). They naturally satisfy the following equation of equilibrium:

$$\{F_P\}+\{F_G\}=\{0\} \tag{4}$$

As seen in Fig. 1(c), the total displacement vector in Eq. (2) for the soil system is constituted of the displacement vector $\{u^*\}$ due to the free field motion u_F caused by vertically propagating shear waves and the displacement vector $\{\Delta u\}$ due to the interaction forces F_G acting on the nodal points within the soil medium. Applying the superposition theory, the resulting displacement vector is given by

$$\{u\}=\{u^*\}+\{\Delta u\} \tag{5}$$



(a) Total system (b) Structure-pile system (c) Soil system

Fig. 1 Separation of structure-pile-soil system based on substructure approach

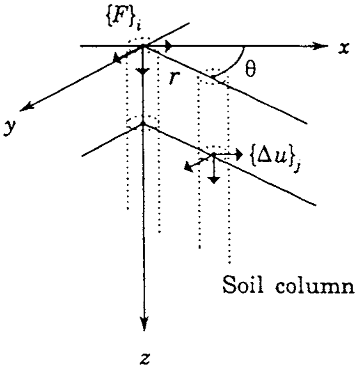


Fig. 3 Geometric relationship between concentrated loads and resulting displacements in thin layered medium

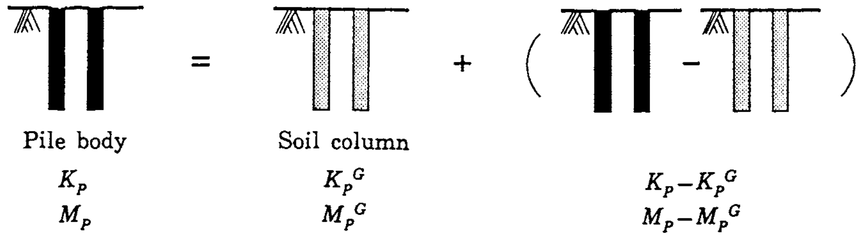


Fig. 2 Superposition principle based on flexible volume method

$\{u^*\}$ can be obtained from Eq. (2) by putting $\{F_G\}=\{0\}$, in which Eq. (2) represents the equation of motion of the soil for the seismic excitation. $\{u^*\}$ consequently denotes the displacement vector of the response of the free field caused by vertically propagating shear waves. This leads to

$$\{u^*\}=\{u_F\} \tag{6}$$

$\{\Delta u\}$ can be obtained from Eq. (2) by considering $\{u_F\}=\{0\}$ in Eq. (3) as follows:

$$\{\Delta u_P\}=[C(i\omega)]\{F_G\} \tag{7}$$

where

$$[C(i\omega)]=[\ ([K^G_{PP}]-\omega^2[M^G_P])-[K_{PG}]([K_{GG}]-\omega^2[M_G])^{-1}[K_{GP}]\ ]^{-1}$$

Eq. (7) represents the relationship between the interaction forces and the resulting displacements at all the nodes where the piles are connected with the soil. Therefore, $[C(i\omega)]$ denotes the frequency dependent flexibility matrix of the soil which accounts for the pile-soil-pile interaction. In this paper, a harmonic point load solution derived from the thin layer formulation (Tajimi, 1980) is effectively utilized to form the flexibility matrix of the soil. In employing the point load solution, it is essential that the soil is treated as the visco-elastic medium consisting of a number of thin layers; and that the nodal points of the soil are lying on the interface of the thin layer in which the pile body is replaced by the soil column, as shown in Fig. 3. When a concentrated load is applied on the arbitrary node, the resulting displacements at all the nodes of interest are evaluated by the point load solution. In particular, displacements at the node acted upon by a point load are approximated by the displacement at a center of the circle of the soil column when a uniformly distributed load is applied within the associated area. Thus, $[C(i\omega)]$ is established.

Substituting from Eq. (5) into Eq. (7) and considering Eq. (4), the interaction force vector applying from the soil to the piles is written by

$$\{F_P\}=-[C(i\omega)]^{-1}(\{u_P\}-\{u^*_P\}) \tag{8}$$

Substituting from Eq. (8) into Eq. (1) and considering Eq. (6), the equation of motion of the structure-pile system including the pile-soil-pile interaction is finally obtained as

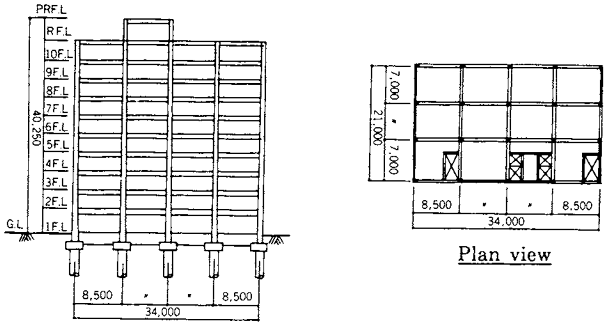
$$\left(\begin{bmatrix} [K_{SS}] & [K_{SP}] \\ [K_{PS}] & [K_{PP}]-[K^G_{PP}]+[C(i\omega)]^{-1} \end{bmatrix} - \omega^2 \begin{bmatrix} [M_S] & \\ & [M_P]-[M^G_P] \end{bmatrix}\right) \begin{Bmatrix} \{u_S\} \\ \{u_P\} \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ \{F^*_P(i\omega)\} \end{Bmatrix} \tag{9}$$

where

$$\{F^*_P(i\omega)\}=[C(i\omega)]^{-1}\{u_F\}$$

MODEL FOR ANALYSIS

A typical 10 story building supported by a group of 20 piles is chosen for investigating the characteristics of the pile forces under seismic loading, as shown in Fig. 4. The building is idealized by a stick model consisting of 11 masses connected with shear spring elements. Reinforced concrete piles cast in-situ, whose diameters are all 1.5m, are modelled by beam elements representing the coupled bending and shear behavior. The damping factors of both the building and the piles are assumed to be 3%. Two different types of soil profiles are considered. One is a two layered soil (Model A) and the other is a four layered soil (Model B). Table 1 shows the soil properties of these models. In the modelling of the soil, each layer is divided into a number of thin layers. The sublayering is described in Table 1. The infinite boundary (Hull and Kausel, 1984) is employed and set at the bottom layer to account for the radiation effect due to an underlying elastic halfspace. Further details concerning the modelling of the structure-pile-soil system are presented in Fig. 5 and Table 2.



Section view

Plan view

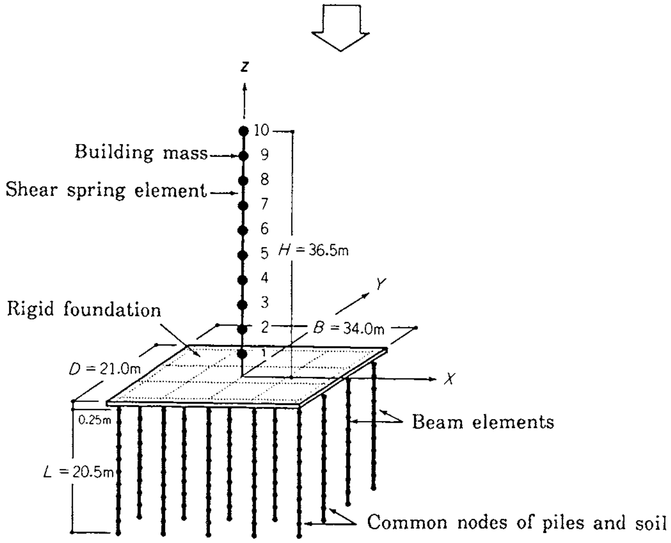


Fig. 4 Idealized reality and model of building supported on pile group

In the earthquake response analysis, an acceleration time history of a simulated earthquake motion is adopted as an input wave with maximum acceleration of 120 gals, which is defined at the surface of the free field. The response analysis is performed in the frequency domain and the transient response is computed by the FFT method, where the cut-off frequency is assumed to be 10Hz. The other assumptions made for the response analysis include: the foundation is treated as a rigid body; the piles are fixed at the rigid cap; and the inertia force of the building is directly transmitted to the soil through the piles, meaning that the radiation and resistance effects of the rigid foundation resting on the soil will be neglected to reduce the complexity of the problem.

NUMERICAL RESULTS AND DISCUSSIONS

Group Effects on Pile Forces

To grasp the characteristics of pile forces under seismic loading, the earthquake response analyses are carried out for both Model A and Model B. Fig. 6 shows the resulting distribution curves of the maximum shearing force and bending moment along the depth of the piles.

Table 1 Soil properties and layered structure

Model A					Model B					
Soil type	H (m)	γ (t/m^3)	V_s (m/s)	v	Soil type	H (m)	γ (t/m^3)	V_s (m/s)	v	sub-layering
Clay	19.0	1.5	150	0.48	Clay	10.0	1.5	130	0.48	10×1.0m
					Sand	4.5	1.9	220	0.46	3×1.5m
					Clay	4.5	1.5	150	0.48	3×1.5m
Sand	60.0	1.9	300	0.46	Sand	60.0	1.9	300	0.46	2×1.5m 19×3.0m

H=Thickness of layer; γ=Weight per unit volume; V_s=Shear wave velocity; v=Poisson's ratio

Table 2 Parameters used for building and piles

Building (SRC)	Piles (RC)
· Young's modulus of $E=210\text{t/cm}^2$ · Damping factor of $h=3\%$ · Total weight of $W=11470\text{ton}$ · Natural period of superstructure, $T_1=0.725\text{sec}$ ($=0.02H$)	· Young's modulus of $E=210\text{t/cm}^2$ · Shear modulus of $G=90\text{t/cm}^2$ · Weight per unit volume of $\gamma=2.4\text{t/m}^3$ · Damping factor of $h=3\%$ · Pile space in transverse, $s_T=8.5\text{m}$ · Pile space in longitude, $s_L=7.0\text{m}$

From this figure, it is found that the pile forces for both models are remarkably large at the depth near the pile head, because the inertia force of the building directly acts on the pile cap. Looking into this figure in detail, it is noticed that the magnitude of the pile head forces of individual pile in the group is quite different. In Fig. 7, the distributions of the maximum shearing force and bending moment at the pile head are schematically illustrated by bar chart in accordance with the pile arrangement. The ratio of the bearing load of each pile to that of the center pile P_4 is given by a parenthesized figure. Referring to the figure, the forces of the outer piles are much larger than those of the inner piles. The reason seems to be that the piles in front of the moving direction are subjected to larger soil reactions than the piles behind them. It is well known that the group effect on pile forces mainly depends on a number of piles, the pile spacing and the fixity condition at the pile cap. Further study from these points will be needed to clarify the group effect on pile forces.

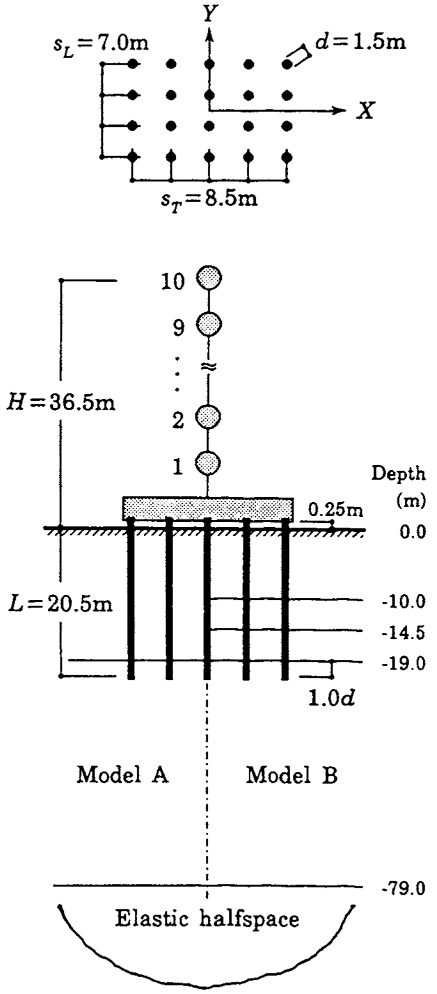
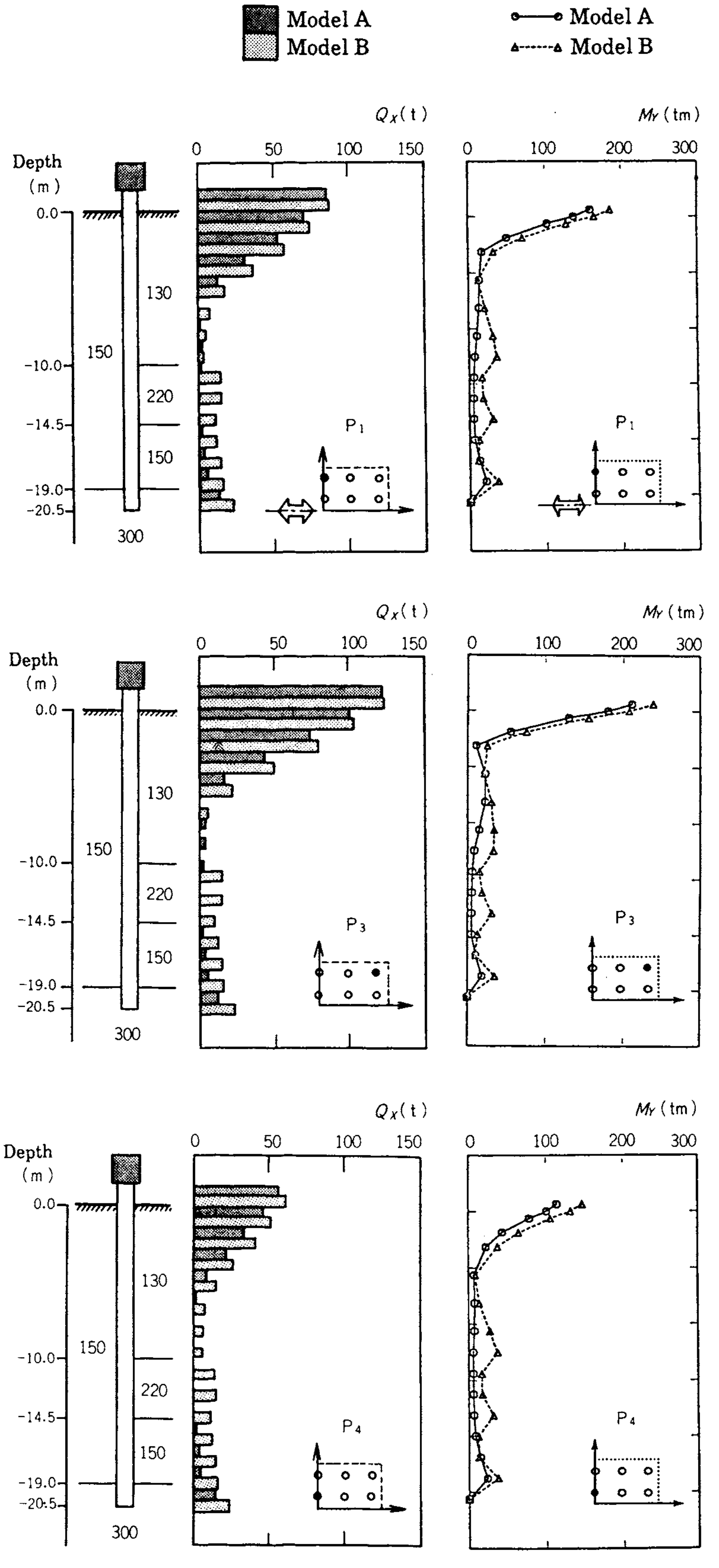
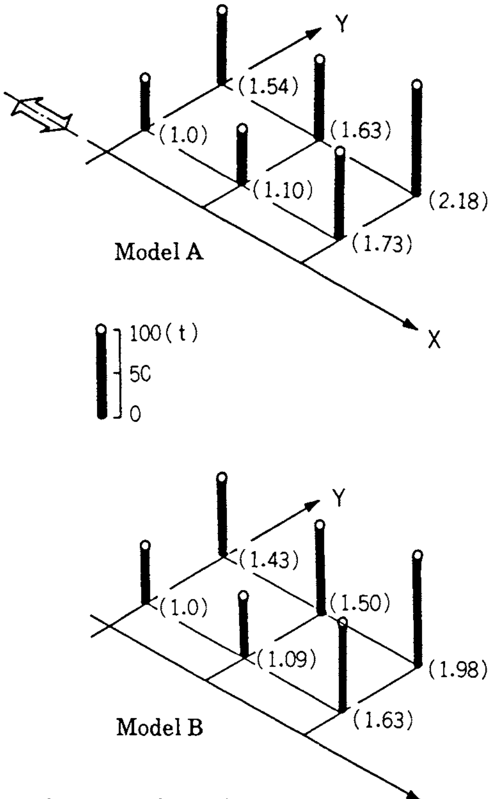


Fig. 5 Analysis model of structure-pile-soil system

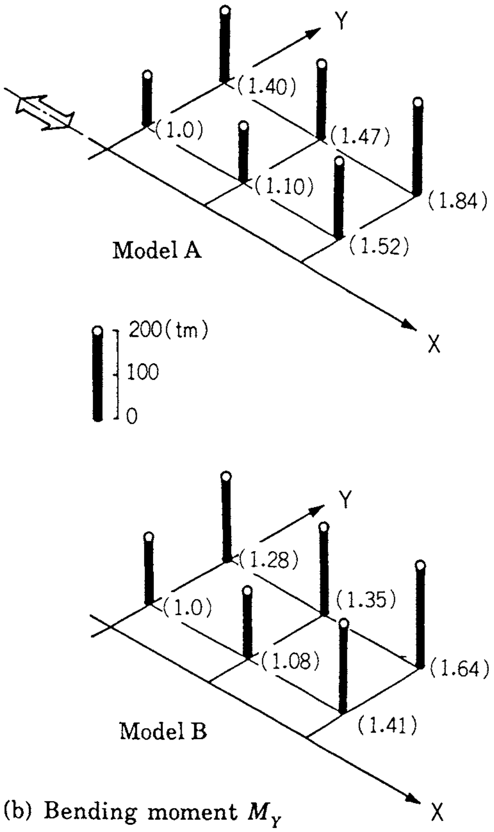


(a) Shearing force Q_X (b) Bending moment M_Y

Fig. 6 Distribution curves of maximum pile forces over depth



(a) Shearing force Q_X



(b) Bending moment M_Y

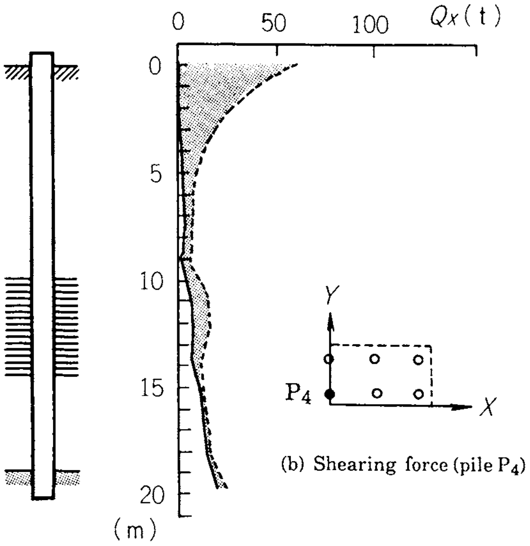
Fig. 7 Distributions of maximum pile forces at pile head

Inertial and Kinematic Interaction Effects on Pile Forces

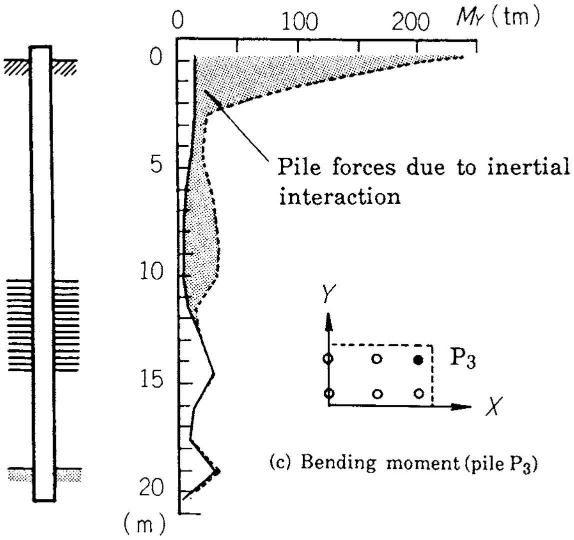
To investigate the effects of the inertial and kinematic interaction on pile forces, the earthquake response analysis, in which the mass of the building is set to zero, is added for Model B. Since there is no mass for the building, this additional model gives a pile force due to the kinematic interaction effect. Fig. 8 shows the resulting pile forces compared with the total pile forces including the effect of the inertial interaction due to the building mass, for the peripheral pile P_3 and the interior pile P_4 in the group. The shaded area depicted in Fig. 8 represents the pile forces due to the inertial interaction effect. By comparing these curves, it is recognized that the pile forces due to the kinematic interaction are comparatively small at the depth near the pile head; and that the forces near the pile head are almost all induced by the inertia force of the building. It is also understood from the figure that the pile forces due to the inertial interaction get smaller as the depth of the piles becomes deep; and that the forces near the pile tip are mostly formed by the kinematic interaction. This indicates that the inertia force of the building does not affect the pile forces at deeper locations. Furthermore, one should note that the pile forces due to the kinematic interaction are concentrated at the interface of the soil layer with large shear wave velocities ratio, because the soil motion is amplified in the soft layer.

-------- Total pile forces

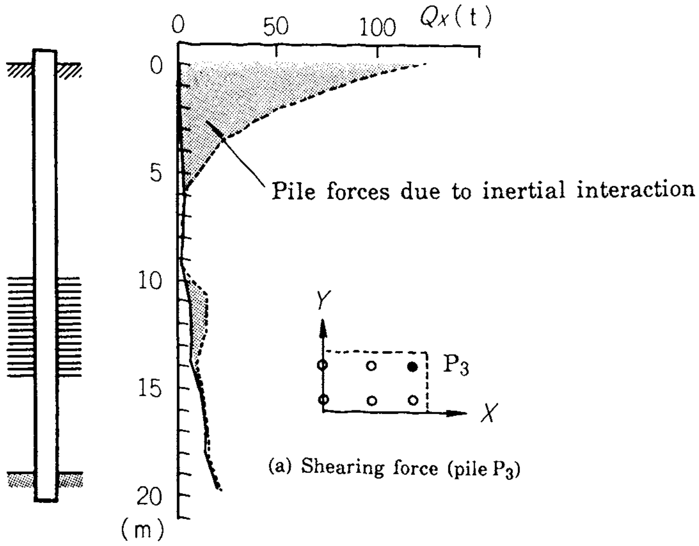
——— Pile forces due to kinematic interaction



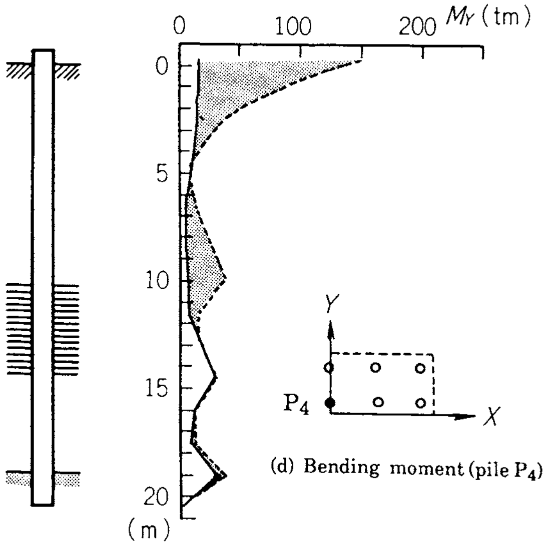
(b) Shearing force (pile P_4)



(c) Bending moment (pile P_3)



(a) Shearing force (pile P_3)

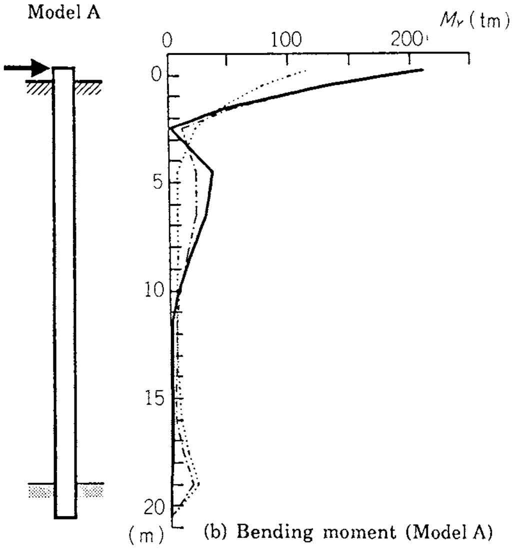


(d) Bending moment (pile P_4)

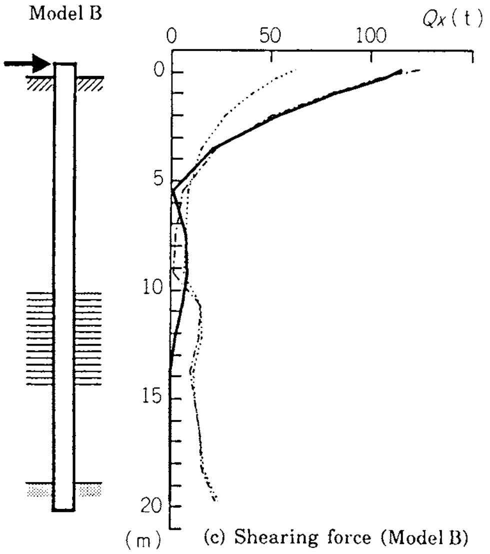
Fig. 8 Inertial and kinematic interaction effects on pile forces

Comparison of Dynamic and Static Results

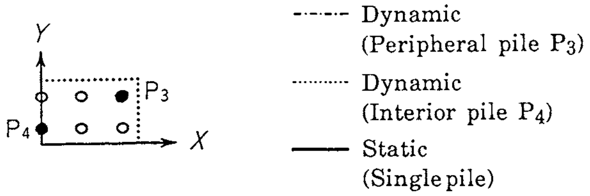
To study dynamic effects on pile forces, the results shown in Figs. 6 and 8 are compared with the results computed by the static method, in which the base shear force obtained from the dynamic analysis is simply applied as a static load at the pile cap of a single pile. Fig. 9 shows the comparison of the dynamic and static pile forces for Models A and B. From this figure, it is seen that the distribution curves near the pile head forces by the static analysis relatively coincide with those by the dynamic analysis. It follows that the pile forces due to the inertial interaction effect are well evaluated by the static method. However, as exhibited in the figure, the distribution curves of the forces near the pile tip where the amplification of the soil motion is dominant can not be represented by the static method, because the effect of the kinematic interaction is not considered in the static analysis. This conclusively indicates that some knowledge on pile forces due to the kinematic interaction effect should be provided into the seismic design of pile foundations, especially in the case of the piles embedded in a layered soil with strong contrast of shear wave velocities, as Model B is the case.

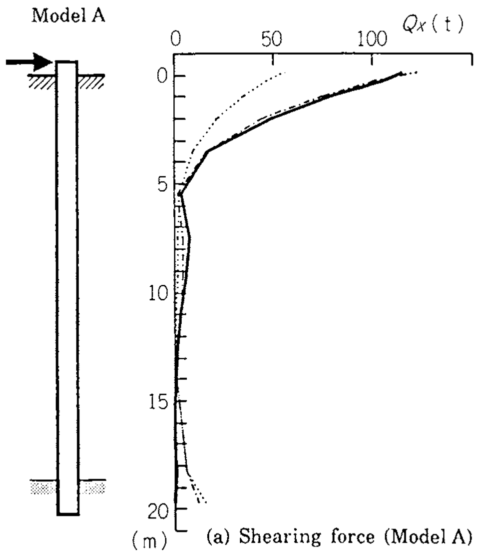


(b) Bending moment (Model A)

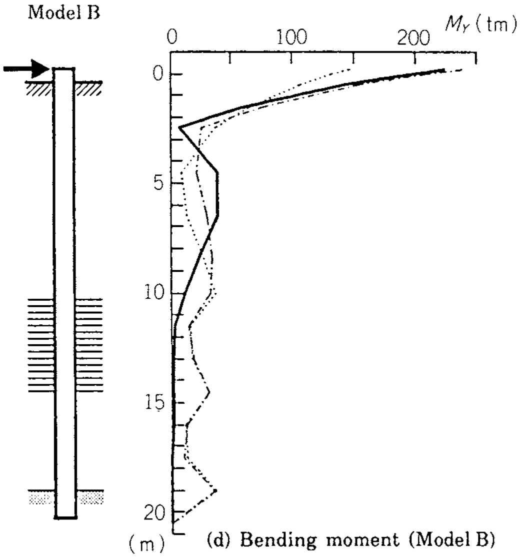


(c) Shearing force (Model B)





(a) Shearing force (Model A)



(d) Bending moment (Model B)

Fig. 9 Comparison of dynamic and static pile forces

CONCLUSIONS

Bearing loads of piles located in the periphery of a group are significantly larger than those of the interior piles when a group of piles is subjected to seismic excitation. Group effects of piles can be appropriately represented by the present method in which the pile-soil-pile interaction is rigorously included by using the Green's function derived by the thin layer method.

Pile forces under seismic loadings are remarkably large at the locality of the pile head, and the forces near the pile head are mostly developed by the effect of the inertial interaction. However, the forces deep in the piles are mostly developed by the effect of the kinematic interaction, and the pile forces due to the effect are concentrated at the interface of soil layers.

Pile forces due to the inertial interaction effect can be approximated by simply applying the static base shear force at the pile cap. However, pile forces due to the kinematic interaction effect can not be properly evaluated by the static method. The kinematic interaction effect on pile forces should be considered in the seismic design procedure by the practical method.

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