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DYNAMIC RESPONSE OF PILE FOUNDATION TAKING INTO ACCOUNT 3-DIMENSIONAL INTERACTION WITH SUPERSTRUCTURE AND GROUND

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ABSTRACT

The first purpose of this study is to investigate the dynamic behavior of piles taking into account the interaction with superstructure, foundation as well as ground by using the 3-D finite element analyses. The second purpose is to investigate the commonality and difference between seismic responses of 3-D structure-foundation-pile-ground system and those of 2-D system. In the performance of the 2-D FEM analysis, determining the thickness of the ground model is one of the most difficult problems. We obtained the optimum ratio of the thickness of ground to that of foundation which gave the least difference between 3-D and 2-D analyses by performing the parametric analysis in changing the number of piles and the height of superstructure. The results indicated that the responses of 3-D systems can be estimated from the responses of 2-D systems by introducing altered coefficients. The coefficients were almost constant according to the number of rows of piles irrespective of the height of superstructure.

KEYWORDS

Pile foundation, Dynamic interaction system, Group piles, Group effect

INTRODUCTION

The pile is one of the most popular foundation of structural systems. There are many studies which investigated the dynamic response of a pile. These analyses, however, treat the behavior of piles separately from that of the foundation and superstructure. There is interaction between pile, foundation and superstructure, therefore, they should be analyzed together as an interaction system. The first purpose of this study is to investigate the dynamic behavior of piles taking into account the interaction with foundation and superstructure as well as ground by using 3-D finite element analyses. For the purpose of the design of pile foundation, 2-D analyses are commonly used because 3-D analyses are not easy and feasible not only because of its technical difficulty but also because of the high cost and extended CPU time. Therefore, we need to know the relationship between the responses from the 3-D analyses and those from the 2-D analyses. The second purpose of this study is, therefore, to investigate the commonality and difference between seismic responses of 3-D and 2-D superstructure-foundation-pile-ground systems. In the performance of the 2-D finite element analysis, determining the thickness of the ground model is one of the most difficult problems. We investigate the optimum ratio of the thickness of ground to that of foundation structure which give the least difference between 3-D and 2-D analyses by performing the parametric analysis in changing the number of piles and the height of superstructures. Prior to performing the parametric study, we first proposed a seismic response analysis method for 3-D superstructure-foundation-pile-ground interaction systems.

ANALYSIS METHOD

Modeling the 3-D superstructure-pile-foundation-ground system

Figure 1 shows the general view of an interaction system. The superstructure is modeled by a series of masses and springs. The foundation is assumed to be a rigid body with 6 degrees of freedom. Piles are modeled in an arrrengement of three-dimensional beam elements. Ground is modeled by hexahedron isoparametric elements. All the materials are assumed to be linear elastic. In modeling the ground with infinite extension by finite number of elements, we need to introduce the artificial boundary as shown in Fig. 1. We proposed a new method to deal with the artificial boundary in order to reduce the number-of-freedom because a large amount of memory and CPU time are needed in 3-D analyses. The method is based on the assumption that the motion of the nodal points on the boundary is same as those of the free field. This assumption is valid if the boundary is located at a far enough distance from the structure. The suitable distance is descussed in the later chapter.

Equation of motion

The equation of motion for the superstructure-foundation-pile-ground system with artifical boundaries of which motions are same as those of free-field shown in Fig.1 is given by the following equation.

$$\begin{vmatrix} [M_{aa}] & [M_{ab}] & \\ [M_{ba}] & [M_{bb}] & [M_{bc}] \\ & [M_{cb}] & [M_{cc}] \end{vmatrix} \begin{vmatrix} \{\ddot{\delta}_a\}+\{\ddot{\delta}_g\} \\ \{\ddot{\delta}_b\}+\{\ddot{\delta}_g\} \\ \{\ddot{\delta}_c\}+\{\ddot{\delta}_g\} \end{vmatrix} + \begin{vmatrix} [C_{aa}] & [C_{ab}] & \\ [C_{ba}] & [C_{bb}] & [C_{bc}] \\ & [C_{cb}] & [C_{cc}] \end{vmatrix} \begin{vmatrix} \{\dot{\delta}_a\} \\ \{\dot{\delta}_b\} \\ \{\dot{\delta}_c\} \end{vmatrix} + \begin{vmatrix} [K_{aa}] & [K_{ab}] & \\ [K_{ba}] & [K_{bb}] & [K_{cc}] \\ & [K_{bb}] & [K_{cc}] \end{vmatrix} \begin{vmatrix} \{\delta_a\} \\ \{\delta_b\} \\ \{\delta_c\} \end{vmatrix} \begin{matrix} \\ = \\ = \end{matrix} \begin{vmatrix} \{P_a\} \\ \{P_b\} \\ \{P_{cd}\} \end{vmatrix} \quad (1)$$

Where, $\{P_{cd}\}=\{P_c\}-[M_{cd}](\{\ddot{\delta}_d\}+\{\ddot{\delta}_g\})-[C_{cd}]\{\dot{\delta}_d\}-[K_{cd}]\{\delta_d\}$ (2)

Where, [M], [C], [K], { δ }, {P} are mass, damping, stiffness matrices and nodal displacement and nodal force vectors, respectively. The subscript, a, means nodal points of surperstructure, b, those of foundation, c, those of piles and surrounding ground, d, those of artificial boundaries and, e, the free field.

Mass matrix of the superstructure and rigid foudation

The mass matrix of the superstructure and rigid foundation is derived as follows by considering the sway and rocking motions of the foundation. The absolute displacements (δ_{xi}, δ_{yi}) at the mass i of the superstructure are given by using the relative displacement for the foundation (u_i, v_i), the sway of the foundation (u_B, v_B) and the rotational angles due to the rocking motion of the foundation (θ_{xB}, θ_{yB}).

$$\delta_{xi}=u_i+u_B+\theta_{yB}\cdot h_i \quad (3)$$

$$\delta_{yi}=v_i+v_B-\theta_{xB}\cdot h_i \quad (4)$$

Where, h_i is the height of the mass i of the superstructure from the center of gravity of the foundation. From eqs. (3) and (4), the absolute accelerations are given by;

$$\ddot{\delta}_{xi}=\ddot{u}_i+\ddot{u}_B+\ddot{\theta}_{yB}\cdot h_i \quad (5)$$

$$\ddot{\delta}_{yi}=\ddot{v}_i+\ddot{v}_B-\ddot{\theta}_{xB}\cdot h_i \quad (6)$$

The inertia forces at the center of the foundation (F_{xB}, F'_{yB}) are, therefore, given by the following equations.

$$\begin{aligned} F'_{xB} &= \Sigma M_i\cdot\ddot{\delta}_{xi}+M_B\cdot\ddot{u}_B \\ &= \Sigma M_i\cdot\ddot{u}_i+(\Sigma M_i+M_B)\cdot\ddot{u}_B+\Sigma M_i\cdot h_i\cdot\ddot{\theta}_{yB} \quad (7) \end{aligned}$$

$$\begin{aligned} F'_{yB} &= \Sigma M_i\cdot\ddot{\delta}_{yi}+M_B\cdot\ddot{v}_B \\ &= \Sigma M_i\cdot\ddot{v}_i+(\Sigma M_i+M_B)\cdot\ddot{v}_B-\Sigma M_i\cdot h_i\cdot\ddot{\theta}_{xB} \quad (8) \end{aligned}$$

The overturning moments about the center of gravity of the foundation (M'_{xB}, M'_{yB}) are given by;

$$
\begin{aligned}
M'_{xB} &= -\Sigma h_i \cdot M_i \cdot \ddot{\delta}_{yi} + J_{xB} \cdot \ddot{\theta}_{xB} \\
&= -\Sigma h_i \cdot M_i \cdot \ddot{v}_i - \Sigma h_i \cdot M_i \cdot \ddot{v}_B \ + \{\Sigma M_i \cdot h_i^2 + J_{xB}\} \cdot \ddot{\theta}_{xB}
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
M'_{yB} &= \Sigma h_i \cdot M_i \cdot \ddot{\delta}_{xi} + J_{yB} \cdot \ddot{\theta}_{yB} \\
&= \Sigma h_i \cdot M_i \cdot \ddot{u}_i + \Sigma h_i \cdot M_i \cdot \ddot{u}_B \ + \{\Sigma M_i \cdot h_i^2 + J_{yB}\} \cdot \ddot{\theta}_{yB}
\end{aligned}
\tag{10}
$$

The obtained mass matrix from the above procedure is given in Table 1 (Ishihara, *et. al.*,1994).

<u>Compativility and equilibrium conditions between the foundation and piles</u>

By assumming that the condition of the piles and the rigid foundation are normal, the displacements ($u_j, v_j, w_j, \theta_{xj}, \theta_{yj}, \theta_{zj}$) at nodal point j of a pile which is connected to the foundation is given by the displacement at the center of gravity of the foundation ($u_B, v_B, w_B, \theta_{xB}, \theta_{yB}, \theta_{zB}$) as;

$$u_j = u_B + \theta_{yB} \cdot L_{zj} - \theta_{zB} \cdot L_{yj} \tag{11}$$

$$v_j = v_B - \theta_{xB} \cdot L_{zj} + \theta_{zB} \cdot L_{xj} \tag{12}$$

$$w_j = w_B + \theta_{xB} \cdot L_{yj} - \theta_{yB} \cdot L_{xj} \tag{13}$$

$$\theta_{xj} = \theta_{xB} \tag{14}$$

$$\theta_{yj} = \theta_{yB} \tag{15}$$

$$\theta_{zj} = \theta_{zB} \tag{16}$$

Where, $L_{xj}=x_j-x_B$, $L_{yj}=y_j-y_B$, $L_{zj}=z_j-z_B$, and (x_j, y_j, z_j) and (x_B, y_B, z_B) are the coordinates of node j and the center of gravity of the foundation.

Forces acting on the foundation from the piles and ground (F_{xB}, F_{yB}, F_{zB}, M_{xB}, M_{yB}, M_{zB}) are expressed as a summary of nodal forces (F_{xj}, F_{yj}, F_{zj}, M_{xj}, M_{yj}, M_{zj}) of nodal point j which is connected to the foundation.

$$F_{xB} = \Sigma F_{xj} \tag{17}$$

$$F_{yB} = \Sigma F_{yj} \tag{18}$$

$$F_{zB} = \Sigma F_{zj} \tag{19}$$

$$M_{xB} = \Sigma F_{zj} \cdot L_{yj} - \Sigma F_{yj} \cdot L_{zj} + \Sigma M_{xj} \tag{20}$$

$$M_{yB} = -\Sigma F_{zj} \cdot L_{xj} + \Sigma F_{xj} \cdot L_{zj} + \Sigma M_{yj} \tag{21}$$

$$M_{zB} = -\Sigma F_{xj} \cdot L_{yj} + \Sigma F_{yj} \cdot L_{xj} + \Sigma M_{zj} \tag{22}$$

Responses of nodal points which are connected to the foundation are expressed by the responses of the center of gravity of the foundation by using eqs. (11) ~(22) (Ishihara *et.al.*, 1994). This results in a reduction of the number-of -freedom.

ANALYSIS RESULTS

<u>Model and analysis conditions.</u>

In the parametric study, we analyzed four kinds of surperstructures, i.e., 3, 6, 9 and 12 stories and for each superstructure five kinds of group pile-foundation systems, i,e., 2x2, 3x3, 4x4, 5x5, and 6x6. The length of the pile is 21m and the thickness of the ground is 54m. The damping factor is assumed to be 5% for all models. The constants of the model are given in Table 2.

Prior to the parametric study, we examined the suitable distance of the artificial boundary from the structure. If the artificial boundary is located four times the width of the foundation from the edge, the differences of the responses of superstructure, foundation and piles are less than 2% compared with the model of five times the width. Therefore, the parametric study is performed using this model.

Sharing ratio of shear force induced at the pile head

First we obtained shear forces induced at pile heads by 3-D analyses and calculated the sharing ratio of shear force for each pile. The results are summarized in Table 3. The sharing ratio is determined as the ratio of the shear force induced at the pile head in consideration to the average shear force of the group pile foundation. From these results, it is found that the sharing ratio of a pile at the same position of the same pile arrangement is almost the same irrespective to the difference of the height of the superstructures. The center pile shares about 60% of the average shear force per a pile, while the corner pile shares from about 120% for 2x2 pile foundation and about 170% for 6x6 pile foundation of the average.

Comparison of the maximum response accelerations between 2-D and 3-D analyses

In 2-D models, the stiffness and mass of the beam elements which represent the pile are muliplied by the number of piles in y-direction (the coordinate system is shown in Fig.1). The size of the 2-D model of the interaction system in x-direction is same as that of 3-D analysis. The size of y-direction is parametrically changed from the same size of the foundation to three times of it. We introduced a coefficient, α, which represents the ratio of the size of the model to that of the foundation, i.e., $1 \leqq \alpha \leqq 3$.

The comparison of the maximum response accelerations between 2-D and 3-D analyses is summarized in Table 4. The input motion is the El Centro NS component of which the maximum amplitude is adjusted to be 100 gals at the surface of the free field. The effect of the sway and rocking motions of the foundation is not included in the maximum accelerations of the superstructure in Table 4, i.e., they are the sum of the relative horizontal accelerations to the foundation and the input motion. We denote the ratios of the maximum responses obtained from 2-D analyses to those from 3-D analysis for the supersutructure as β_{acc} and the ratio of the angular accelerations due to the rocking motion of the foundation as β_R. The obtained maximum values are shown for 3-D analysis and β_{acc} and β_R for 2-D analyses in Table 4.

As Table 4 shows, the best fit for the superstructure is obtained at $\alpha=1.4$ ($\beta_{acc}=1.0$ at almost all the masses), and for the foundation ($\beta_R=1.0$) it is obtained at $\alpha=1.2$. Because the coefficients which give the best fit for the superstructure and for the foundation are different there is no coefficient which gives the best fit for both the absolute accelerations which include the sway and rocking motions of the foundation and the angular acceleration of the foundation at the same time. Therefore, we need to compromise to obtain the coefficient α which gives the best fit of the maximum responses of the whole structure. From this point of view, we obtained the range of α which give $\beta_{acc} \leqq 1.0 \pm 0.03$ and $\beta_R \leqq 1.0 \pm 0.03$ and summarized it in Fig. 2.

The results indicate that there is a common range of α for $\beta_{acc} \leqq 1.0 \pm 0.03$ and $\beta_R \leqq 1.0 \pm 0.03$ for small number of piles but the common range decreases with increment of number of piles. On the other hand, the tendency of the common range of α does not change so much with respect to the number of stories of the superstructure. We obtained the optimal α from Fig.2 for the different number of piles and stories. The results are summarized in Table 5. With these optimal α, we compared the absolute maximum accelerations with those of obtained from 3-D analysis. The results are shown in Table 6. The results are expressed in the manner of ratios of the results from 2-D analyses to those from 3-D analysis. θ_r means the ratio of the angular accelerations of the foundation and e the standard deviation of the error. The results are satisfied for structures of smaller number of stories.

Estimation of the 3-D sharing ratio from the 2-D analysis

We tried to estimate the sharing ratio of shear force at the pile head of 3-D pile foundation from 2-D analyses. For this purpose, we obtained the sharing ratios from the 2-D analyses by using the optimal α which are given in Table 5 and the results are shown in Table 3. They are normalized by dividing the corresponding average shear force obtained from the 3-D analysis. Let Q_{ij} be the shear force at the pile head of the (i,j)th pile which are obtained from 3-D analysis and Q_i be the shear force of the ith pile obtained from 2-D analyses, and by introducing altered coefficient ξ_j, we define the relation between Q_{ij} and Q_i as follows.

$$Q_{ij} = \xi_j \, Q_i \tag{23}$$

By using the sharing ratios η_{ij} and η_i for 3-D and 2-D analyses respectively instead of Q_{ij} and Q_i , Eq.(23) is rewritten as

$$\xi_j = \Sigma(\eta_{ij} / \eta_i)/n \tag{24}$$

They are tabulated in Table 7, with the standard deviations. From these coefficients shearing force at pile heads in 3-D arrangement are estimated from 2-D analysis.

CONCLUSIONS

In order to estimate the maximum responses of the 3-D structure foundation system from the 2-D analysis, we performed dynamic response analyses of 3-D and 2-D interaction systems. By comparing these results and introducing two kinds of altered coefficients, we proposed the methodology to estimate the 3-D analysis responses. The conclusions obtained from this study are summarized as follows.

(1) The sharing ratio of a pile at the same position of the same pile arrangement is almost the same irrespective to the difference of the height of the superstructure. The center pile shares about 60% of the average shear force per a pile, while the corner pile shares from about 120% for 2x2 group pile foundation and about 170% for 6x6 group pile foundation.

(2) We proposed the methodology to estimate the sharing ratio from 2-D analyses by introducing the altered coefficient based on the result mentioned above.

(3) We obtained the optimal ratio of the thickness of ground to that of foundation which give the least difference between 3-D and 2-D analyses. The ratio is 2.0 for the 2x2 group pile foundatiom and 1.1 for 6x6 group pile foundation.

REFERENCE

Ishihara, T. and F. Miura. Comparison of seismic responses of 3-dimensional structure-pile foundation-ground interaction systems with those of 2-dimensional systems. Proc. of JSCE, No.501/I-29, 123-131 (in Japanese).

Table 1 Mass matrix of the superstructure and foundation

$\ddot{u}_1$	$\ddot{v}_1$	$\ddot{\theta}_{z1}$	$\ddot{u}_2$	$\ddot{v}_2$	$\ddot{\theta}_{z2}$	$\cdots$	$\ddot{u}_B$	$\ddot{v}_B$	$\ddot{w}_B$	$\ddot{\theta}_{xB}$	$\ddot{\theta}_{yB}$	$\ddot{\theta}_{zB}$
M_1							M_1	0	0	0	$M_1 \cdot h_1$	0
	M_1						0	M_1	0	$-M_1 \cdot h_1$	0	0
		J_{z1}					0	0	0	0	0	0
			M_2				M_2	0	0	0	$M_2 \cdot h_2$	0
				M_2			0	M_2	0	$-M_2 \cdot h_2$	0	0
					J_{z2}		0	0	0	0	0	0
						$\ddots$	$\ddots$			$\vdots$	$\vdots$	
M1	0	0	M2	0	0	$\cdot$	$\Sigma M_i + M_B$	0	0	0	$\Sigma M_i \cdot h_i$	0
0	M1	0	0	M2	0	$\cdot$	0	$\Sigma M_i + M_B$	0	$-\Sigma M_i \cdot h_i$	0	0
0	0	0	0	0	0		0	0	$\Sigma M_i + M_B$	0	0	0
0	$-M_1 \cdot h_1$	0	0	$-M_2 \cdot h_2$	0	$\cdot$	0	$-\Sigma M_i \cdot h_i$	0	$\Sigma M_i \cdot h_i^2 + J_{xB}$	0	0
$M_1 \cdot h_1$	0	0	$M_2 \cdot h_2$	0	0	$\cdot$	$\Sigma M_i \cdot h_i$	0	0	0	$\Sigma M_i \cdot h_i^2 + J_{yB}$	0
0	0	0	0	0	0		0	0	0	0	0	J_{zB}

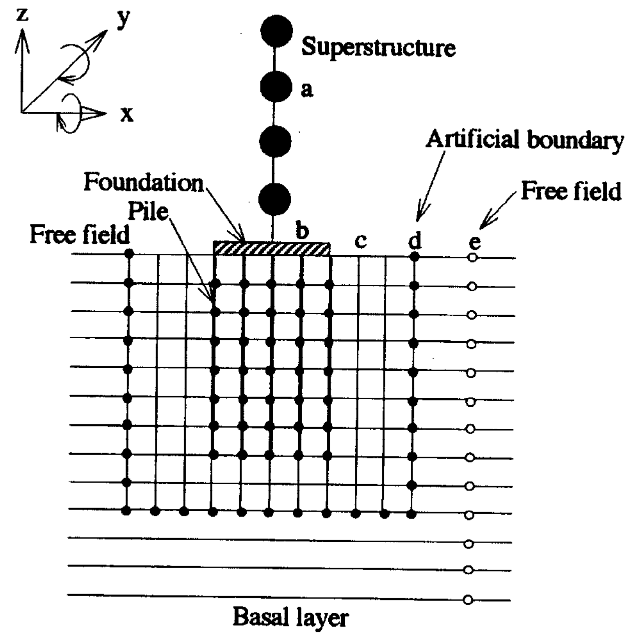


Fig.1. General view of the superstrcture-foundation-pile-ground system for the finite element analysis.

Table 2. Material Constants of the model

Ground depth	Unit weight (tf/m^3)	Shear Modulus (tf/m^2)	Poisson's Ratio
0 ~ 18m	1.8	4.70×10^3	0.45
18~30m	2.0	2.09×10^4	0.45
30~∞	2.0	4.70×10^4	0.45

Stories		3		6		9		12	
		W_i	K_i	W_i	K_i	W_i	K_i	W_i	K_i
Structure	RF							30	60
	12F							30	70
	11F							30	80
	10F					30	50	30	90
	9F					30	60	30	100
	8F					30	70	30	110
	7F			30	40	30	80	30	120
	6F			30	50	30	90	30	130
	5F			30	60	30	100	30	140
	4F	25	30	30	70	30	110	30	150
	3F	25	40	30	80	30	120	30	160
	2F	25	50	30	90	30	130	30	170
	T_1	0.344		0.536		0.660		0.764	
	T_2	0.134		0.201		0.246		0.284	
	T_3	0.090		0.097		0.152		0.175	
Foundation	W_B	25		30		30		30	
	J_B	250		750		1500		2500	
Pile	A_P	0.283		0.785		1.54		2.55	
	I_P	2.03×10^3		1.56×10^2		6.00×10^2		1.64×10	
	W_P	0.650		1.81		3.54		5.85	

W_i: Mass of the story i (tf) K_i: Stiffness of the story i (tf/m)
W_B : Mass of the foundation (tf)
J_B : Moment of inertia of the foundation (tf/m^4)
A_P : Area of section of a pile (m^2) I_P : Moment of inertia of area (m^4)
W_P : Weight of pile per unit length (tf/m)
T_1, T_2, T_3 : 1st, 2nd and third natural period of the superstructure

Table 3. Sharing ratio of the shear force at pile head.

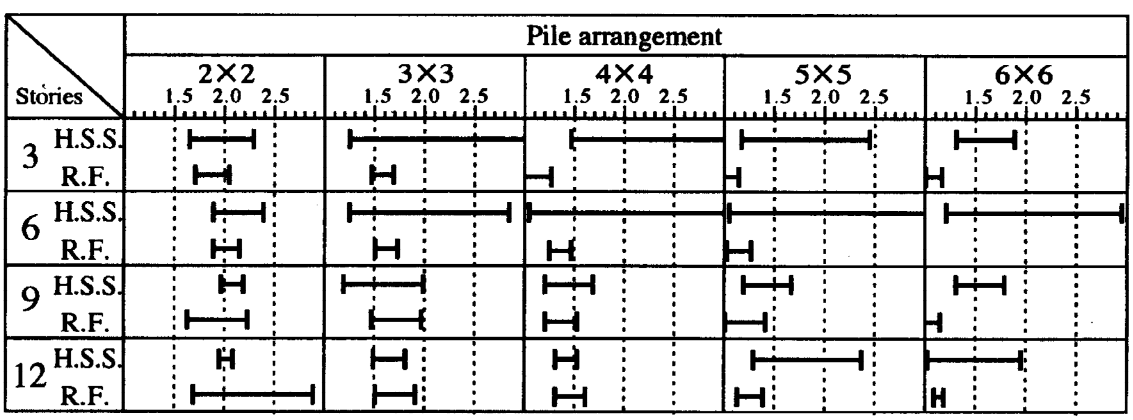
Stories	Row	2×2 1st	3×3 1st	3×3 2nd	4×4 1st	4×4 2nd	5×5 1st	5×5 2nd	5×5 3rd	6×6 1st	6×6 2nd	6×6 3rd
3	1st	1.00	1.17	1.14	1.36	1.18	1.55	1.26	1.22	1.76	1.37	1.28
	2nd		0.72	0.61	0.82	0.64	0.93	0.67	1.62	1.05	0.70	0.53
	3rd						0.88	0.66	0.61	0.95	0.67	0.59
	2-D	0.95	0.80	0.81	0.97	0.84	1.09	0.85	0.81	1.26	0.92	0.83
6	1st	1.00	1.18	1.29	1.34	1.22	1.53	1.27	1.23	1.72	1.36	1.28
	2nd		0.56	0.59	0.77	0.67	0.90	0.70	0.66	1.01	0.74	0.67
	3rd						0.82	0.68	0.64	0.90	0.70	0.63
	2-D	1.13	0.59	0.87	0.85	0.86	0.96	0.84	0.81	1.10	0.87	0.81
9	1st	1.00	1.18	1.31	1.35	1.18	1.53	1.22	1.18	1.71	1.30	1.22
	2nd		0.51	0.64	0.78	0.69	0.93	0.72	0.67	1.05	0.76	0.69
	3rd						0.84	0.69	0.64	0.92	0.71	0.64
	2-D	1.19	0.54	0.98	0.88	0.89	1.00	0.86	0.82	1.12	0.89	0.82
12	1st	1.00	1.23	1.26	1.39	1.17	1.57	1.20	1.16	1.74	1.27	1.19
	2nd		0.48	0.62	0.77	0.67	0.94	0.71	0.66	1.08	0.76	0.68
	3rd						0.84	0.69	0.63	0.94	0.71	0.63
	2-D	1.17	0.56	1.01	0.91	0.90	1.04	0.88	0.83	1.17	0.90	0.83

Table 4. Comparison of the maximum response accelerations between 2-D and 3-D analyses.

3-D analysis Acc (cm/s^2)	α for 2-D analyses 1.0	1.2	1.4	1.6	1.8	2.0	3.0
RF 302	0.91	0.96	1.00	1.03	1.05	1.07	1.13
9F 288	0.91	0.96	1.00	1.03	1.05	1.07	1.14
8F 264	0.91	0.96	1.00	1.03	1.05	1.07	1.14
7F 234	0.91	0.96	1.00	1.02	1.05	1.07	1.14
6F 199	0.91	0.96	0.99	1.02	1.05	1.07	1.14
5F 162	- 0.92	0.96	0.99	1.02	1.04	1.06	1.13
4F 128	- 0.94	0.96	0.99	1.02	1.04	1.06	1.12
3F 98.3	0.94	0.97	1.00	1.01	1.03	1.04	1.09
2F 74.0	0.96	0.98	1.00	1.01	1.02	1.03	1.05
BF 89.8	0.96	0.98	1.00	1.01	1.02	1.02	1.04
1.17×10^{-2}	1.06	1.00	0.95	0.90	0.86	0.83	0.69

Table 5. The optimal α

	Pile arrangements 2x2	3x3	4x4	5x5	6x6
3	1.9	1.6	1.2	1.1	1.2
6	2.0	1.6	1.4	1.1	0.9
9	2.0	1.7	1.4	1.2	1.1
12	2.1	1.6	1.4	1.3	1.2
Average	2.0	1.6	1.4	1.2	1.1



* H.S.S. : Horizontal acceleration of the superstructure
* R.F. : Rocking motion of the foundation

Fig.2 The range of α which give $\beta_{acc.}\leqq1.0\pm0.03$ and $\beta_R\leqq1.0\pm0.03$

Table 6. The ratios of absolute accelerations.

		Pile arrangement				
		2×2	3×3	4×4	5×5	6×6
3 stroies	RF	0.95	0.97	1.00	1.01	1.03
	3F	1.05	1.03	1.07	1.07	1.07
	2F	0.93	0.97	0.99	1.01	1.04
	BF	1.00	1.00	1.01	1.02	1.04
	Θ_y	0.96	0.94	0.90	0.91	0.96
	e	0.048	0.034	0.054	0.052	0.045
6 stroies	RF	0.99	1.00	0.99	0.99	0.97
	5F	0.94	0.96	0.98	0.99	1.00
	3F	0.82	0.90	0.93	0.97	0.99
	BF	1.01	1.00	1.01	1.01	1.00
	Θ_y	0.98	0.98	0.99	0.94	0.91
	e	0.091	0.052	0.067	0.060	0.056
9 stroies	RF	0.81	0.90	0.91	0.94	0.94
	9F	0.64	0.84	0.92	0.97	0.98
	7F	0.66	0.85	0.95	0.99	1.01
	5F	0.69	0.87	0.99	1.02	1.03
	3F	0.69	-0.74	0.80	0.84	0.88
	BF	1.01	1.01	1.00	0.99	0.98
	Θ_y	0.99	1.00	1.00	0.97	0.96
	e	0.314	0.187	0.121	0.094	0.084
12 stroies	RF	1.01	1.00	0.99	1.00	1.01
	11F	0.97	0.98	0.97	0.99	1.00
	9F	0.90	0.94	0.95	0.98	0.99
	7F	-0.85	0.90	0.90	0.95	0.97
	5F	-0.72	0.82	0.89	0.90	0.94
	3F	-0.85	0.87	0.93	0.95	0.95
	BF	1.01	1.01	1.00	1.00	0.99
	Θ_y	1.00	0.99	0.99	0.99	1.01
	e	0.185	0.108	0.089	0.069	0.065

2F~RF : Absolute acceleration of the superstructure
BF : Absolute acceleration of the foundation
Θ_y : Angular acceleration of the foundation
e : Standard deviation

Table 7. Altered coefficients ξ_j

Stories		Pile arrangement			
		3×3	4×4	5×5	6×6
3	ξ_1	1.44 (0.03)	1.41 (0.00)	1.46 (0.03)	1.48 (0.06)
	ξ_2	0.85 (0.08)	0.81 (0.05)	0.81 (0.04)	0.79 (0.03)
	ξ_3			0.78 (0.02)	0.73 (0.02)
6	ξ_1	1.83 (0.24)	1.50 (0.08)	1.55 (0.04)	1.57 (0.01)
	ξ_2	0.86 (0.13)	0.84 (0.06)	0.87 (0.05)	0.86 (0.04)
	ξ_3			0.83 (0.02)	0.80 (0.02)
9	ξ_1	1.91 (0.40)	1.44 (0.10)	1.47 (0.05)	1.49 (0.02)
	ξ_2	0.84 (0.13)	0.83 (0.05)	0.87 (0.05)	0.88 (0.04)
	ξ_3			0.81 (0.02)	0.80 (0.02)
12	ξ_1	1.87 (0.43)	1.42 (0.12)	1.43 (0.07)	1.44 (0.03)
	ξ_2	0.77 (0.11)	0.80 (0.05)	0.85 (0.05)	0.86 (0.04)
	ξ_3			0.79 (0.02)	0.79 (0.02)
Ave.	ξ_1	1.52 (0.20)			
	ξ_2	0.84 (0.07)			
	ξ_3	0.79 (0.03)			