Transactions, SMiRT 16, Washington DC, August 2001 *Paper # 1518*

A Fundamental Study on Dynamic Cross Interaction of Adjacent Structures Supported on Pile Foundations

Yukio Shimomura[1], Kaiji Oshima[2], Yoshio Ikeda[3], Ryuji Kondo[4], Mitsukazu Nakanishi[5] and Hiromi Adachi[5]

1)Junior College of Nihon University, Funabashi City, JAPAN
2)Fudo Construction Co., Ltd, Tokyo, JAPAN
3)Taisei Corporation, Tokyo, JAPAN
4)Graduate Student of Nihon University, Funabashi City, JAPAN
5)College of Science and Technology, Nihon University, Funabashi City, JAPAN

ABSTRACT

Massive structures, that is, reactor, turbine and other buildings, have been closely constructed in nuclear power plants. Therefore the consideration of the dynamic interaction effects not only between soil and structure but also among adjacent structures is indispensable to understanding the response of these buildings in detail. Some of these buildings might have to be supported on pile foundations due to the restriction of soil condition at power plant sites and so on. In some studies on the dynamic cross interaction (DCI) the adjacent structures have normally rested on the soil surface, and studies related to DCI of structures supported on pile foundation have been rarely seen. First, this paper proposes the numerical analysis scheme for foundations supported on piles considering with the influence of the adjacent structures, effects of the dynamic cross interaction (DCI). Then some discussions are presented through the numerical analysis of field horizontal excitation tests of four mock-up pile foundations. One of the four pile foundation models has been subjected to horizontal exciting forces in the tests, and the response displacement of each foundation has been recorded. Using the 3-dimensional thin layer soil model, the simulation analysis for the test results has been carried out. The numerical result of the foundations, not only the foundation subjected to excitation directly but also the adjacent foundations, shows a good agreement with the test result. Further, it is found that the difference of the effects of DCI was negligibly small through a comparison with the numerical result of the foundation on which the vibration generator lies. Finally, the earthquake response analysis, which considered the effects of DCI, has been also conducted. It is concluded that the influence of the adjacent structures more strongly affects the response of models subjected to earthquakes than that obtained by forced vibration tests.

1 INTRODUCTION

In some studies [*e.g.* 1] on the dynamic cross interaction (DCI) the adjacent structures have normally rested on the soil surface, and studies related to DCI effects of structures supported by pile foundation have been rarely seen. This paper presents discussions and numerical analyses concerning DCI of structures supported on pile foundations through field tests of four mock-up pile foundation models.

The in-situ measuring facilities of the pile-foundation system were installed at the Funabashi Campus of Nihon University as a part of the research program promoted by Nihon University and Nishimatsu Co. Ltd. in which some of the authors are involved. These facilities are composed of four different-sized foundation models supported on the mock-up piles. After installing the models, the research group has carried out forced vibration tests twice, and is continuously executing earthquake observations. The simulation analyses of the excitation experiment and the earthquake observation were conducted by the 3-dimensional thin layer method [2]. In these simulation analyses, the authors assumed that only one single foundation existed in the test field and disregarded the dynamic cross interaction among pile foundations. Actually the four foundations locates closely, furthermore a schoolhouse building exists nearby. Therefore, the results of the simulation analysis do not have an agreement with those of the excitation experiment and the earthquake observation.

In this paper, we aim to perform the analysis considering the influence of adjacent structures, so as to obtain basic findings concerning the dynamic cross interaction effects of pile foundations supported structures. In the tests one of the four pile foundation models has been subjected to horizontal exciting forces, and the response displacement of each foundation has been recorded. Using the 3-dimensional thin layer soil model, the simulation analysis for the test results has been carried out. The numerical result of the foundations, not only the foundation subjected to excitation directly but also the other adjacent foundations, shows a good agreement with the test one.

Further, it is found that the difference of the numerical result considering and omitting DCI effects was negligibly small. Finally, the earthquake response analysis, which considered the DCI effect, has been also conducted. It is concluded that the influence of the adjacent structures more strongly affects the response of models subjected to earthquakes than that obtained by forced vibration tests.

2 OUTLINE OF COMPUTATIONAL METHOD

2.1 Computational Method for Single Structure

The computational method employed in this paper is based on the Green's function method and is formulated in accordance with the substructure technique. First, the total system (a) is divided into the two sub-systems, *i.e.* Structure-Piles system (b) and Ground system (c), as shown in Fig.1. By employing the flexible volume method for the pile columns and the soil with excavation, the steady state equation of motion for Structure-Piles system is finally formulated as [3,4]

$$\left(\begin{bmatrix}[k_{SS}] & [k_{SP}] \\ [k_{PS}] & [k_{PP}]-[k^{G}_{PP}]+[A(i\omega)]^{-1}\end{bmatrix} - \omega^{2}\begin{bmatrix}[m_{S}] & \\ & [m_{P}]-[m^{G}_{P}]\end{bmatrix}\right)\begin{bmatrix}\{u_{S}\} \\ \{u_{P}\}\end{bmatrix} = \begin{bmatrix}\{P(i\omega)\} \\ \{F(i\omega)\}\end{bmatrix} \qquad (1)$$

where $\{P(i\omega)\}$ and $\{F(i\omega)\}$ represent the external force vector of structure and the driving force vector, $[k]$ and $[m]$ express static stiffness and mass matrices, respectively. Subscript "*S*" and "*P*" denote Structure and Pile, respectively, and superscript "*G*" denotes the excavated soil columns. The pile-soil-pile interaction can be appropriately included in the complex flexibility matrix of the soil system without excavated columns, $[A(i\omega)]$, by using the Green's function derived from the thin layer formulation. In the above and followings, the time function $e^{i\omega t}$ is omitted.

Now, let's define the dynamic stiffness matrix of surrounding soil as following;

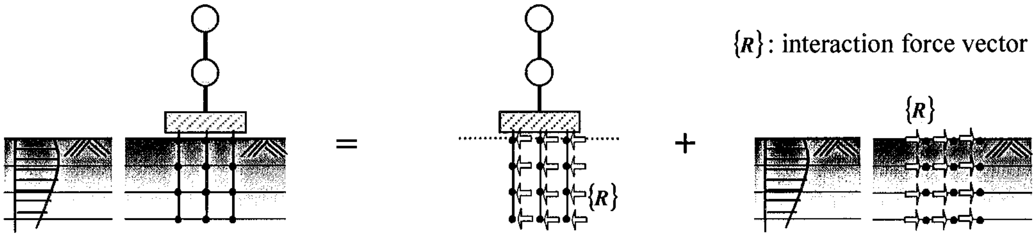
$$[S(i\omega)] = [A(i\omega)]^{-1} - [k^{G}_{pp}] + \omega^{2}[m^{G}_{p}] \qquad (2)$$

The interaction force vector is given by

$$\{R\} = [S(i\omega)]\ (\{u_{p}\} - \{\tilde{u}\}) \qquad (3)$$

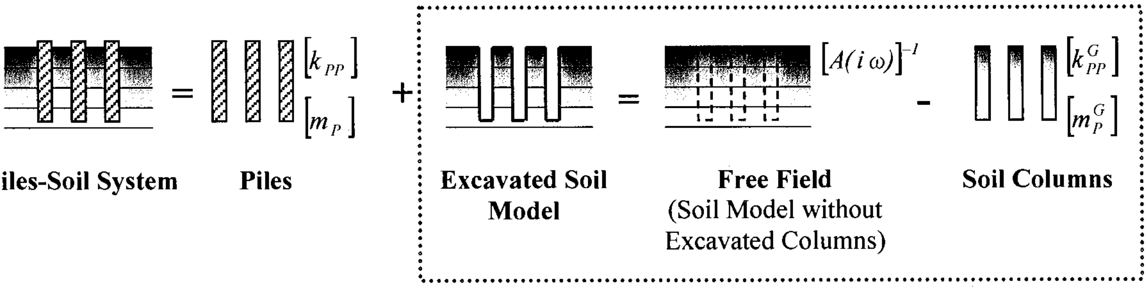
where, $\{\tilde{u}\}$ denotes the displacement vector of free field.

The complex flexibility matrix of soil which can account for pile-soil-pile interaction is formed by the superposition of the complex flexibility coefficient between nodes of soil columns, *i.e.* harmonic point, disk and ring load solutions [5]. In the right term of Eq.(1), $\{F(i\omega)\} = \{0\}$ and $\{P(i\omega)\} = \{0\}$ are employed for the cases of excitation problem and earthquake input motion problem, respectively.



(a) Structure-Piles-Soil System **(b) Structure-Piles System** **(c) Soil System**

Fig. 1: Two Sub-systems Separated by Substructure Method



Piles-Soil System **Piles** **Excavated Soil Model** **Free Field** (Soil Model without Excavated Columns) **Soil Columns**

Fig. 2: Flexible Volume Method for Calculating Flexibility Coefficient of Soil

2.2 Computational Method for Two or More Structures (DCI Analysis)

The equation of motion for two or more structures supported by the pile is also given by Eq.(1). If n structures supported on piles exsit, each stiffness matrix and the mass matrix in Eq.(1) should be rewritten as follows,

$$[k_{**}]=\begin{bmatrix} {}^{1}k_{**} & & & \\ & {}^{2}k_{**} & & \\ & & \ddots & \\ & & & {}^{n}k_{**} \end{bmatrix},\quad [m_{*}]=\begin{bmatrix} {}^{1}m_{*} & & & \\ & {}^{2}m_{*} & & \\ & & \ddots & \\ & & & {}^{n}m_{*} \end{bmatrix} \tag{4}$$

where, the subscript * of the above expression means S and P. In addition, the superscript j means the j-th structure and its piles. The complex flexibility matrix and stiffness matrix can be written as follows in similar manner.

$$[A]=\begin{bmatrix} {}^{11}A & {}^{12}A & \cdots & {}^{1n}A \\ {}^{21}A & {}^{22}A & & \vdots \\ \vdots & \vdots & \ddots & \\ {}^{n1}A & {}^{n2}A & & {}^{nn}A \end{bmatrix},\quad [K]=[A]^{-1}=\begin{bmatrix} {}^{11}K & {}^{12}K & \cdots & {}^{1n}K \\ {}^{21}K & {}^{22}K & & \vdots \\ \vdots & \vdots & \ddots & \\ {}^{n1}K & {}^{n2}K & & {}^{nn}K \end{bmatrix} \tag{5}$$

Moreover, the displacement vector, the external force vector and driving force vector can be written as follows.

$$\{u_S\}=\begin{bmatrix} {}^{1}\{u_S\} \\ {}^{2}\{u_S\} \\ \vdots \\ {}^{n}\{u_S\} \end{bmatrix},\quad \{u_P\}=\begin{bmatrix} {}^{1}\{u_P\} \\ {}^{2}\{u_P\} \\ \vdots \\ {}^{n}\{u_P\} \end{bmatrix},\quad \{P(i\omega)\}=\begin{bmatrix} {}^{1}\{P(i\omega)\} \\ {}^{2}\{P(i\omega)\} \\ \vdots \\ {}^{n}\{P(i\omega)\} \end{bmatrix},\quad \{F(i\omega)\}=\begin{bmatrix} {}^{1}\{F(i\omega)\} \\ {}^{2}\{F(i\omega)\} \\ \vdots \\ {}^{n}\{F(i\omega)\} \end{bmatrix} \tag{6}$$

Then, the interaction vector, which acts between the pile nodes and the soil nodes of the i-th (i,j=1,2,.....,n) structure, can be written as follows.

$${}^{i}\{R\}=({}^{ii}[K]-{}^{i}[k_{PP}^{G}]+\omega^{2}\,{}^{i}[m_{P}^{G}])({}^{i}\{u_P\}-\{\tilde{u}\})+\sum_{\substack{j=1\\ j\neq i}}^{n}{}^{ij}[K]\,({}^{j}\{u_P\}-\{\tilde{u}\}) \tag{7}$$

2.3 Simplification of Equation of Motion

Let's think three foundations supported on the piles as shown in Fig. 3. For simplification, it is assumed that no superstructure exists and all foundations are symmetry against x-axis. Now, consider the first foundation subjected to forced excitation of the x direction. Here, the vertical displacement of the first foundation is neglected. Further, when the y component of the horizontal displacement, the rocking angle about x-axis and torsion angle about z-axis are disregarded, the entire equation of motion can be written as follows.

$$[B]\{U\}=\{F\} \tag{8}$$

where, $\{U\}$ and $\{F\}$ are the displacement vector and the external force vector, respectively. These vectors can be written as follows.

$$\begin{aligned} \{U\}^{T}&=({}^{1}U_{F}\;{}^{1}\theta_{F}\;{}^{1}\{U_{P}\}^{T}\;{}^{1}\{\theta_{P}\}^{T}\;{}^{1}\{\mathrm{V}_{P}\}^{T}\;{}^{2}U_{F}\;{}^{2}\theta_{F}\;{}^{2}\mathrm{V}_{F}\;{}^{2}\{U_{P}\}^{T}\;{}^{2}\{\theta_{P}\}^{T}\;{}^{2}\{\mathrm{V}_{P}\}^{T}\;{}^{3}U_{F}\;{}^{3}\theta_{F}\;{}^{3}\mathrm{V}_{F}\;{}^{3}\{U_{P}\}^{T}\;{}^{3}\{\theta_{P}\}^{T}\;{}^{3}\{\mathrm{V}_{P}\}^{T}) \\ \{F\}^{T}&=({}^{1}Q_{F}\;{}^{1}\mathrm{M}_{F}\;{}^{1}\{Q_{P}\}^{T}\;{}^{1}\{\mathrm{M}_{P}\}^{T}\;{}^{1}\{\mathrm{P}_{P}\}^{T}\;{}^{2}Q_{F}\;{}^{2}\mathrm{M}_{F}\;{}^{2}\mathrm{P}_{F}\;{}^{2}\{Q_{P}\}^{T}\;{}^{2}\{\mathrm{M}_{P}\}^{T}\;{}^{2}\{\mathrm{P}_{P}\}^{T}\;{}^{3}Q_{F}\;{}^{3}\mathrm{M}_{F}\;{}^{3}\mathrm{P}_{F}\;{}^{3}\{Q_{P}\}^{T}\;{}^{3}\{\mathrm{M}_{P}\}^{T}\;{}^{3}\{\mathrm{P}_{P}\}^{T}) \end{aligned} \tag{9}$$

The displacement of the foundations is estimated at the center of the bottom surface. When the horizontal x direction excitation acts on the height of H from the bottom surface of the first foundation F1 as shown in Fig. 3, the external force vector can be written as follows.

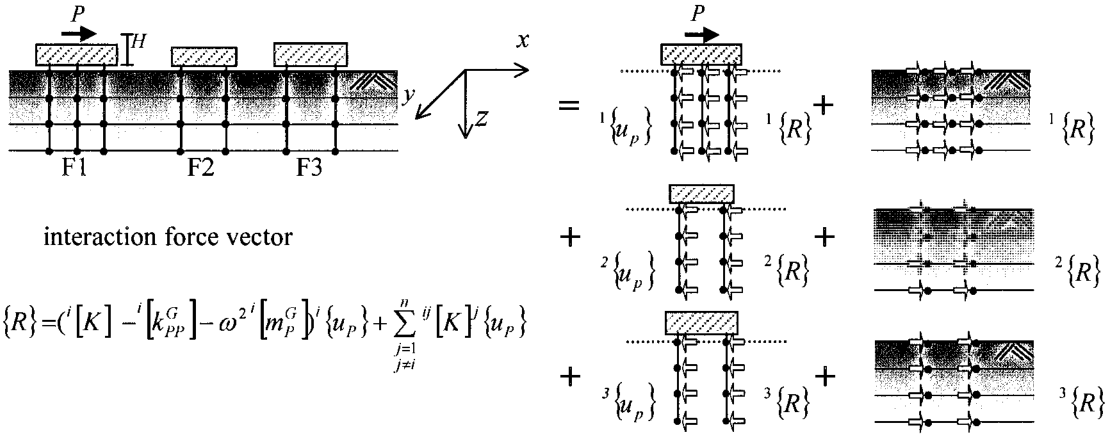


Fig. 3: Illustration of Substructure Method for Three Foundations Supported on Piles

$$\{F\}^{T}=(P\ PH\ \{0\}^{T}\{0\}^{T}\{0\}^{T}\ 0\ 0\ 0\ \{0\}^{T}\{0\}^{T}\{0\}^{T}\ 0\ 0\ 0\ \{0\}^{T}\{0\}^{T}\{0\}^{T}) \tag{10}$$

$[B]$ is an obtained dynamic stiffness matrix, and can be derived from Eqs. (4) and (5) as follows.

$$[B]=\begin{bmatrix} {}^{11}B & {}^{12}B & {}^{13}B \\ {}^{21}B & {}^{22}B & {}^{23}B \\ {}^{31}B & {}^{32}B & {}^{33}B \end{bmatrix} \tag{11}$$

In addition, $[{}^{ij}B]$ is given by the following expression.

$$[{}^{ij}B]=\begin{bmatrix} {}^{ij}B_{HH}^{FF} & {}^{ij}B_{H\theta}^{FF} & {}^{ij}B_{HV}^{FF} & ({}^{ij}B_{HH}^{FP}) & ({}^{ij}B_{H\theta}^{FP}) & ({}^{ij}B_{HV}^{FP}) \\ {}^{ij}B_{\theta H}^{FF} & {}^{ij}B_{\theta\theta}^{FF} & {}^{ij}B_{\theta V}^{FF} & ({}^{ij}B_{\theta H}^{FP}) & ({}^{ij}B_{\theta\theta}^{FP}) & ({}^{ij}B_{\theta V}^{FP}) \\ {}^{ij}B_{VH}^{FF} & {}^{ij}B_{V\theta}^{FF} & {}^{ij}B_{VV}^{FF} & ({}^{ij}B_{VH}^{FP}) & ({}^{ij}B_{V\theta}^{FP}) & ({}^{ij}B_{VV}^{FP}) \\ \{{}^{ij}B_{HH}^{PF}\} & \{{}^{ij}B_{H\theta}^{PF}\} & \{{}^{ij}B_{HV}^{PF}\} & [{}^{ij}B_{HH}^{PP}] & [{}^{ij}B_{H\theta}^{PP}] & [{}^{ij}B_{HV}^{PP}] \\ \{{}^{ij}B_{\theta H}^{PF}\} & \{{}^{ij}B_{\theta\theta}^{PF}\} & \{{}^{ij}B_{\theta V}^{PF}\} & [{}^{ij}B_{\theta H}^{PP}] & [{}^{ij}B_{\theta\theta}^{PP}] & [{}^{ij}B_{\theta V}^{PP}] \\ \{{}^{ij}B_{VH}^{PF}\} & \{{}^{ij}B_{V\theta}^{PF}\} & \{{}^{ij}B_{VV}^{PF}\} & [{}^{ij}B_{VH}^{PP}] & [{}^{ij}B_{V\theta}^{PP}] & [{}^{ij}B_{VV}^{PP}] \end{bmatrix} \tag{12}$$

In the above expression, the superscripts ij, F, and P denote foundation's number, foundation, and the pile respectively. Further, the subscript H, θ, and V denote the horizontal, rotation and vertical degree of freedom, respectively. When i or j is 1, ${}^{ij}B$ does not have V component, the element concerning vertical component, of the foundation F1 from the above-mentioned assumption. Though the equation of motion for the earthquake input problem could be similarly shown, we herein omit the expression. Assuming that piles consist of the soil properties, the response of the neighboring soil can be approximately estimated by the response of soil pile.

3 OUTLINES OF FOUNDATION MODELS AND SOIL PROFILE

The forced vibration tests of the mock-up foundation models supported on piles were carried out at Funabashi Campus of our college in Chiba Prefecture in Japan. Fig. 4 shows an illustration of the test field. The soil profile of the field that is mainly obtained by the measurement from P-S seismic logging conducted in the borehole A is shown in Fig. 5. The foundation models F1-F4 are supported on piles whose bottoms are located at the depth of 26.1m. The piles for all foundations were made of steel pipes and the same geometries, that is, diameter, wall thickness and length are 0.406m, 9.5mm and 26.6m, respectively.

4 FORCED VIBRATION TEST AND ITS SIMILATION ANALYSIS

4.1 Outlines of Vibration Test and Numerical Model for Simulation Analysis

A rotating mass type vibration generator placed on the upper surface of the foundation model F1 excited other foundation models. The tests were carried out for the cases of NS and EW direction excitation with several force levels. Here we describe only the case of NS direction sweep excitation with 0.3tf target force level. Assuming that the dynamic cross interaction effects of the foundations which deviate from the excitation axis would be negligible, F1, F2 foundations and the schoolhouse building that exist on the axis are adopted as analysis models. In order to focus on the influence of the dynamic cross interaction between both foundations, the schoolhouse building (reinforced concrete framed structure) was modeled as simply as possible. The influence of the superstructure was represented by additional mass and the rotation inertia. The each pile head of the foundation models was clamped and located at 50cm height from the ground surface. The center of gravity of the vibration generator was set at 20cm above the center of upper surface of the foundation model F1. Further, it is assumed that several piles that support each column are modeled as an equivalent pile.

Table 1, 2, and 3 show the physical constant of the foundation models, the pile parameters, and the soil properties, respectively. Fig. 6 shows the pile arrangement of the analytical model and their cross sections. A depth of the soil model is twice as long as the pile length and is divided into thin layers so as to satisfy the precision of the analysis solutions. The soil model is supported at G.L.-52m with the dashpot mat that represents a half-space. Assuming that each structure that is on the same axis (excitation direction) generates no torsional vibration, the simulation analysis is carried out by using Eqs. (8)-(12).

4.2 Simulation Analysis for Single Foundation

First, on the assumption that the foundation model F1 exists alone in the test field, the simulation analysis for its experimental result is conducted. The calculation result and the experimental one are compared in Fig.7. The solid circles in Fig. 7 show the experiment result, and the black solid line depicts the numerical result by M0S model employing the soil constant in Table 3. Both the frequency characteristics and the amplitude of the resonance curve obtained in the calculation agree less with the experiment result. Then, three models M1S, M2S and M3S are proposed as additional calculations. These models take account of the nonlinear interaction effects, that is, both the material nonlinearity of the soil neighboring pile heads and the separation between the pile and surrounding soil, as shown in Fig.8.

M1S: Neglecting the material nonlinearity of the soil and considering the separation between the pile side surface and the surrounding soil at the depth of 0.5m.

M2S: Considering the material nonlinearity of the soil at the depth of 1.5m and neglecting the separation.

M3S: Considering both the material nonlinearity of the soil at the depth of 1.5m and the separation between the pile side surface and the surrounding soil at the depth of 0.5m.

According to the result of M2S and M3S that take into account nonlinear interaction effects in Fig. 7, the agreement with the numerical and experiment results is improved. Although the resonance curve obtained by the M3S model somewhat overestimates the equivalent damping constant, this model simulates the experimental results better than the other models.

4.3 Simulation Analysis Considering with DCI

Next, to investigate the influence of the adjacent structures, the simulation analysis was carried out for the foundation model F1, F2, and schoolhouse building S bldg.. These models (M1, M2 and M3) described in the previous section were employed for the analysis. Fig. 9(a) shows the comparison with the resonance curves of the foundation F1 obtained by the calculation and experiment. Last character of the model name, that is, D means the dynamic cross interaction of the adjacent structures.

The response result of M3D, which considers the existence of the adjacent structures, became somewhat small compared with M3S. Consequently, the difference of the result between M3D and M3S was negligibly small. Fig. 9(b) presents the resonance curve of each foundation model M1D, M2D and M3D, and that of experimental result at the foundation model F2. It is indicated that the resonance curves of analysis have a good agreement with that of the experiment except for the numerical model M1D. The analytical natural frequency of the foundation F2 with no DCI is about 9Hz. Taking into account DCI for the foundation F2, its resonance curve has a peak near the natural frequency of the foundation F1 (about 6Hz). The resonance curve of the S bldg obtained by the calculation is shown in Fig. 9(c). Because no measurement data from the S bldg. exist, only an analytical result is examined. While there is no peak on the resonance curve of F2 at its natural frequency (about 9Hz), the resonance curve has peaks at its natural frequency (about 3Hz) and a dimple nearby F1's natural frequency. Fig. 9(d) indicates the comparison with the resonance curve of ground point [A] obtained from the experiment and the analysis. Results of both models M2D and M3D coincide well with the experiment one. It is found that the effect of the adjacent structures to the response of the foundation F1 and the ground point [A] is negligible small.

5 PREDICTION OF EARTQUAKE RESPONSE IN COSIDERATION OF DCI

Assuming that no separation phenomenon between the pile and the soil occurs, we investigate the dynamic characteristics of the foundations subjected to an earthquake. In the analysis, we herein treat all of the models and properties as same as those in the previous section and assume that the soil and the foundations are completely bonded.

Fig.10 shows the frequency response amplification of each model to the free field soil surface for cases of considering or neglecting existence of the adjacent structures. It is understood that the influence of the adjacent structures more strongly affects the response of models subjected to earthquakes than that obtained by forced vibration tests. In particular, the influence of large mass foundation has a strong effect on the small mass foundation in the natural frequency vicinity of large mass foundation. On the other hand, the large mass foundation is less affected by the existence of the adjacent structures.

6 CONCLUSION

In this paper, first, the numerical calculation scheme of pile foundations that take into account the influence of the adjacent structures was presented. Then using the present procedure, the simulation analysis for the forced vibration tests of pile foundations was carried out. As a result, it turned out that the calculation results have a good agreement with the experiment ones, and the difference of the influence of DCI is negligible small. Finally, we conduct the earthquake response of the group foundations. It is foreseen that the influence of the adjacent structures more strongly affects the response of models subjected to earthquakes than that obtained by forced vibration tests. In the future, it is necessary to accumulate the observation data and to perform analyses in detail.

Acknowledgement

This research was conducted as a part of the Academically Promoted Frontier Research Program on "Sustainable City Based on Environmental Preservation and Disaster Prevention" at Nihon University, College of Science and Technology (Head Investigator: Prof. Nagakatsu Kawahata) under a Grant from the Ministry of Education, Science and Sports, Japan.

REFERENCES

1.Yano, T., Kitada, Y., Iguchi, M., Hirotani, T. and Yoshida, K. “Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants”, Proc. of 12WCEE, No.477 (CD), 2000.

2.Suzumura, J., Asega, H., Arai, T., Nakamura, M., Hanada, K., Shiojiri, H. and Kasahara, A. “ Dynamic Properties of Structure-Pile System Using Mock-up Model”, Proc. of 12WCEE, No.1273 (CD), 2000.

3.Hasegawa, M., Ichikawa, T., Nakai, S. and Watanabe, T. “Nonlinear Seismic Response Analysis of an Embedded Reactor Building Based on the Substructure Approach”, Nuclear Engineering and Design, Vol.104, pp.175-186, 1987.

4.Shimomura, Y., Ikeda, Y., Ohshima, K., Ishimaru, S. and Niiya, T. “A Study of Dynamic Interaction of Soil and Pile with Non-uniform Section”, Proc. of 12WCEE, No.875 (CD), 2000.

5.Tajimi, H. ”A Contribution to Theoretical Prediction of Dynamic Stiffness of Surface Foundations”, Proc.7th WCEE, Vol.5, pp.873-880, 1980.

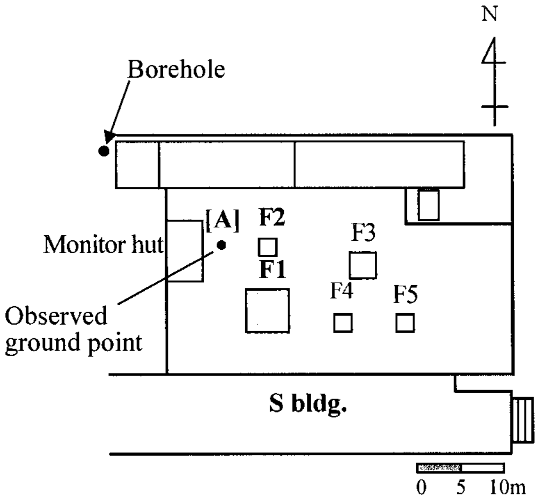


Fig. 4: Illustration of Test field

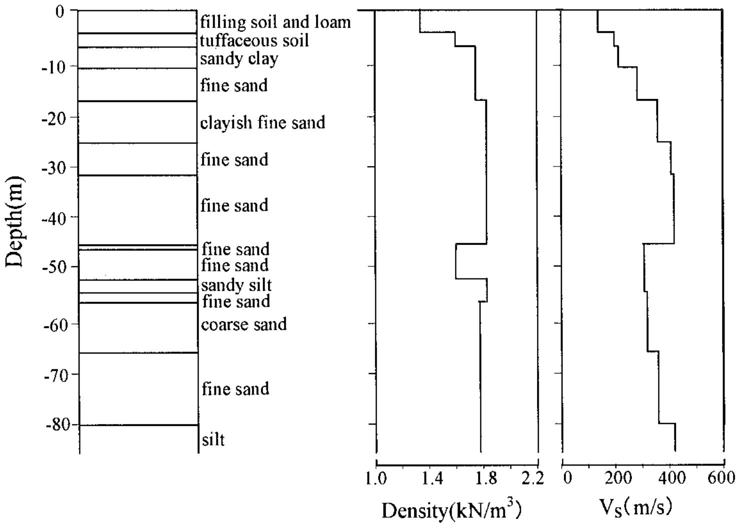


Fig.5: Soil Conditions at Test Field

Table 1: Physical Properties of Foundations

	Size(m)	Mass(t)	Number of piles
F1	5×5×1	60	4
F2	2×2×1.2	11.5	4
S bldg.	47×8.6×4	3680	16

Table 2: Physical Properties of Piles

	F1,2	S bldg.
Length(m)	26.6	26.6
Diameter(mm)	406	640
Section area(m^2)	1.19×10^{-2}	0.32
Moment of inertia of area(m^4)	2.334×10^{-4}	0.41
Young's modulus(kN/m^2)	2.06×10^{8}	2.06×10^{7}
Damping ratio	0.01	0.01

Table 3: Soil Profile for Numerical Analysis

Depth(m)	Vs(m/s)	Density (kN/m^3)	Poisson's ratio	Damping ratio
3.15	130	1.40	0.420	0.01
6.95	150	1.50	0.488	0.01
19.10	255	1.85	0.486	0.01
26.00	350	1.85	0.476	0.01
52.00	400	1.85	0.469	0.01
Semi-infinite soil	400	1.85	0.469	0.01

(Dashpot mat)

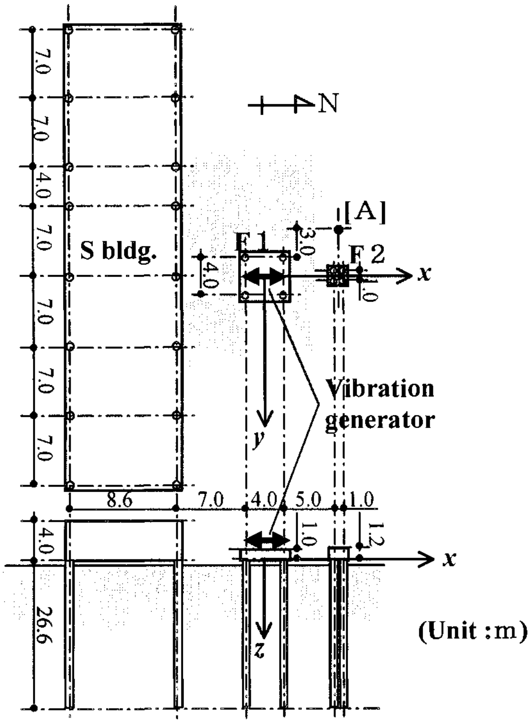


Fig. 6: Pile Arrangement and Cross Section of Foundations

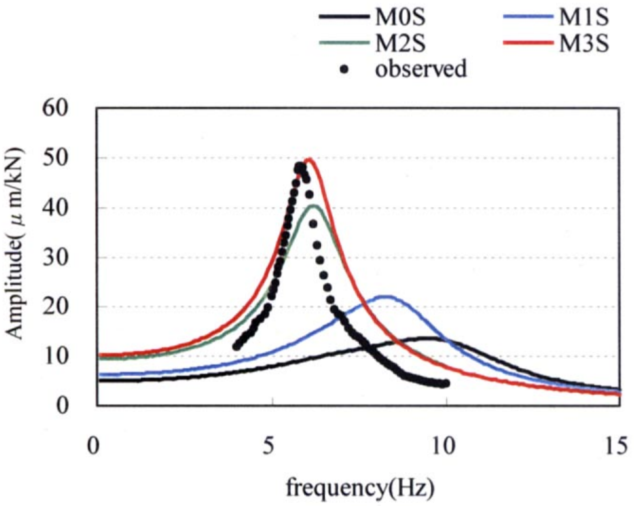


Fig. 7: Comparison of Numerical and Test Results of Foundation F1

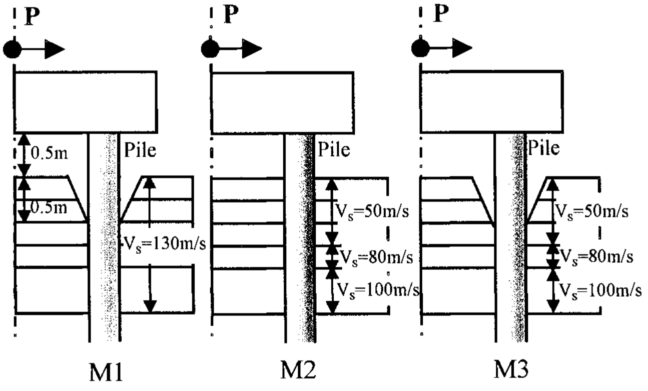
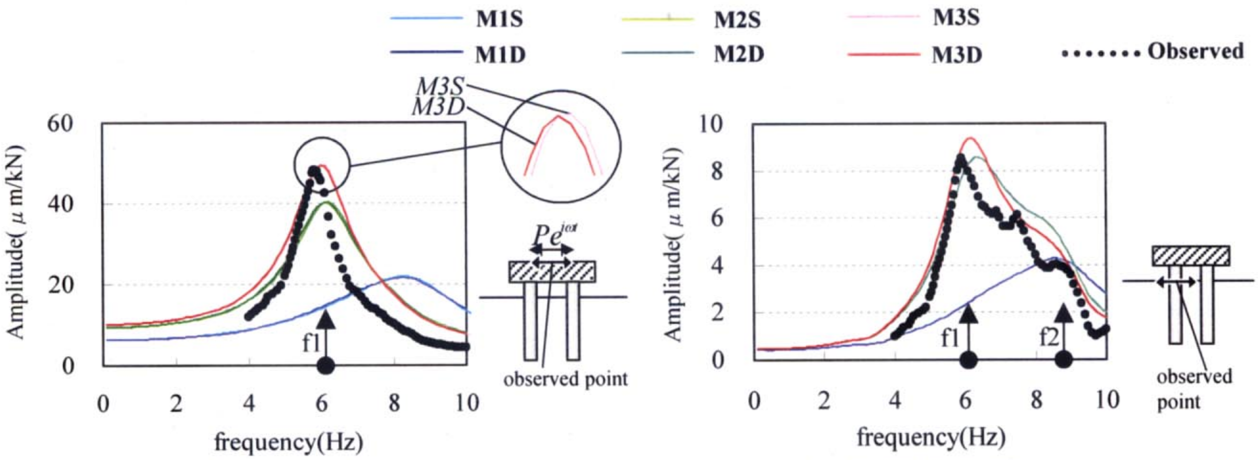
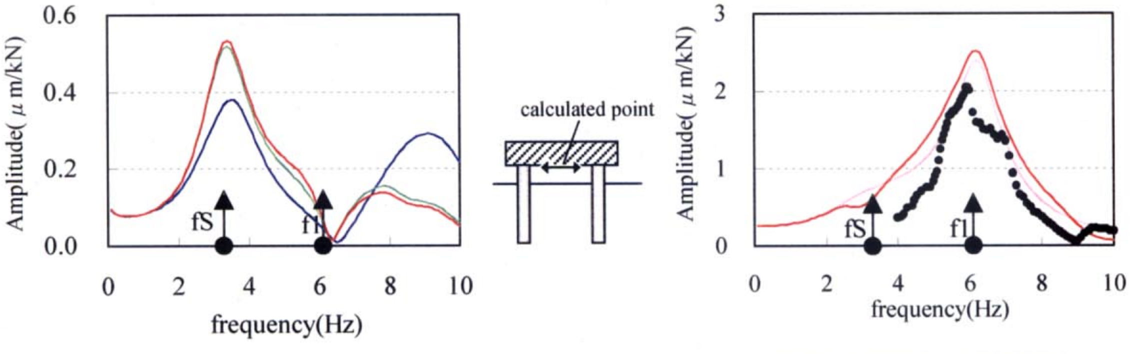


Fig. 8: Numerical Models for Additional Analysis



(a) Foundation F1

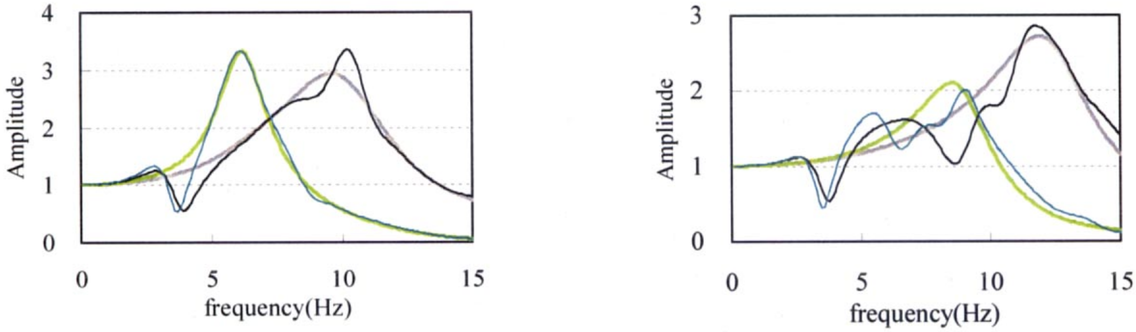
(b) Foundation F2



(c) Schoolhouse S bldg.

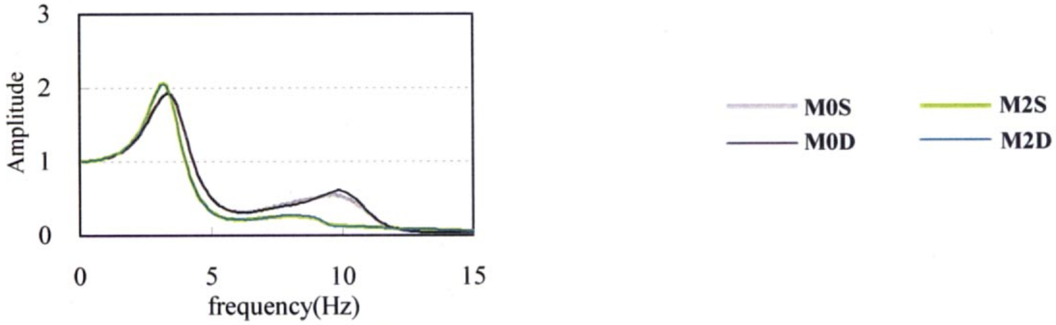
(d) Adjacent soil at point A

Fig. 9: Comparison of Numerical and Experimental Displacement Resonance Curves



(a) Foundation F1

(b) Foundation F2



(c) Schoolhouse S bldg.

Fig. 10: Transfer Functions $u/\tilde{u}$ ($\tilde{u}$: Displacement of Free Field Surface)