

Shaking table test and analysis of embedded structure soil interaction considering input motion

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1 Introduction

The dynamic interaction between soil and structure is decomposed into inertial interaction (II) and kinematic interaction (KI). II denotes the interaction due to inertial force applied on foundations. KI denotes the interaction of massless foundations subjected to seismic waves. Forced vibration tests by exciters are not enough to evaluate the complete soil-structure interaction due to the lack of KI. To clarify the effects of KI on the seismic response of structure, we intended to carry out shaking table tests of the interaction between the soil and the embedded structure. A method to decompose II and KI is introduced which reveals the construction of embedment effects. Finally we discuss the validity of three kinds of simulation analyses, that is, two-dimensional, approximate three-dimensional and rigorous three-dimensional analyses, comparing with the test results.

2 Outline of Tests

A BWR type building was employed as the prototype. The dimensions of the prototype are listed in Table 1. The superstructure was condensed into a mass-spring system connected to the foundation using the concept of effective mass and height. According to the similitude ratios listed in Table 2, the specifications of the model soil-structure system were decided as listed in Table 3. The model soil was composed of polyacrylamide and bentonite, and confirmed to be elastic. In order to simulate the vertically propagating shear wave in a semi-infinite layered medium, "Boundary Apparatus for Shear Deformation" was newly developed and installed on the lateral sides of the model soil. The outline of the model soil-structure system is illustrated in Fig.1.

Major parameters of the tests were as follows : Embedment depth($D/L=0, 1/2, 1$ and 2 D; embedment depth, L; half width of foundation), shear wave velocity of sublayer($V_s= 300, 600$ and 1000m/sec , V_s ; shear wave velocity of actual ground), and that of backfill soil($1/3, 1/1$ of sublayer).

3 Test Results

3.1 Foundation Input Motion

Figure 2 presents the comparison between the horizontal free field motion u_{ff} at the surface of the model soil and the horizontal foundation input motion u_f at the bottom of the rigid embedded foundation. In these

curves, the peaks observed at 4.5Hz, 14.5Hz, and 25.0Hz are considered due to the resonance of the model soil. Although foundation input motions are defined as the responses of massless foundations subjected to seismic waves, the influence of II due to the foundation mass was confirmed to be negligible through the numerical check using the measured impedance functions. Therefore, the reduction of the foundation input motion recognized in Fig.2 is principally caused by KI.

The horizontal and rocking components of the foundation input motions normalized by ${}_H U_F^*$ are shown in Figs.3(a) and 3(b), respectively. The horizontal input motions at the location of the superstructure are also shown in Fig.4.

3.2 Contributions of Kinematic Interaction and Inertial Interaction

Figure 5 shows the resonance curves of the superstructure for various shear wave velocity of the sublayer and various embedment depths. In these figures except Fig.5(a), it is not evident which peaks correspond to the resonance of II. The response of the superstructure should be decomposed into the effects of II and KI, to discuss the test results for further details. The decomposition method will be explained in the followings.

The equation of motion of the soil-structure system subjected to seismic waves is given as follows.

$$[M] \begin{Bmatrix} \ddot{U}_S^t \\ \ddot{U}_F^t \end{Bmatrix} + \begin{bmatrix} K_{SS} & K_{SF} \\ K_{FS} & K_{FF} + K_G \end{bmatrix} \begin{Bmatrix} U_S^t \\ U_F^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ F_F^* \end{Bmatrix} \quad (1)$$

The superscript t represents the total displacement. The subscripts S and F are used to refer to superstructure nodes and foundation nodes. F_F^* is the driving force which is related to the foundation input motion U_F^* as follows.

$$F_F^* = K_G U_F^* \quad , \quad U_F^* = ({}_H U_F^* \quad \Theta_F^*)^T \quad (2)$$

where K_G is the impedance matrix for the foundation. The total displacement may be written in the form,

$$\begin{Bmatrix} U_S^t \\ U_F^t \end{Bmatrix} = [\alpha] U_F^* + \begin{Bmatrix} U_S \\ U_F \end{Bmatrix} \quad , \quad [\alpha] = \begin{bmatrix} 1 & 0 & 1 & 0 \\ h & 1 & 0 & 1 \end{bmatrix}^T \quad (3)$$

where $[\alpha]$ is the operator which represents the rigid displacement, $\{U_S \ U_F\}^T$ is the displacement relative to the foundation input motion and h is the height of structure. According to the definition of stiffness matrix, the substitution of Eq.(3) into Eq.(1) derives the following equation.

$$[M] \begin{Bmatrix} \ddot{U}_S \\ \ddot{U}_F \end{Bmatrix} + \begin{bmatrix} K_{SS} & K_{SF} \\ K_{FS} & K_{FF} + K_G \end{bmatrix} \begin{Bmatrix} U_S \\ U_F \end{Bmatrix} = -[M][\alpha] \ddot{U}_F^* \quad (4)$$

As illustrated in Fig.6, Eq.(4) implies that the relative displacement $\{U_S \ U_F\}^T$ is equal to the response of the system subjected to the equivalent excitation $-m_F ({}_H U_F^* + h \Theta_F^*)$. The excitation corresponds to the inertial force caused by the foundation input motion. Now, considering the relative displacement ${}_H U_S$ normalized by the input motion at the location of superstructure, which is defined in following equation,

$${}_H \bar{U}_S = \frac{{}_H U_S}{{}_H U_F^* + h \Theta_F^*} \quad , \quad {}_H U_S = {}_H U_S^t - ({}_H U_F^* + h \Theta_F^*) \quad (5)$$

it is evident that ${}_H \bar{U}_S$ is dependent not on KI including the resonant effects of the model ground, but on II including the dynamic deformations of superstructure, referring to Eq.(4). Hereinafter ${}_H U_S$ is briefly called the response depending on II.

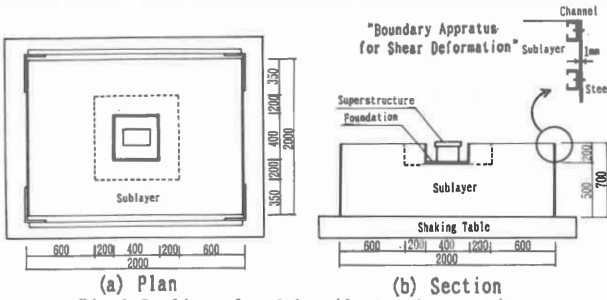


Fig. 1 Outline of model soil-structure system

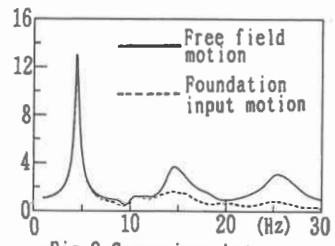
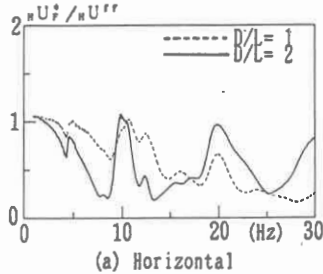
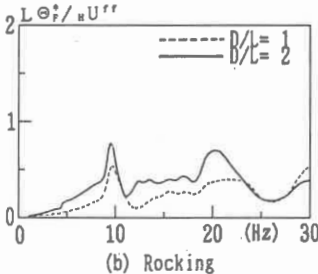


Fig. 2 Comparison between free field motion and foundation input motion



(a) Horizontal



(b) Rocking

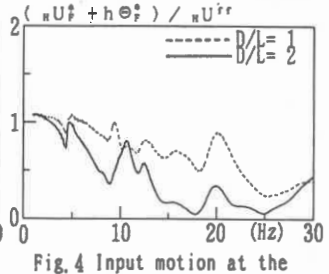
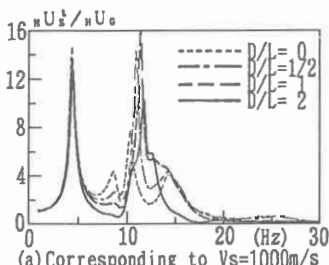
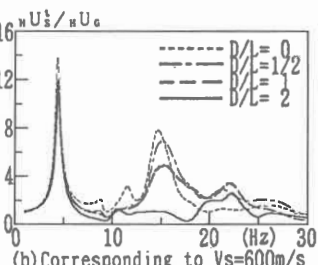


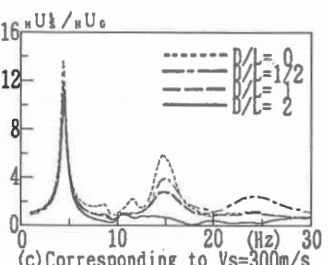
Fig. 4 Input motion at the location of superstructure



(a) Corresponding to $V_s=1000\text{m/s}$



(b) Corresponding to $V_s=600\text{m/s}$



(c) Corresponding to $V_s=300\text{m/s}$

Fig. 5 Total response of structure (U_s : motion of shaking table)

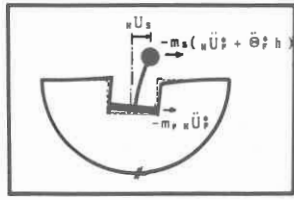
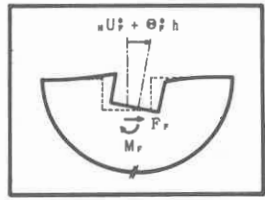
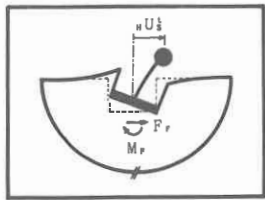
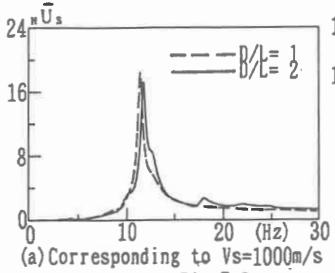
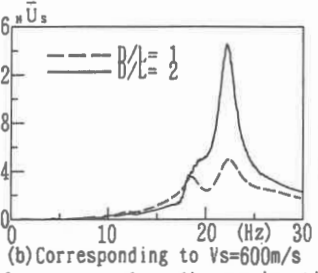


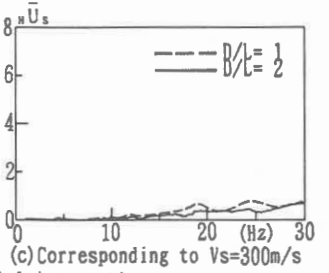
Fig. 6 Decomposition of seismic response into kinematic and inertial interaction



(a) Corresponding to $V_s=1000\text{m/s}$



(b) Corresponding to $V_s=600\text{m/s}$



(c) Corresponding to $V_s=300\text{m/s}$

Fig. 7 Response of structure depending on inertial interaction

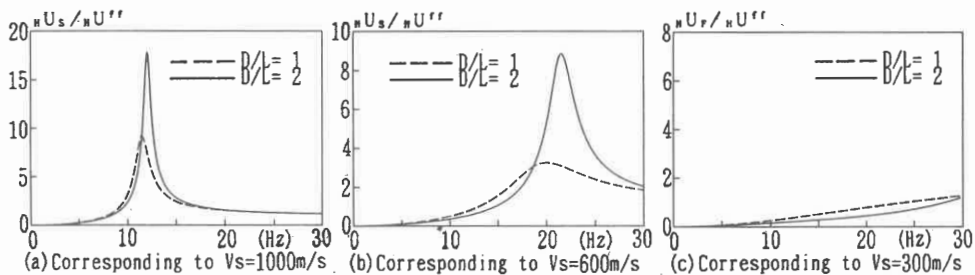


Fig.8 Results of analyses by S-R model subjected to constant input motion

Figure 7 shows the response depending on II of the test results. These curves are simplified drastically from the original test results shown in Fig.5, since the effects of KI and the resonant effects of the model soil have been removed.

The proposed method was verified in comparison with the results of sway-rocking model analyses. The foundation input motions were assumed to be constant in these analyses. Although the extent of the model soil is finite, it was assumed to be uniform semi-infinite for simplicity. The impedance functions obtained by R.J.Apsel(Ref.1) were adopted in these analyses. The results of the analyses are shown in Fig.8. The resonant frequencies observed in Fig.7 agree with those of the analyses.

3.3 Discussions

The effects of the test parameters on the response of the structure are discussed on the basis of the decomposed test results.

(1) Shear wave velocity of sublayer

The seismic response of the structure decreases as the shear wave velocity of the sublayer decreases.

(2) Embedment depth

When the foundation is deeply embedded, the variation of the foundation input motion caused by KI provides the considerable effect on the response of the structure. It is interesting to point out the followings ; The total response in the case of $D/L=2$ is smaller than that of $D/L=1$ (Fig.5(b)), while the responses depending on II present the contrary results (Fig.7(b)). These reversed results are explained by the fact that the input motion at the location of the superstructure in the case of $D/L=2$ is smaller than that of $D/L=1$ (Fig.4). This result demonstrates the importance of KI.

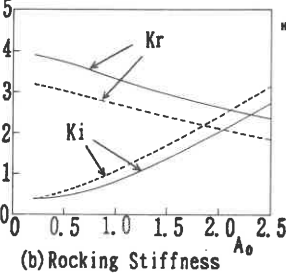
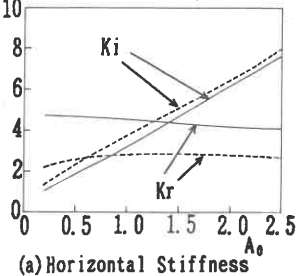
Another interesting point is that the response depending on II in the case of $D/L=2$ is larger than that of $D/L=1$ (Fig.7(b)). This result is agreeable to that of analysis shown in Fig.8(b). It should be noted that the response of the structure does not always decrease as the embedment depth increases by the effect of II, except the case where the structure is completely rigid.

4 Simulation Analysis

4.1 A general discussion on 2-D and 3-D Analyses

Figure 9 shows the impedance functions for the rigid flat foundation on the uniform semi-infinite visco-elastic medium evaluated by 2-D and 3-D boundary element methods. In this figure, the real part (K_r) of the 2-D impedance function is far smaller than that of the 3-D impedance function, while the imaginary part (K_i) of the 2-D impedance function conforms with that of the 3-D. This fact implies the overestimation of the damping factor ($h=K_i/2K_r$) in the 2-D analysis, which results in the underestimation of the seismic response of the structure as shown in Fig.10.

$K_{hh}/(GL)$ --- 2-D Analysis $K_{hh}/(GL^2)$ — 3-D Analysis



(a) Horizontal Stiffness A_0 (b) Rocking Stiffness A_0
Fig. 9 Impedance functions of flat foundation

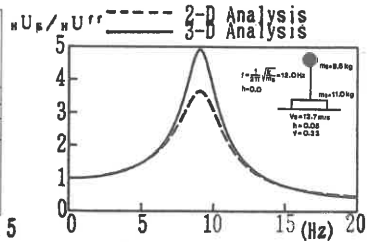
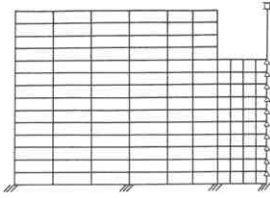
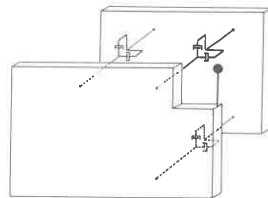


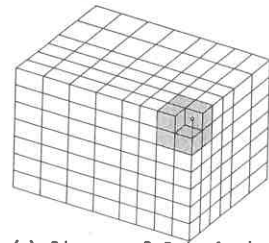
Fig. 10 Response of structure



(a) 2-D Analysis

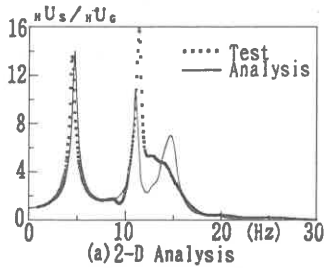


(b) Approximate 3-D Analysis

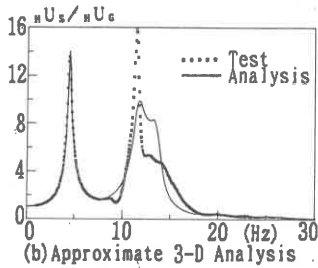


(c) Rigorous 3-D Analysis

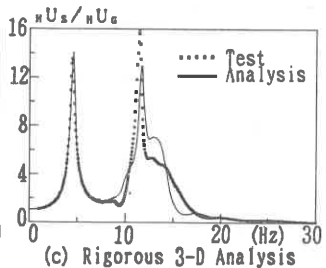
Fig. 11 Models for simulation analyses



(a) 2-D Analysis

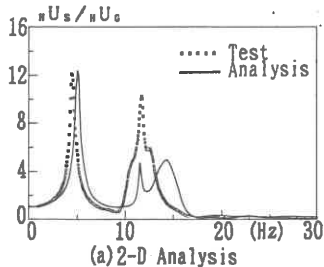


(b) Approximate 3-D Analysis

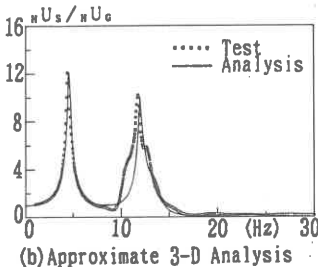


(c) Rigorous 3-D Analysis

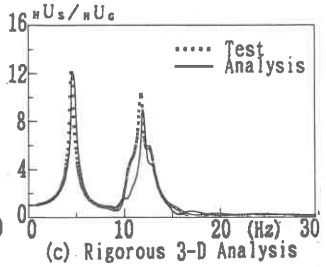
Fig. 12 Comparison of response of structure in the case of $D/L=1, V_s=1000m/s$



(a) 2-D Analysis

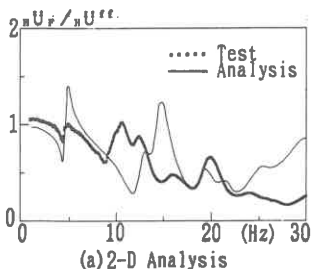


(b) Approximate 3-D Analysis

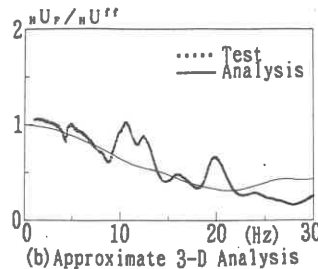


(c) Rigorous 3-D Analysis

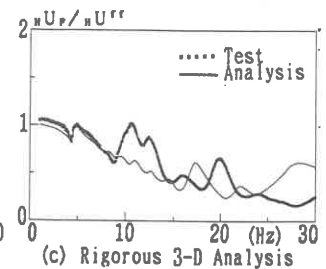
Fig. 13 Comparison of response of structure in the case of $D/L=2, V_s=1000m/s$



(a) 2-D Analysis



(b) Approximate 3-D Analysis



(c) Rigorous 3-D Analysis

Fig. 14 Comparison of input motion in the case of $D/L=1$

Table 1 Dimensions of prototype

Super-structure	Weight (ton)	2.1*10 ³
	Height (m)	70.0
	Natural Frequency (Hz)	4.3
	Effective Weight (ton)	1.29*10 ³
Foundation	Effective Height (m)	36.3
	Weight (ton)	1.2*10 ³
	Width*Depth (mm)	80.0*80.0
	Embedment Depth (m)	6.5

Table 2 Similitude ratios

		Corresponding to the Actual Ground		
		Vs=100m/s	Vs=600m/s	Vs=300m/s
Length L	1/200	1/200	1/200	
Time T	0.357	0.214	0.107	
Mass M	7.5*10 ⁻⁸	7.5*10 ⁻⁸	7.5*10 ⁻⁸	
Density ML ⁻³	1.2/2.0	1.2/2.0	1.2/2.0	

Table 3 Specifications of model soil-structure system

		Target Value	Design Value	Measured Value
Super-structure	Effective Weight (kg)	9.68	9.61	9.60
	Effective Height (cm)	18.15	18.15	18.15
	Natural Frequency (Hz)	12.0	12.0	12.1
	Vs=100m/s Vs=600m/s Vs=300m/s	20.2 40.2	20.2 40.2	21.6 41.0
Foundation	Weight D/L= 0, 1/2, 1 (kg)	9.00 9.00	11.18 15.34	11.04 15.31
	Width*Depth (cm*cm)	40.0*40.0	40.0*40.0	40.0*40.0
	Supporting Ground	Shear Wave Velocity (m/s)	14.0	14.0
Backfill Soil	Damping Factor (%)	5.0	5.0	4.9
	Shear Wave Velocity (m/s)	4.5	4.5	3.7
	Damping Factor (%)	8.0	8.0	7.2

4.2 Results of Analysis

The simulation analyses were conducted by the 2-D finite element method, the rigorous 3-D finite element method, and the approximate 3-D finite element method adding viscous dashpots to the 2-D analysis. Three simulation models of these analysis methods are presented in Fig.11.

Comparisons between the test results and the results of the analyses are presented in Figs.12-14. Figures 12 and 13 show the response of the superstructure in the case of D/L=1 and D/L=2, respectively. Figure 14 shows the foundation input motions of the case D/L=1.

The following items are found from these figures.

- (1) The rigorous 3-D analyses agree well with the test results.
- (2) The 2-D analyses underestimate the response of the structure around the resonant frequency of II. These defects of the 2-D analyses are consistent with the above-mentioned case of uniform semi-infinite medium.
- (3) The approximate 3-D analyses considerably improve the defects of the 2-D analyses. Taking the computational efforts into account, the approximate 3-D analyses seem to be fairly effective for simulation.
- (4) The rigorous 3-D, the approximate 3-D and the 2-D analyses are fitting in this order for simulation of the foundation input motion.

5 Conclusion Remarks

- (1) The decomposition method, which separates kinematic interaction and inertial interaction from complete soil-structure interaction, is powerful to reveal the construction of embedment effects.
- (2) When the foundation is deeply embedded, the seismic response of structure is affected by kinematic interaction as well as inertial interaction. In general, kinematic interaction contributes the reduction of seismic response, but it should be noted that kinematic interaction is significantly frequency-dependent phenomenon.
- (3) Considering the flexibility of structure, inertial interaction does not always decrease the response of structure as the embedment depth increases.
- (4) The two-dimensional analyses considerably underestimate the seismic response of structure. For the appropriate evaluation of the seismic response of structure, the three-dimensional effect in the soil-structure interaction problem should be taken into account.

REFERENCES

- /1/R.J.Apsel. 1979. Dynamic Green's Functions for Layered Media and Applications to Boundary Value Problems. Ph.D Thesis.