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건물-지반 시스템에 관한 진동대실험 (2) : 성층지반위의 구조물

Shaking table test on soil-structure interaction system (2) : Superstructure with foundation on layered soil

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ABSTRACT

This paper proposes the shaking table testing method, without any soil specimen only using building model as an experimental part, considering dynamic soil-structure interaction based on the substructure method. The two-layered soil is assumed as a soil model of the entire soil-structure interaction syhstem(SSI) in this paper. Differently from the constant soil stiffness, the frequency-dependent dynamic soil stiffness is approximated for the case of both acceleration and velocity feedback, respectively. The interaction force is observed from measuring the accelerations at superstructure. Using the soil filters corresponding to the approximated dynamic soil stiffness, the shaking table drives the acceleration or velocity, which the needed motion to give the building specimen the SSI effects. Experimental results show the applicability the proposed methodologies to the shaking table test considering dynamic soil-structure interaction.

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1. INTRODUCTION

It has widely been recognized for structural engineers that the grasping of the dynamic vibration characteristics of soil-structure interaction(SSI) system subjected to seismic loading is required to adequately evaluate the structural response under earthquake loads.

For this purpose, the application of substructure method to the numerical evaluation of dynamic soil-structure interaction system gives less calculating time than Finite Element Method. With the endeavor to calculate the non-linear superstructure on unbounded linear soil media, one of authors has applied this method to the numerical evaluation of large nuclear power plant, which contains many vibration-sensible devices[Motosaka et al, 1992, 1993].

The concept of substructure method has recently applied to the development of testing techniques. Iemura's group has applied this method to the shaking table test including the vibration control device, to verify its control efficacy. In his method, the experimental part is the vibration control device and the computing part is the building or bridge structure[Iemura et al, 2002], [Igarashi et al, 2002]. Meanwhile,

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Konagai has carried out the shaking table test on the SSI system as an application of substructure method[Konagai et al, 1998]. In his method, the experimental part is the superstructure and the computing part is the soil model. A force sensor, installed between the bottom of superstructure's specimen and the shaking table, was used for observation of interaction force and an analog circuit was used for expressing the dynamic soil stiffness. The shaking table was used for producing the motion corresponding the foundation of total SSI system, by observing the fed-back interaction force and the signal from analog circuit corresponding to soil model. However, considering the following items:

① the problem of the active vibration control of SSI system, the measuring of the structural responses is needed since the active vibration control device usually is driven by the fed-back structural responses.

② the problem of experimental installation, for example, accelerometers are easy to install in experiment and frequently used for the typical shaking table testing.

③ the problem of expenses for implementing experiment, the using of analog circuits may be increased in its expense, due to its remaking for reflecting the change of soil model.

From these reasons, his method is not necessarily easy method for carrying out the testing.

Paying attention to these points, this paper newly proposes the shaking table testing method of SSI system, using the structural response, based on the substructure method. In this method, the shaking table is used for generating the motion of the foundation in the total SSI system by observing the fed-back accelerations from superstructure and the signal from digital filter, which correspond to the dynamic soil stiffness and is changeable in the control computer. Differently from an accompanying paper dealing with constant soil stiffness[Lee et al, 2004], SSI system having the frequency-dependent dynamic soil stiffness is discussed in here. The experimental system discussed in an accompanying paper is also used in here; a building specimen, which is used as an experimental part of total SSI system, and the two degree-of-freedom controller.

2. ANALYTICAL SSI SYSTEM

Fig. 1 illustrates the SSI system comprising the superstructure, which is identified for its damping and stiffness coefficients in an accompanying paper, and the assumed two-layered soil model with the depth of $d = 50\mathrm{cm}$, Poisson's ratios of $\nu_1 = \nu_2 = 0.3$, shear velocities of $V_{s1} = 416.7\,\mathrm{cm/s}$ and $V_{s2} = 616\,\mathrm{cm/s}$, and specific weights of $\gamma_1 = 10.1\,\mathrm{kN/m^3}$ and $\gamma_2 = 11.7\,\mathrm{kN/m^3}$.

The dynamic soil stiffness, $S_b^g(\omega)$, of the above two-layered soil model that is obtained by the thin layer method[AIJ, 1996], one of methods of calculating the exact solution for the dynamic soil stiffness. The calculated dynamic soil stiffness has the real(dark solid line) and imaginary part(light solid line), as shown in Fig. 2.

The equation of motion in the frequency domain is expressed as:

$$\begin{bmatrix} S^s_{ss}(\omega) & S^s_{sb}(\omega) \\ S^s_{bs}(\omega) & S^s_{bb}(\omega) \end{bmatrix} \begin{Bmatrix} \{Y_s(\omega)\} \\ Y_b(\omega) \end{Bmatrix} = -\begin{Bmatrix} \{0\} \\ R_b(\omega) \end{Bmatrix} \tag{1}$$

where, $\{Y_s(\omega)\}$ and $Y_b(\omega)$ are the Fourier transforms of the absolute displacements of superstructure, $\{Y_s(t)\}$, and of foundation, $Y_b(t)$, respectively.

The dynamic stiffness of superstructure in the left side of Eq. (1) is given by:

$$\begin{bmatrix} S^s_{ss}(\omega) & S^s_{sb}(\omega) \\ S^s_{bs}(\omega) & S^s_{bb}(\omega) \end{bmatrix} = \begin{bmatrix} [K_{ss}] & [K_{sb}] \\ [K_{bs}] & [K_{bb}] \end{bmatrix} + i\omega \begin{bmatrix} [C_{ss}] & [C_{sb}] \\ [C_{bs}] & [C_{bb}] \end{bmatrix} - \omega^2 \begin{bmatrix} [M_{ss}] & [M_{sb}] \\ [M_{bs}] & [M_{bb}] \end{bmatrix} \tag{2}$$

where, $[M_{ss}]$, $[C_{ss}]$ and $[K_{ss}]$ are the structural mass, damping and stiffness matrix whose components are the values identified in an accompanying paper, and

$$\begin{aligned} [M_{sb}] &= [M_{bs}]^T = [0\ 0\ 0]^T, & [M_{bb}] &= m_b \\ [C_{sb}] &= [C_{bs}]^T = [0\ 0\ -c_1]^T, & [C_{bb}] &= c_1 \\ [K_{sb}] &= [K_{bs}]^T = [0\ 0\ -k_1]^T, & [K_{bb}] &= k_1 \end{aligned} \tag{3}$$

The interaction force appeared in the right side of Eq. (2) is also expressed as:

$$R_b(\omega) = S^g_b(\omega) \cdot \left[Y_b(\omega) - Y^g_b(\omega) \right] \tag{4}$$

The superstructure under the interaction force excitation expressed in Eq. (4) also satisfies the dynamic equilibrium expressed as the following Eq. (5).

$$m_b \ddot{Y}_b(\omega) + \sum_{i=1}^{3} m_i \ddot{Y}_i(\omega) = -R_b(\omega) \tag{5}$$

3. EXPERIMENTAL VERIFICATION OF NUMERICAL SSI SYSTEM

At first, the approximation on the numerically calculated dynamic soil stiffness shown in Fig. 2 is discussed for performing the test. Then, the controller design for experimentally realizing the motion of SSI system expressed in Eq. (1) and its experimental verification are investigated in here.

3.1 Approximation of the dynamic soil stiffness

The approximation of dynamic soil stiffness is needed to reflect the dynamic soil stiffness shown in Fig. 2 on the control computer and perform the test.

The following Fig. 2 compares between the exact dynamic soil stiffness and its approximated ones in both real and imaginary parts. The 'Exact' in the figure denotes the dynamic soil stiffness calculated by the thin layer method, as shown in Fig. 2. The 'Acc. fit' and 'Vel. fit' indicate the approximated dynamic soil stiffness for the acceleration and velocity feedback experiment, respectively.

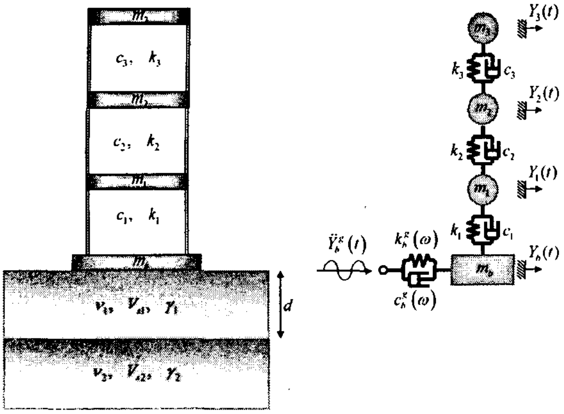


Figure 1. Superstructure with foundation on two-layered soil

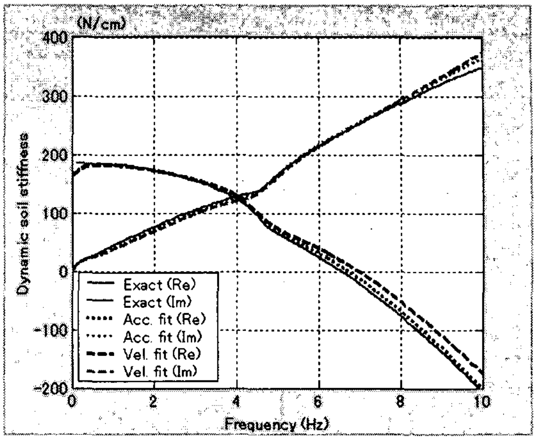


Figure 2. Approximated dynamic soil stiffness

The corresponding filters for the above approximated dynamic soil stiffness in Fig. 2 are expressed as the following Eqs. (6)~(11).

The approximated dynamic soil stiffness for the acceleration feedback is given by:

$$ {}_aS_b^g(s) = \frac{n_a(s)}{d_a(s)} = \frac{(s-p_{a1})\cdot(s-p_{a2})\cdot(s-p_{a3})\cdot(s-p_{a4})\cdot(s-p_{a5})}{(s-z_{a1})\cdot(s-z_{a2})\cdot(s-z_{a3})} \tag{6} $$

where, $s = i\omega$

$$ z_{a1} = -1.49,\ z_{a2} = -5.00+2.87i,\ z_{a3} = -5.00-2.87i \tag{7} $$

and

$$ p_{a1} = -1.32,\ p_{a2} = -3.13+3.16i,\ p_{a3} = -3.13-3.16i,\ p_{a4} = -4.16+2.89i,\ p_{a5} = -4.16-2.89i \tag{8} $$

The approximated dynamic soil stiffness for the velocity feedback is also expressed as:

$$ {}_vS_b^g(s) = \frac{n_v(s)}{d_v(s)} = \frac{(s-p_{v1})\cdot(s-p_{v2})\cdot(s-p_{v3})\cdot(s-p_{v4})\cdot(s-p_{v5})}{(s-z_{v1})\cdot(s-z_{v2})\cdot(s-z_{v3})\cdot(s-z_{v4})} \tag{9} $$

where,

$$ z_{v1} = -1.49,\quad z_{v2} = -9.61,\quad z_{v3} = -5.00+2.87i,\quad z_{v4} = -5.00+2.87i \tag{10} $$

and

$$ p_{v1} = p_{a1},\quad p_{v2} = p_{a2},\quad p_{v3} = p_{a3},\quad p_{v4} = p_{a4},\quad p_{v5} = p_{a5} \tag{11} $$

3.2 Controller Design Of SSI System

(1) Acceleration feedback

The interaction force based on the acceleration formulation is given by[Motosaka et al, 1990]:

$$ R_b(s) = \frac{{}_aS_b^g(s)}{s^2}\cdot\left[\ddot{Y}_b(s) - \ddot{Y}_b^g(s)\right] \tag{12} $$

The acceleration at the shaking table, which is required to excite the building specimen with the interaction force expressed as Eq. (12), is derived from substituting Eq. (6) into Eq. (12) and rearranging it.

$$\ddot{Y}_b(s)=\frac{s^2\cdot d_a(s)}{n_a(s)}\cdot R_b(s)+\ddot{Y}_b^g(s) \tag{13}$$

The interaction force in the above Eq. (13), as known from Eq. (5), can be found by observing the absolute accelerations from the all floors of building specimen and the shaking table.

The following Fig. 3 shows the experimental set-up and its signal flow in the control computer, in which the digital signal processing board is installed, for the experiment of the soil-structure interaction system with foundation on two-layered soil in case of the acceleration feedback. The signal flow in the figure was constructed based on the above Eq. (13). The interaction force is observed from the accelerations from the shaking table in addition to those from building specimen. The acceleration, which has to be driven by shaking table, is calculated from adding assumed effective ground input acceleration to the observed interaction force. Finally, the shaking table moves according to it, through the 2 D.O.F. controller based on acceleration observation.

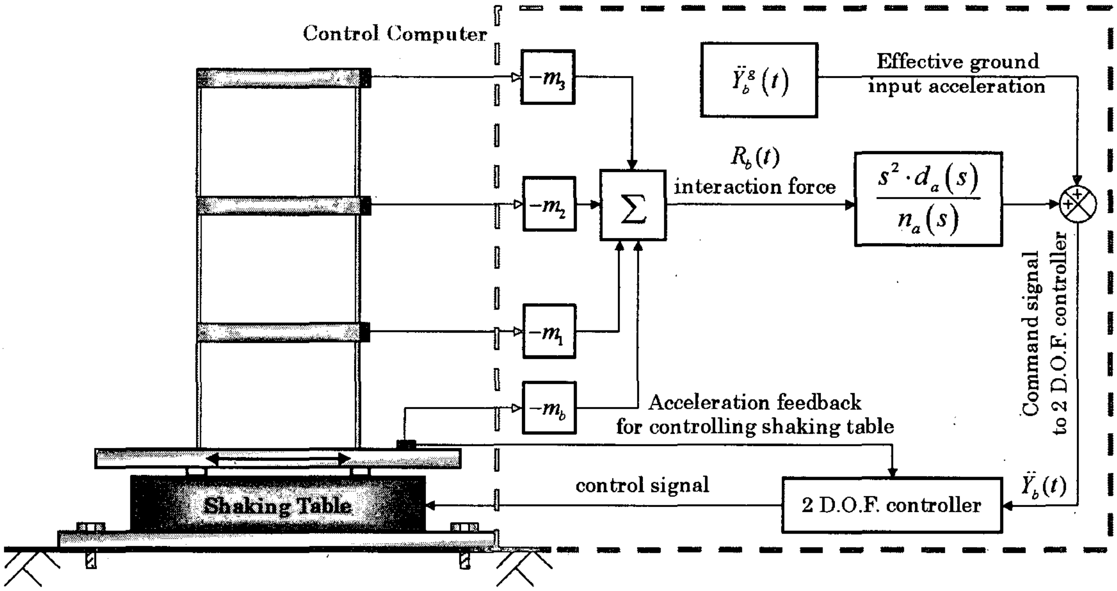


Figure 3. Signal flows in control computer in case of acceleration feedback

The following Figs. 4 and 5 show the experimental results obtained from converting the filters and 2 D.O.F. controller in Fig. 3 into their digital version and reflecting them on LabVIEW[Robert, 2001]. Fig. 4 compares the results observed from the shaking table test in Fig. 3(solid line) with those calculated from the numerical analysis in Eq. (1)(dotted line). Fig. 5 compares the experimental results between the foundation-fixed system and the SSI system shown in Fig. 3.

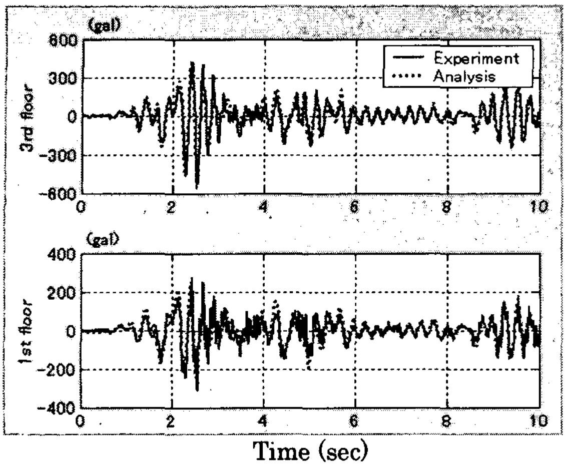


Figure 4. Comparison of results between the numerical analysis and the experiment of SSI system (Acceleration feedback)

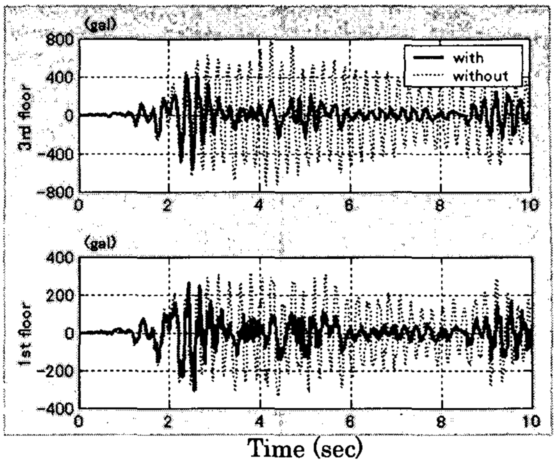


Figure 5. Comparison of experimental results with and without SSI effect (Acceleration feedback)

(2) Velocity feedback

The interaction force based on the velocity formulation is expressed as[Motosaka et al, 1990]:

$$R_b(s)=\frac{{}_vS_b^g(s)}{s}\cdot\left[\dot{Y}_b(s)-\dot{Y}_b^g(s)\right] \tag{14}$$

The velocity at the shaking table, which is required to give the building specimen the interaction force expressed as Eq. (14), is derived from substituting the approximated dynamic soil stiffness for the velocity feedback, Eq. (9), into the velocity-formulated interaction force, Eq. (14), and rearranging it.

$$\dot{Y}_b(s)=\frac{s\cdot d_v(s)}{n_v(s)}\cdot R_b(s)+\dot{Y}_b^g(s) \tag{15}$$

In the same manner as the case of the acceleration feedback, the interaction force in the above Eq. (15), as known from Eq. (5), is also found by observing the absolute accelerations from the all floors of building specimen and the shaking table.

The following Fig. 6 shows the experimental set-up and its signal flow in control computer for the experiment on the SSI system with foundation on two-layered soil in case of velocity feedback. The signal flow in the figure is based on the above Eq. (15). Effective ground input velocity is inputted and the integrator is added to integrate the fed-back acceleration at the shaking table for the velocity feedback.

Fig. 7 compares the results observed from the shaking table test in Fig. 6(solid line) with those calculated from the numerical analysis in Eq. (1)(dotted line). Fig. 8 compares the experimental results between the foundation-fixed system and the SSI system shown in Fig. 6.

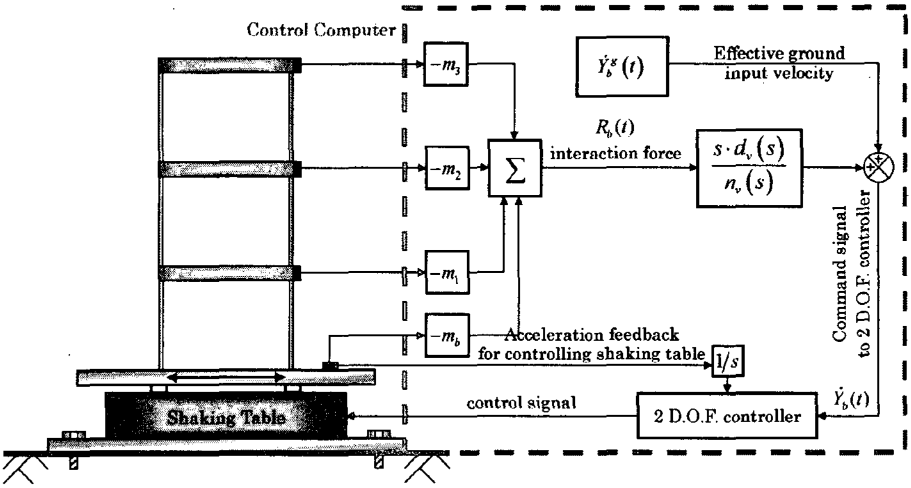


Figure 6. Signal flows in control computer in case of velocity feedback

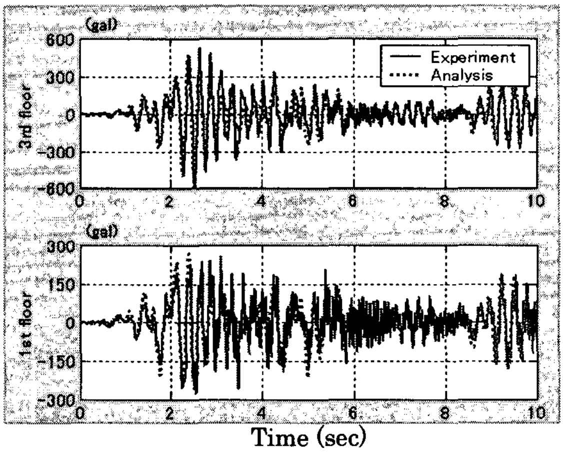


Figure 7. Comparison of results between the numerical analysis and the experiment of SSI system (Velocity feedback)

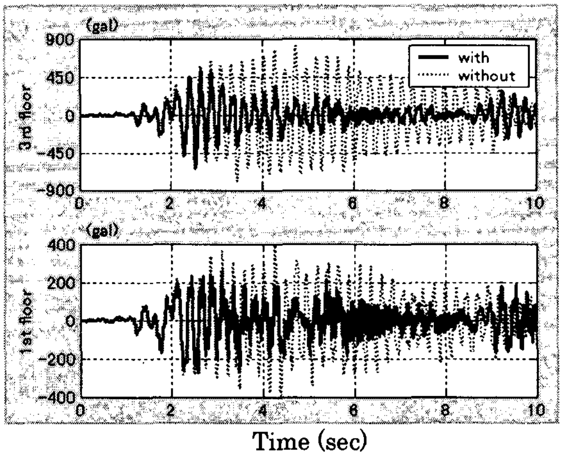


Figure 8. Comparison of experimental results with and without SSI effect (Velocity feedback)

3.3 Identification of experimental dynamic soil stiffness

(1) Acceleration feedback

Substituting $s = i\omega$ and Eq. (6) into Eq. (13) and rearranging it with ${}_aS_b^g(\omega)$ gives,

$$ {}_aS_b^g(\omega) = \frac{-\omega^2 \cdot R_b(\omega)}{\ddot{Y}_b(\omega) - \ddot{Y}_b^g(\omega)} \tag{16}$$

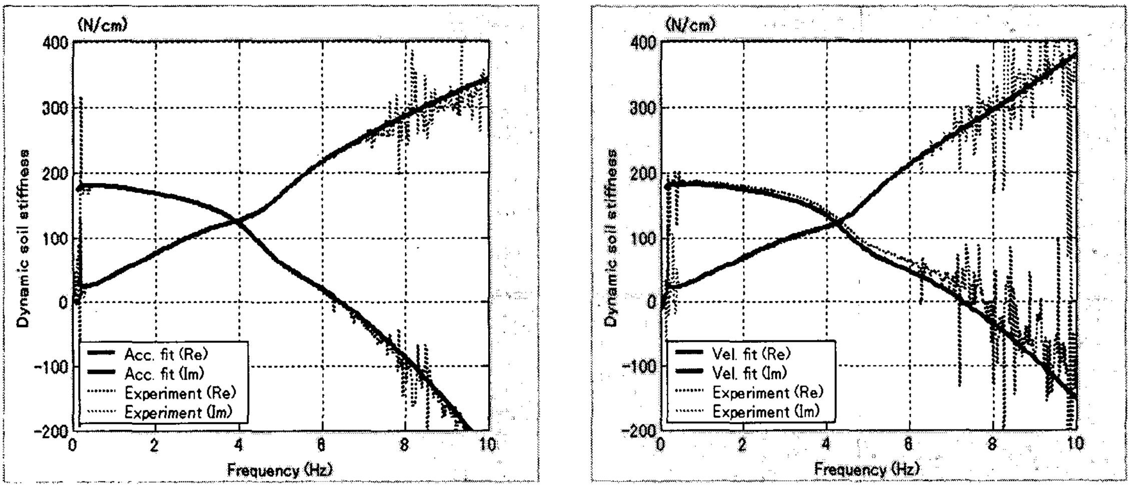
The interaction force, $R_b(t)$, the absolute acceleration at the shaking table, $\ddot{Y}_b(t)$, and the effective ground input acceleration, $\ddot{Y}_b^g(t)$, can be experimentally obtained in the control computer, as shown in Fig. 3. Therefore, the experimentally obtained soil stiffness such as the following Fig. 9 (a) is calculated from taking the Fourier transform into them and from the relation of the above Eq. (16). The 'Acc. fit' in Fig. 9 (a) denotes the approximated dynamic soil stiffness for the acceleration feedback in Fig. 2.

(2) Velocity feedback

Substituting $s = i\omega$ and Eq. (9) into Eq. (15) and rearranging it with ${}_{v}S_{b}^{g}(\omega)$ leads to,

$$
{}_{v}S_{b}^{g}(\omega) = \frac{i\omega \cdot R_{b}(\omega)}{\dot{Y}_{b}(\omega) - \dot{Y}_{b}^{g}(\omega)} \tag{17}
$$

The interaction force, $R_b(t)$, the velocity at the shaking table, $\dot{Y}(t)$, and the effective ground input velocity $\dot{Y}_b^g(t)$, can be experimentally measured in the control computer, as shown in Fig. 6. Taking the Fourier transform into them and using the relation of the above Eq. (17) give the experimentally obtained dynamic soil stiffness, as shown in Fig. 9 (b). The 'Vel. fit' in the figure indicates the approximated dynamic soil stiffness for the velocity feedback in Fig. 2.



(a) Acceleration feedback (b) Velocity feedback

Figure 9. Comparison between the analytical and the experimental soil stiffness

4. CONCLUSIONS

This paper proposed the shaking table testing methods of SSI system having a soil model with the frequency-dependent dynamic soil stiffness, using the feed-back of structural response, based on the substructure method.

The shaking table was used for producing the motion at the foundation of entire SSI system comprising the building model as an experimental part and the assumed soil as a computational part.

The proposed acceleration and velocity feedback methodologies were experimentally verified in its validity by their experimental performing through reflecting the approximated dynamic soil stiffness on the control computer for the soil's effect on the superstructure.

REFERENCES

AIJ, (1996), *An Introduction to Dynamic Soil-Structure Interaction*, AIJ.(in Japanese)

Iemura, H., Igarashi, A. and Toyooka, A. (2002), "An Experiment of Full-Scale Damper Under Earthquake Using Inertia-Force-Driven Loading System with A Hypothetical Mass", *Proc. Of the 11th JEES*, pp.1643-1648.

Igarashi, A., Iemura, H. and Tanaka, H. (2002), "Substructure Hybrid Shake Table Test Using Digitally Filtered Displacement Compensation Control Scheme", *Proc. Of the 11th JEES*, pp.1637-1642.

Konagai, K., Uemura, O., Suzuki, T. and Katsukawa, T. (1998), "Real Time Simulation of Soil-Structure Interaction Effects on Shaking Tables", *Proc. Of the 10th JEES*, pp.1647-1652.

Lee, S.K. and Motosaka, M. (2004), "Shaking Table Testing Method Based on the Substructure Method Considering Dynamic Soil-Structure Interaction (1)", presented in *Proc. of Smart Structures Technologies and Earthquake Engineering.*

Motosaka, M. and Nagano, M. (1990), "BASIC INVESTIGATION ON THE EVAUATION OF INTERACTION FORCES OF UNBOUNDED SOIL IN THE TIME-DOMAIN SUBSTRUCTURE METHOD", *Proc. Of the 8th JEES*, pp.1137-1142.

Motosaka, M. and Nagano, M. (1992), "Recursive Evaluation of Convolution Integral in Nonlinear Soil-Structure Interaction Analysis and Its Applications", *Journal of Struct. Constr. Engng*, AIJ, No.436, pp.71-80.(in Japanese)

Motosaka, M. and Nagano, M. (1993), "Dynamic Partial Uplift Analysis of a Structure on a 3-D Layered Half-Space Based on Recursive Evaluation of Interaction Forces Using Dynamic Stiffness of The Unbounde Soil in the Frequency Domain", *Journal of Struct. Constr. Engng*, AIJ, No.451, pp.79-88.(in Japanese)

Robert, H. B. (2001), *LabVIEW Student Edition 6i*, Prentice Hall.