STUDY ON EVALUATION OF PARAMETERS IN THE SOIL-BUILDING SYSTEM

by

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SUMMARY

A method of evaluating parameters of an analytical simple model for a soil-building system was investigated. By comparing the results of experimental and analytical investigation, the equivalent radius of the circular foundation, the equivalent stiffness and damping coefficients of the soil in the analytical simple model were estimated. It is pointed out from the result that the shear wave velocity of soil and the effect of wave reflection at the boundary of layered soil play an important role in determining the appropriate parameters of the analytical simple model.

INTRODUCTION

Since the various parameters related to interaction effects are involved as a whole in the earthquake response of buildings, it is necessary to evaluate separetely each of parameters used in the analytical model. The purpose of this study is to evaluate these parameters for improving the dynamic desing method of buildings through the analytical and experimental investigations.[1)]

It is mainly intended in this paper to estimate the equivalent radius of foundation, the equivalent stiffness and damping coefficients of soil in the analytical simple model resting on a half space elastic medium, by comparing the results of the analytical and experimental investigations. The experimental investigation using a vibraor was carried out to detect the dynamic properties of the simple test model. And, the effect of wave reflection at the boundary of the layered soil as practical underground structure was examined using the two dimensional finite element model for further development in this kind of study.

MODELING OF THE SOIL-BUILDING SYSTEM

In order to know the contribution of each of parameters to interaction effects, the analytical simple model resting on a half space elastic medium was selected. This model has three degrees of freedom which are known as swaying, rocking and relative displacement of model, taking account of the compliance theory by G.N. Bycroft.[2)] The displacement due to these three modes are expressed in terms of the steady-state input wave (Ug) on ground surface as shown in Fig. 1.[1)] Five nondimensional parameters which are considered to be suitable to examine the interaction effects were rearranged as shown in Table 1.

In order to investigate the effect of each of the parameters mentioned above, the maximum magnification factor for swaying, rocking,relative and total displacement ($MMF_{X,Y,Z,T}$) were calculated under the condition that one parameter was variable while others being kept constant as illustrated

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in Fig. 2. For example, the effect of the rigidity ratio ($a=w_0R/V_E$) on the MMF was shown in Fig. 3, where w_0, R and V_E mean the undamped natural frequency of the analytical simple model, the equivalent radius of foundation and the equivalent shear wave velocity of soil, respectively. The influence of the rigidity ratio on the maximum magnification factor of the total displacement (MMF_T) is large in the range of small value of the rigidity ratio. This result means that the equivalent radius (R) and the equivalent shear wave velocity of soil (V_E) included in the rigidity ratio have much influence on the response of the building.

OUTLINE OF SUBSOIL AND TEST MODELS

Subsoil - The Fuchinobe district, Kanagawa prefecture near Tokyo was selected as an experimental site. The subsoil below the test model consists of a few layers. The soil profile, the results of the penetration test and the seismic prospecting test, the densities and the poisson's ratio of layerd soil are shown in Fig. 4.

Test models - The test models employed in this experiment are reinforced concrete mat foundation resting on the relatively simple layered soil, sizes of which are 2m x 2m (Model B), 2m x 2m (Model C) and 4m x 4m (Model A_0) with 1m thick. Fig.5 shows a plan and section of these models. In this figure, A_0 indicates the mat foundation and A_4 indicates the test model structure constructed on A_0, having four steel pipe columns and braces. The apperance of the test model B and A_4 are shown in Phto. 1.

DYNAMIC CHRACTERISTICS OF TEST MODELS

Outline of Experiments - Forced vibration tests using a vibrator resting on the center of the mat foundation were performed to ascertaine the dynamic chracteristics of the test models. Characteristics and capacities of equipments used in the forced vibration test are as follows; The vibrator is of rotating mass type enable to vibrate in two horizontal and one vertical direction, with the maximum vibrating power of 3,000kg (at over 17 Hz), the frequency range of 1 to 40 Hz , and the weight of about 900kg, having an equipment for generating a rectangular pulse every rotation of an eccentric mass of the vibrator. The seismograph for measuring displacements has a natural frequency of 1 Hz and a damping constant of 0.67.

The experiments in the three directions were carried out being applied by the various level of the constant exciting force. Experimental series were named by the test models and vibrated direction, for an example, such as BX, which means that model B was vibrated in horizontal X (EW) direction. The order of the experiments is shown in Table 2.

Table 2 Order of Experiments

series \ order	1	2	3	4
AX	1000kg	—	—	—
AY	1000kg	—	—	—
BX	100kg	500kg	100kg	—
BY	100kg	200kg	—	—
CX	200kg	500kg	1000kg	200kg
CY	200kg	500kg	200kg	—

Results of Experiments - The resonant curve and the phase lag between the exciting force and the displacement of the test model B are shown in Fig. 6 and Fig. 7. As shown in these figures, resonant frequency decreases with the increase of exciting force, and phase lag is about 90° at the resonant frequency. Similar results were obtained from the test model C. Fig. 8 shows the phase lag between the exciting force and the displacements of top and base mass of the test model A_4. As shown in this figure, the top and the base mass move in phase untill a little over first resonant frequency(f_1) of 5.7 Hz, but each mass moves out of phase in the range over 8.5 Hz. Relations between the exciting force and the resonant frequencies, the resonant amplitudes, the damping constants and the vibration modes to total displacements are shown in Fig. 9 to Fig. 12. Damping constants are obtained from the half power method. Vibration modes are measured at the gravity center of the foundation and vibrator. In these figuers, small circles and rectangles mean the results obtained from the last experiment of each series.

Main results obtained are as follows; 1) Resonant frequency and damping constant of these models decrease slightly with the increase of exciting force except damping constant of the test model B. 2) Displacement at resonant frequency increase parabolically with the increase of exciting force. 3)Displacement of swaying to total displacement on the foundation is predominant and independent on the increase of exciting force. Strain level of soil calculated by using the shear wave velocity of soil beneath the test models under the exciting force of 200kg were pressumed to be about 1.2, 0.6 and 0.36 x 10^{-4}, in case of the experiments BY,CY and CX, respectively. It can be considered that the soil behaves elastically through the experiments.

EVALUATION OF VARIOUS PARAMETERS

Among the five parameters shown in Table 1, the equivalent radius of foundation, the stiffness and the damping coefficients of soil in the analytical simple model have much influence on the response of the soil-building system as shown in Fig. 3. Displacements, frequencies and phase lags between the exciting force and displacements of the test models were measured. But, pressure distributions beneath the foundation was not measured. So some assumptions should be introduced in the analytical simple model. The evaluating method were investigated, under an assumption of three types of a pressure distribution, where the equivalent shear wave velocity of soil were determined by averaging the shear wave velocities of soil layers within the width of foundation obtained by the prospecting test.[1)]

Equivalent Radius of Foundation - In order to estimate the analytical equivalent radius, the pressure distribution beneath the foundation and the equivalent shear wave velocity should be known. In this study pressure distribution is pressumed to be the following three types, the one produced by a rigid base, uniform loading and parabolic loading. Shear wave velocity is assumed to be constant to infinite as a half space elastic medium.

The radius is calculated as the horisontal and the rotational spring constant of a circilar foundation correspond to ones of a rectangular foundation, in accordance with a horizontal and rotational motions, respectively.

The equivalent radius of foundation can be determined by adopting the radius thus calculated considering the contribution of the swaying and rocking mode shapes. A relation of the half of the width of rectangular foundations and the equivalent radii of circular foundations under the assumptions of three types of pressure distribution are shown in Fig. 13. In case of square foundation (test model A_0 and B), the equivalent radii are not influenced by the difference of pressure distributions, while, in case of rectangular ones (test model C), they are influenced moderately.

Reflection of waves at the boundary of soil layers has little influence on a frequency characteristics of the response. So, pertinency of the method of determining the equivalent radius can be estimated, by comparing the resonant frequencies obtained from the analytical model with ones obtained from experiments. Fig. 14 shows the relation of the experimental and the calculated resonant frequencies of the response. Close agreement between the experimental and the analytical resonant frequency is obtained. It is pointed out from these results that the evaluation of the analytical equivalent radius of foundation mentiond above is appropriate under the assumption of the pressure distribution produced by a rigid base.

Equivalent Stiffness and Damping coefficients of Soil - Certain amounts of disagreement is seen between the amplitude chracteristics of the analytical model and those of the forced vibration test for the test model A_0 as shown in Fig. 15. The two result differ in the amplitudes by 40% at the resonant frequency. On the other hand, good agreement is seen in the resonant frequency between them. In the previous study[1], it was pointed out that one of the main reason for the disagreement might be the effect of wave reflection at the boundary of soil layers. To estimate the effect of wave reflection, the two dimensional finite element model shown in Fig. 16 was employed,as the first step.[3] Fig.17 shows that response of a foundation resting on a layered soil are larger than that of a foundation resting on half space elastic medium, where R and D mean the equivalent radius of the circular foundation and the depth of the first soil layer, respectively. As shown in Fig. 17, the maximum influence of the effect of wave reflection took place at $D/R = 1.5$. If this value is applied to modify the amplitude chracteristics, good agreement will be obtained between the analytical and the experimental results at resonant frequency. These tendencies were obtained from the results from the test model B amd C.

The experimental stiffness and dampling coefficients were obtained from the displacement of the foundation and the phase lag between the exciting force and the displacement. Fig. 18 shows the results of the experimental and the analytical stiffness and damping coefficients for the test model B. The analytical stiffness coefficients were obtained from the analytical simple model resting on a half space elastic medium under the assumption of three types of pressure distributions. The experimental and the analytical stiffness and damping coefficients for test model B and C at the resonant frequency are shown in Fig. 19 and Fig. 20. As shown in Fig. 19, the analytical horizontal stiffness coefficients under the assumption of a parabolic pressure distribution coinside with the experimental ones. As shown in Fig. 20, the analytical damping coefficients are larger than the experimental ones. From these results, the effect of wave reflection at the boundary of soil layers is important in case of evaluating the equivalent stiffness and damping coefficients. By considering this effect refered to Fig. 15, analytical stiffness and damping coefficients under the assumption of a parabolic pressure distribution agree fairely with the experimental ones.

It seems to be contradictory that assumption of pressure distribution used in determining the equivalent radius differs from that used in detemining the equivalent stiffness and damping coefficients. This can be considered as follows; The discrepancy results from the uncertainty in determining the equivalent shear wave velocity of soil (V_E). V_E was determined by averaging the shear wave velocities of soil layers within the width of foundation obtained by the seismic prospecting test. V_E thus determined is the major factor for determining the dynamic characteristics of the analytical simple model. By employing V_E in the analytical simple model, other parameters, such as the pressure distribution beneath the foundation, should be changed from the practical one. The analytical frequency characteristics agreed well with the experimental ones. But, the analytical amplitude are smaller than the experimental ones by 40%. So, it may be unsuitable to employing V_E determined by the method mentioned above, under strain level caused by the forced vibration test.

CONCLUDING REMARKS

Various parameters in the analytical simple model was evaluated by comparing the analytical and the experimental results. Main results of this study are as follows;

1) The analytical equivalent radius of a circular foundation for square or rectangular foundation can be determined, by considering the contribution of swaying and rocking mode to the total displacement under the assumption of the pressure distribution produced by the rigid base. The resonant frequencies obtained from the analytical simple model agree fairly well with the one obtained from experiments. It is pointed out that the determining the equivalent shear wave velocity of soil is important.

2) The analytical equivalent stiffness and damping coefficients at the resonant frequency can be determined under the assumption of the pressure distribution produced by the parabolic loading. However, these coefficients should be modified by considering the effect of wave refrection at the boundary of soil layers.

From these results, the analytical simple model employed in this study is one of the useful model to analyse the earthquake response of the soil-building system. In order to make this model more realistic, that is to eable to represent the effect of wave refrection at the boundary of soil layers, the more improved analysis is now under investigation.

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Table 1 Arrangement of Parameters

Step of Arrange.		Building Characteristics				Soil Characteristics		Input Wave Char.
Parameters	I 1)	k, m_1		h	$2b, 2c$	ρ	V_s	p
	II 2)	C, ω_0	M_1, M_0	H	R	ρ	V_E	p
Nondimensional Parameters	I 3)	$h_0 = \frac{C}{2M_1\omega_0}$	$\alpha = \frac{M_0}{M_1}$	$\eta = \frac{H}{R}$	$\beta = \frac{M_1}{\rho R^3}$	$a_0 = \frac{pR}{V_E}$	In the case of Resonance → $a_0 = \frac{\omega R}{V_E}$	
	II 4)	$h_0 = \frac{C}{2M_1\omega_0}$	$\alpha = \frac{M_0}{M_1}$	$\eta = \frac{H}{R}$	$\beta' = \frac{M_1}{\rho R^2 H}$	$a = \frac{\omega_0 R}{V_E}$	$\zeta = \frac{\omega_0}{\omega}$	
		Structural Damping	Building's Mass Ratio	Building's Shape Ratio	Effective Mass Ratio	Rigidity Ratio	Elongation of fundamental periods of S.F.B. system	

1) Measured Parameters 2) Equivalent Parameters in the FUNDAMENTAL MODEL
3) Arrangement of Past Studies 4) Rearrangement presented in this study

5) $\beta = \frac{M_1}{\rho R^3} = \frac{M_1}{\rho R^2 H} \cdot \frac{H}{R} = \beta' \cdot \eta$ 6) $a_0 = \frac{\omega R}{V_E} = \frac{\omega_0 R}{V_E} \cdot \frac{1}{\omega_0/\omega} = \frac{a}{\zeta}$

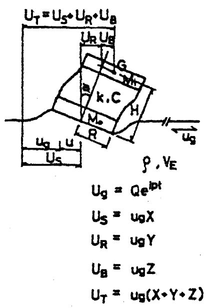

Fig. 1 Analitycal simple model

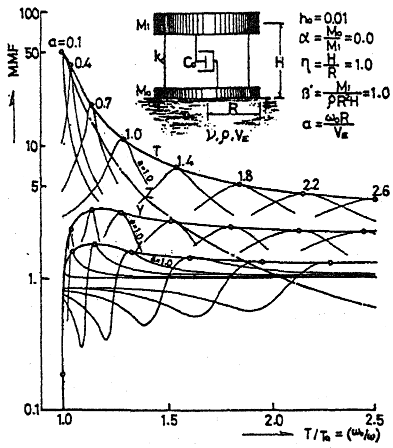

Fig. 2 Maximum Magnification Factor

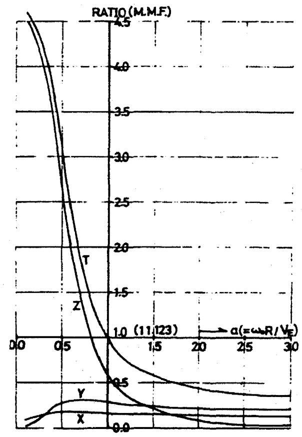

Fig. 3 Relation between MMF and Rigidity Ratio

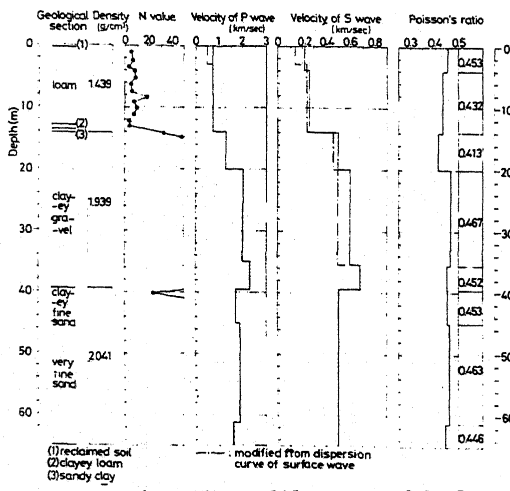

Fig. 4 Soil profile at Huchinobe

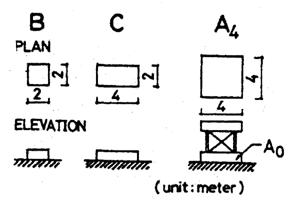

Fig. 5 Plan and Elevation of Test Models

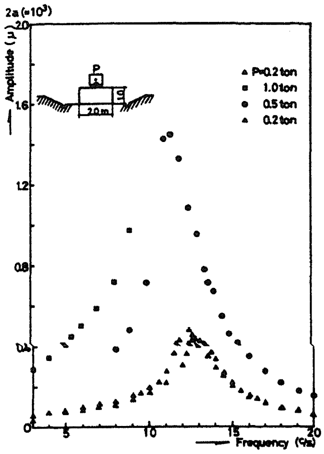

Fig. 6 Resonant Curve of Test Model B

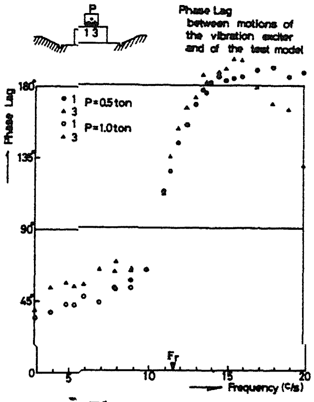

Fig. 7 Phase Lag between exciting Force and Displacement of Test Model B

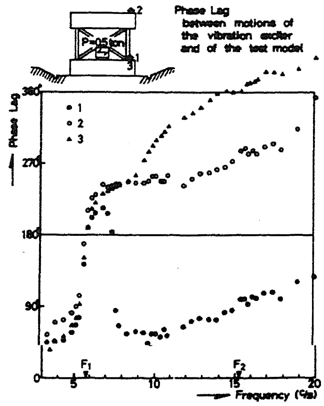

Fig. 8 Phase Lag between exciting Force and Displacement of Test Model A4

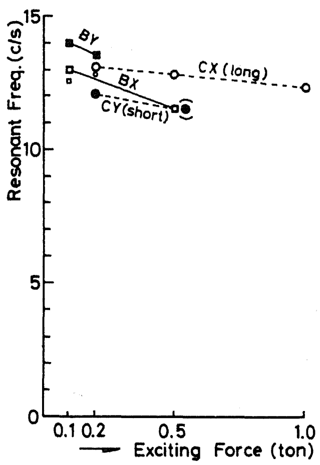

Fig. 9 exciting Force and Resonant Frequency

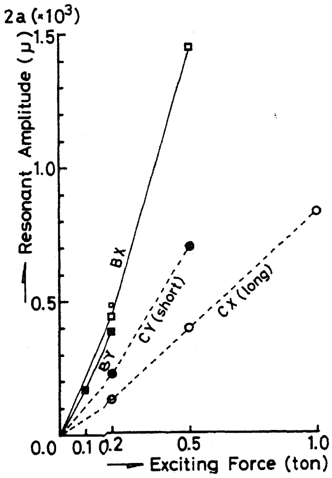

Fig. 10 exciting Force and Resonant Amplitude

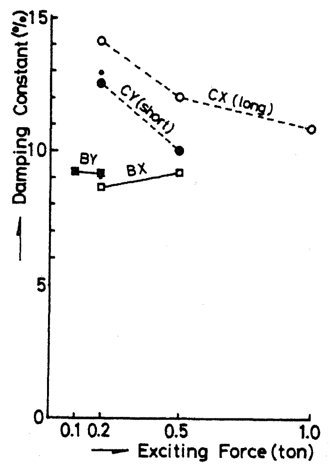

Fig. 11 exciting Force and Damping Constant

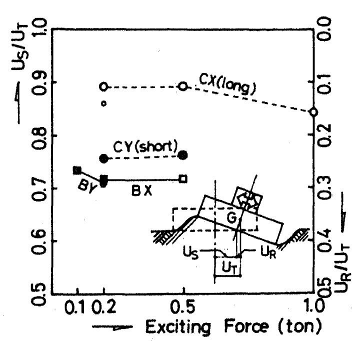

Fig. 12 exciting Force and Vibration Mode

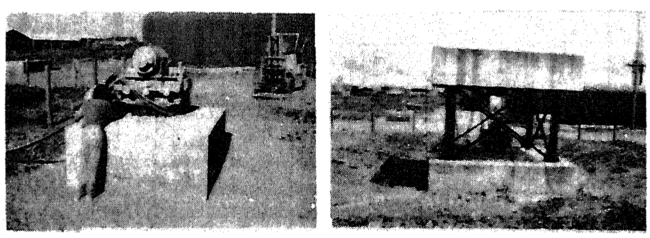

Photo 1 View of Test Model B and A_4

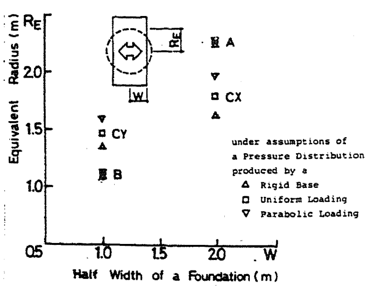

Fig.13 Equivalent Radius of Foundation of Test Model

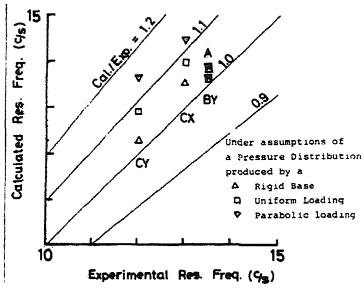

Fig.14 Comparison of Experimental and Analytical Resonant Frequency

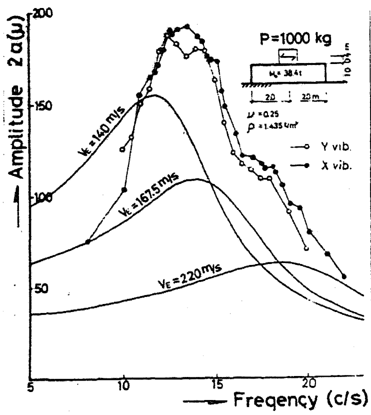

Fig.15 Experimental and Analytical Resonant Curve

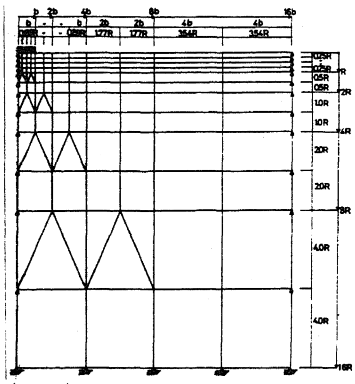

Fig.16 Two dimentional FEM Model

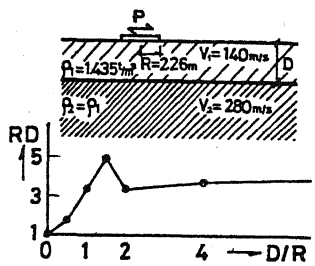

Fig.17 Effect of Wave Reflection at Boundary of Soil Layers

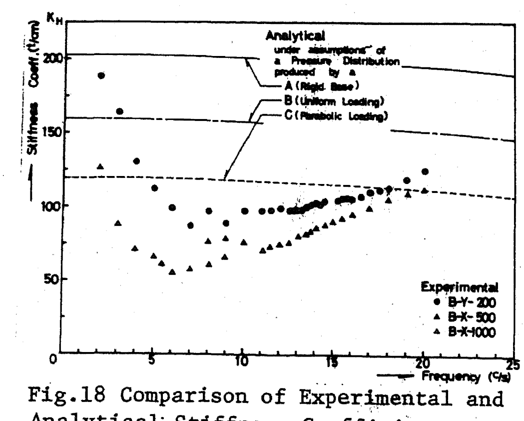

Fig.18 Comparison of Experimental and Analytical Stiffness Coefficients of Test Model B

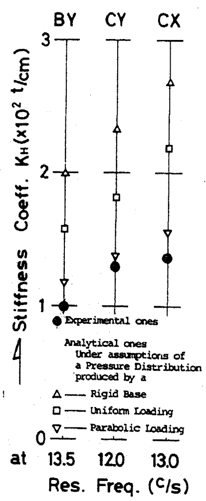

Fig.19 Experimental and Analytical Stiffness Coefficients

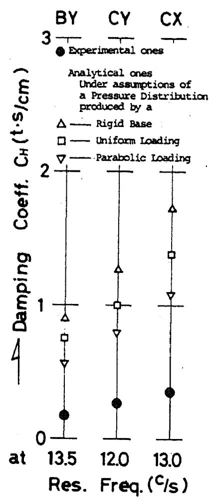

Fig.20 Experimental and Analytical Damping Coefficients