RESPONSE ANALYSES OF EARTHQUAKE MOTIONS OBSERVED IN AND AROUND A REINFORCED CONCRETE BUILDING INCLUDING BUILDING-SUBSOIL SYSTEM

by

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SYNOPSIS

The recorded accelerations of an actual six story building and its surrounding subsoil during minor and moderate earthquakes were compared with those obtained from the computation using some proposed soil-structure interaction models. A fairly good agreement was seen between frequency characteristics of recorded and computed accelerations. Since it was difficult to justify each of model constants used in the computation because of this limited observation system, the influences of the variation in these constants on the interaction effects were evaluated using the ground compliance model and from the results a comment was given of the future observation projects for soil-structure systems.

INTRODUCTION

It has been widely recognized that soil-structure interaction is one of the most important problems in the field of earthquake engineering. Although considerable methods of theoretical and numerical approaches to this problem have been presented, very few recorded data have been made available.

For the purpose of providing recorded earthquake motions of an actual soil-structure system, the main building of the Earthquake Research Institute and its surrounding subsoil were instrumented with a large number of seismographs. The outline of the test building and the subsoil as well as the instrumentation are described in a previous paper(1). Since 1964, a great amount of records has been accumulated from this long-term observation project, and it is now possible to interprete these records by means of analytical investigation using some realistic models for soil-building interaction system.

This paper first presents the results of comparison between recorded and computed earthquake motions in and around the ERI building (test building). The interaction models employed in this study are a lumped mass model, a finite element model, a one-dimentional wave propagation model and a soil-structure model with consideration of dynamic ground compliance (ground compliance model). And further, the influence of various parameters on the interaction effects is examined using the ground compliance model for the purpose of planning further development in this kind of observational study.

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OUTLINE OF THE BUILDING AND SUBSOIL

The test building is a six-story reinforced concrete structure with one basement story. It is 15.8m x 84m in plan as shown in Fig. 1. The west part of the building was first constructed during 1962-1963 and extensions were made three times up to 1970. Each construction stage is indicated in Fig. 2.

Forced vibration tests using a vibrator, simultaneous measurements of microtremors at the top and bottom of the building as well as theoretical analyses of the horizontal rigidities of the building were performed to ascertain the dynamic characteristics of the test building. The results are shown in Table 1 for construction stage III.

The subsoil below the test building consists of several layers. They are the Kanto loam layer, alternative layers of fine and sandy loam, alternative layers of fine sand and silty or clayey sand, and a gravel layer, in order from the surface. The water level is 8.8m below the ground surface. The soil profile and penetration test results (N-value) are shown in Fig. 3.

The S-wave velocities of the various soil layers were determined by means of explosion tests,the results being shown in Fig. 4. The densities of various soil layers obtained from boring tests are also shown in the same figure. Fig. 5 shows the values of transfer function H(jw) versus frequency calculated by the use of Haskel's method(2) assuming that SH-waves are propagated and reflected only in the vertical direction.

EARTHQUAKE OBSERVATION AND DYNAMIC MODELS

Earthquake observation

The locations of seismometers in the building and underground are shown in Fig. 6. Seismometers A, B, C, D, and E are placed along the vertical line from the top of the building to the soil layer 42m below the surface. Seismometers F, G and H are also arranged along a vertical line 60m south from the abovementioned group. The locations of these instruments were selected to achieve two objects. The first object was to learn: (1) modifications of ground motions in accordance with depth of soil; (2) the characteristics of the soil-building interaction system; (3) the characteristics of the soil layers and of the structure by comparing the records obtained from each group along the vertical lines. The second purpose was to learn: (1) effect of the building on the soil and the variation in this effect with distance from the building, (2) the characteristics of boundary conditions between building and soil layer and so on, by comparing the records of the two groups on the same level of a horizontal line. Seismograms of 29 earthquakes (Intensity I - III in JMA scale) were recorded until 1972 (see Fig. 7), an example which is shown in Fig. 8.

Dynamic models and earthquake input

The vibration characteristics of a building including the supporting ground during an earthquake can be resolved into those of two independent systems and an additional one representing the interaction effect between the building and the ground, that is,

1. Characteristics of the ground itself,
2. Characteristics of the building itself, and
3. Characteristics caused supplementally by the fact that the building is supported on the ground.

These characteristics should be considered when analyzing the soil-building system during an earthquake.

It is also pointed out that the type of analytical model should be selected in accordance with the location of input earthquake motion. When calculating the response of an actual building to the earthquake records obtained through a simultaneous observation system, the relationship between the model and the input in the proposed methods of analysis can be classified into the following three cases (see Fig. 9): for the records obtained (a) at the bottom of the building, (b) at the ground surface not affected by vibration of the building, and (c) underground at considerable depth.

In case of (a), it is sufficient to consider the characteristics of the building only as the other two characteristics are already included in the records. Fig.10 illustrates the Fourier spectrum of computed acceleration (response) at the top of the building as an example. Since the characteristics of the ground are included in the records in case (b), only the rest of the characteristics should be considered. In case of (c) all the characteristics should be considered except those of the ground below the observation point.

Comparison between observed and computed accelerations

To compare the observed accelerations with computed ones, three kinds of models were employed in this study. These were a one-dimensional wave propagation model, a finite element model, and a model in which the interaction effect was considered by introducing the dynamic ground compliance. The comparisons were mainly made in the frequency domain using Fourier spectra, as it presents the characteristics of the system in a suitable form.

The main results obtained from the comparisons are as follows:

(1) Ground compliance model

The fundamental functions of the ground compliance by Bycroft[3] were used in the computation after reducing the multi-mass system to a single-mass system. In this model the equivalent circular base was determined so that it had the same moment of inertia and base area as those of the rectangular base of the test building[4]. The Fourier spectral ratios between the accelerations at the base of the building (BA) and at the ground surface (GL) are shown in Fig. 13 for observed and computed accelerations. It can be seen in this figure that the periods at peaks and valleys between 0.3 to 0.4 sec are almost the same for both computed and observed ones, although the ratios take different values. The period at peak point indicates the one including the effect of rocking and swaying motions while the period at valley indicates the one including the effect of rocking motion.

(2) Wave propagation model

The constants used in this model were determined based on the results of forced vibration tests and seismic prospecting. A comparison was made between the frequency characteristics of accelerograms at the -42m level

for observed and computed ones. There was some disagreement between them in this comparison. It was intended thus to make modifications on the rigidities and densities for the layer representing the building and the first soil layer so as to approximately satisfy the compatibility at the boundary. As the result of the modifications a good agreement was obtained as shown in Fig. 14.

(3) Finite element model

This model consisted of numerous finite elements and a mass-spring system representing the ground and the building respectively. The constants of the model were again determined based on various test results. The Fourier spectral densities of the accelerograms at the top of the building for observed (solid line) and computed (dotted line) ones are shown in Fig. 15. They are fairly close to each other within the period range of 0.1 to 1.0 sec.

The above comparison was made under the assumption of identical incident waves at the point at the -41m level beneath the test building (E) and at the point at the -42m level 60m distant in the horizontal direction from the building (H). For the purpose of checking the validity of this assumption, the incident waves at both points were made from the observed records with the aid of the wave propagation theory. The Fourier spectral densities of these waves are shown in Fig. 16. It can be said that the shapes of both curves are quite similar.

AMPLIFICATION CHARACTERISTICS CONSIDERING INTERACTION EFFECTS

Parameters influencing interaction effects

In order to know how much the various related parameters contribute to interaction effects, some parametric studies were made on a subsoil-building system having the following conditions: (1) all stories and the foundation of the building have the same cross-sectional area, (2) all story heights of the building are the same (3) the mass per unit area of the building is constant, and (4) the building rests on a half-space elastic medium.

According to the equation of motion, displacements are expressed in terms of the input wave Ug and the corresponding magnification factor as follows:

$$U_B = X \cdot U_g \ , \quad U_\phi = Y \cdot U_g \ , \quad U_S = Z \cdot U_g \ , \quad U_T = (X + Y + Z) \cdot U_g$$

where X, Y and Z are complex magnification factors. The final equation for three degrees of freedom, namely horizontal displacement at the top M_t, horizontal displacement at the bottom M_B and rotation about a horizontal axis through ϕ , is as follows:

$$(1+\alpha+A_1+iA_2)\cdot X + Y + Z = A_1 + iA_2$$
$$X + (1 + \frac{1+\alpha}{4\eta} + B_1 + iB_2)\cdot Y + Z = 0$$
$$X + Y + (1-(\frac{w}{p})^2 - 2hi(\frac{w}{p}))\cdot Z = 0$$

$$A = \frac{M_T p^2}{\beta}(A_1 + iA_2) \ , \qquad B = \frac{M_T p^2 H^2}{\beta \eta}(B_1 + iB_2)$$
$$A_1 = f_{1H}/a_0^2(f_{1H}^2 + f_{2H}^2) \ , \qquad A_2 = -f_{2H}/a_0(f_{1H}^2 + f_{2H}^2)$$
$$B_1 = f_{1R}/a_0^2(f_{1R}^2 + f_{2R}^2) \ , \qquad B_2 = -f_{2R}/a_0(f_{1R}^2 + f_{2R}^2)$$

where $\alpha = M_B/M_T$, $\eta = (H/R)^2$, $\beta = M_T/\rho_{soil}R^3$, h = structural damping, W = undamped natural frequency of the structure, P = circular frequency of the force, R = radius of the base, V_s = shear wave velocity of soil layer, $a = PR/V_s = WR/V_s$. $1/(W/P)$, f_1, f_2 = fundamental function of the ground compliance obtained by Bycroft.

The following variables as parameters were used to examine the characteristics of the model:

h = structural damping ratio

β = mass ratio

H/R = slenderness ratio

W/V_s = rigidity ratio

Characteristics of maximum amplification factor

To investigate the effects of the above parameters h, H/R, and β, the maximum amplification factors Y, Z and T were calculated for various combinations of the model properties. The envelope curves of these typical responses are shown in Figs. 17 and 18. For different values of the response frequency ratio (W/P_R), where P_R means response frequency including rocking and swaying motions, and the value of (W/P_R) is derived from the relation between (WR/V_s) and (H/R). Judging from these figures, general tendencies were observed as follows:

1. Structural damping (h) has a direct influence reducing the magnification factors. However, its influence decreases extremely as frequency ratio (W/R_R) increases.

2. The slenderness ratio H/R has much influence on rocking motion (Z) and all magnification factors increase with (H/R) as (W/P_R) increases.

3. The influence of the mass ratio (β) is small for the magnification factor in comparison of (h) and (H/R). Because for given (H/R) and (WR/V_s) the increase in (W/P_R) tends to cancel the effect on the amplification factor, the major effect is to modify the fundamental period of vibration of the system.

Variation of amplification

The data accumulated in the same observation system make it possible to statistically evaluate the response of the system to earthquake motion. It was intended to examine whether or not statistical treatment is necessary in establishing the method of computation of earthquake responses.

Power spectral ratios are shown in Fig. 19 for transfer function of building versus frequency, where average value $X = \frac{1}{n}\Sigma X_i$ and standard deviation value $\sigma = \frac{1}{n}\Sigma(\bar{X}-X_i)^2$. It is pointed out from this figure that some statistical consideration must be introduced in order to determine the parameter of transfer function, structural damping, amplification factors, etc. On the other hand, a comparison in the form of power spectral ratios was made between the observed data at -42m level below the building and at -41m level below the free surface 60m distant from the building as shown in Fig. 19a. It can be said from the results that incident waves at -42m and -41m level are almost same in the frequency characteristics except the period range shorter than 0.2 sec.

CONCLUDING REMARKS

The recorded accelerations of an actual six story building and its surrounding subsoil during earthquakes were compared with those obtained from the computation using several soil-structure interaction models. The results can be summerized as follows:

(1) When utilizing the one-dimensional wave propagation model, it is required to modify the rigidities and densities both for the layer representing the building and for the first soil layer so as to approximately satisfy the compatibility at the boundary between the soil and the building.

(2) About 10% difference was observed between recorded predominant periods in the recorded accelerograms and the natural periods of the finite element model. There are also some differences in the response of the building between recorded and computed.

(3) Good agreement was seen between frequency characteristics of recorded accelerograms and computed ones using the ground compliance model near the natural frequencies of the building including either rocking and swaying or rocking only, but agreement was not so good between recorded and computed spectral amplitudes.

In the comparative studies mentioned above, it was difficult to justify each of model constants used in the computation since the various factors were involved as a whole. Therefore, a parametric study was made to examine the influence of variation in these model constants taking the damping of the building (h), height to width ratio (H/R) and mass ratio (β) as parameters. From the result of this study it is pointed out that other observation systems than the present one should be planned to justify the various constants in the soil-structure interaction models, and the selection of site and building should be made based on the result of above parametric study.

ACKNOWLEDGMENT

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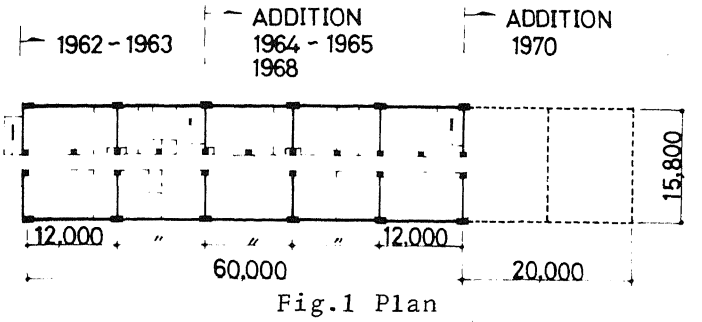

Fig.1 Plan

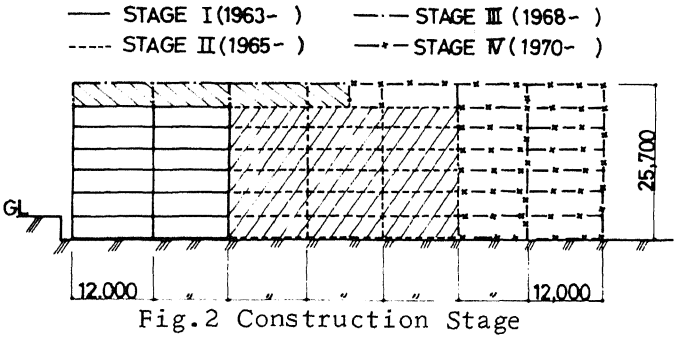

Fig.2 Construction Stage

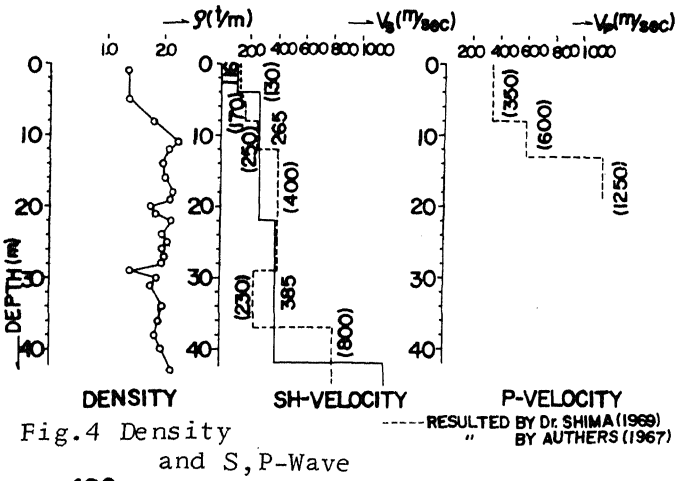

Fig.4 Density and S,P-Wave

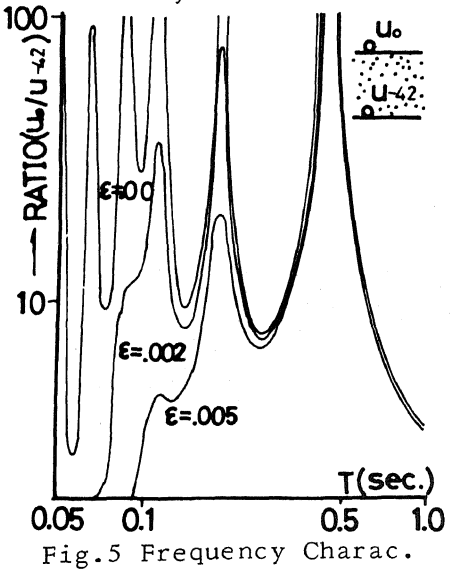

Fig.5 Frequency Charac.

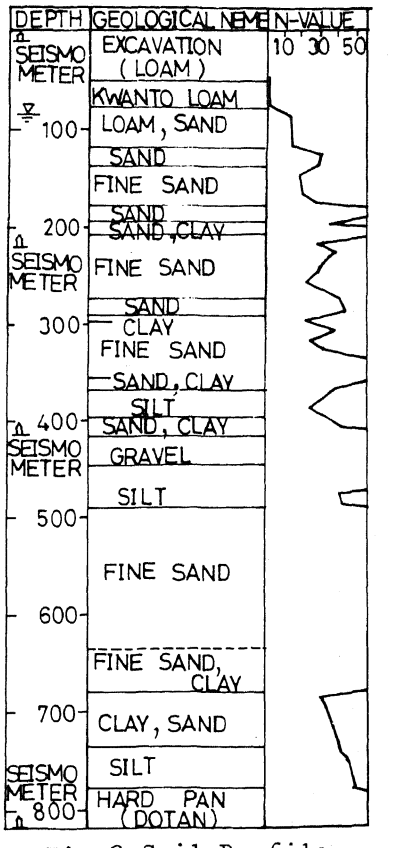

Fig.3 Soil Profile

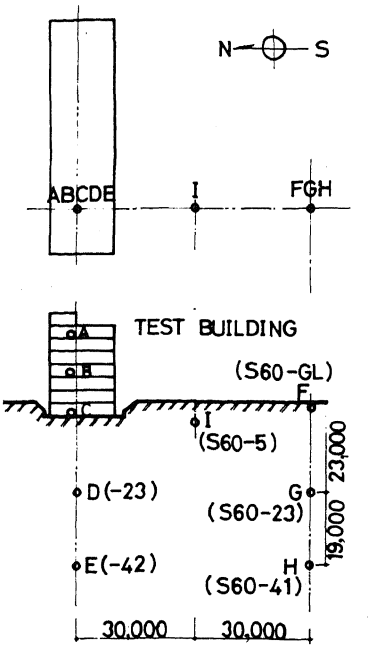

Fig.6 Location of Seismometers

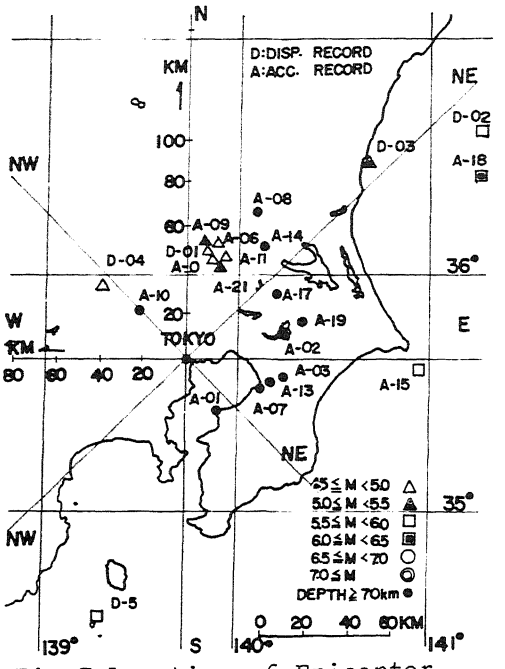

Fig.7 Location of Epicenter

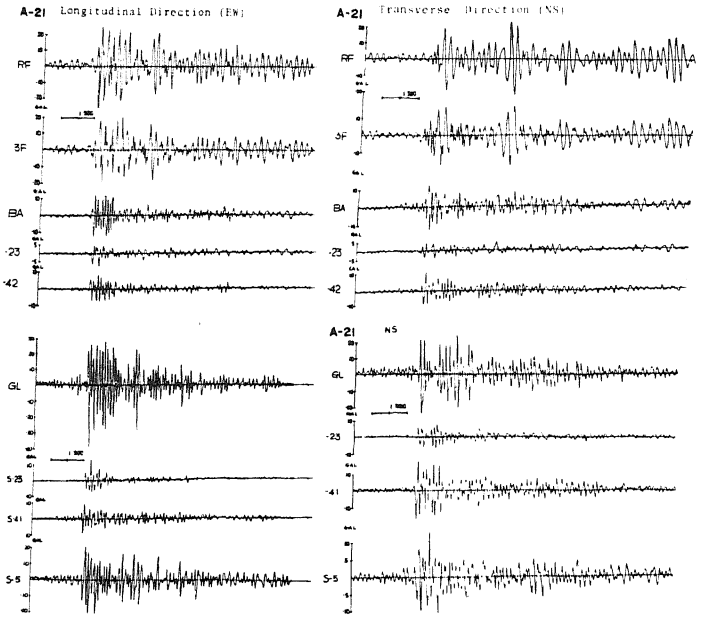

Fig.8 Acc. Records

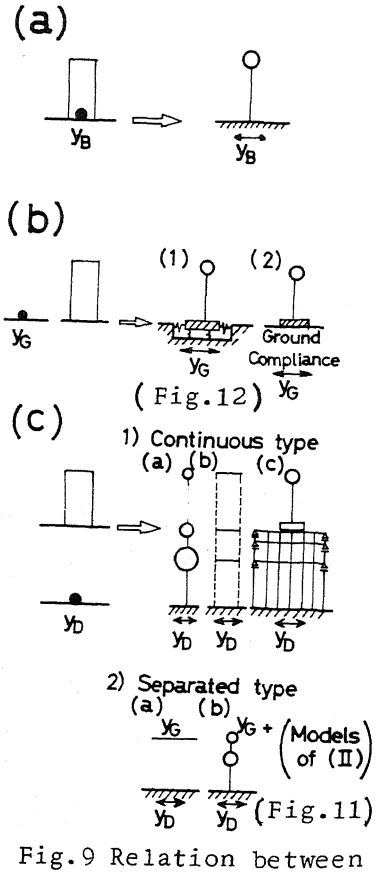

Fig.9 Relation between Model and Input

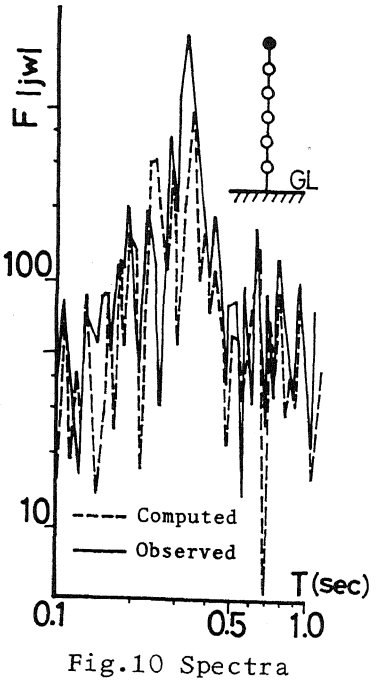

Fig.10 Spectra

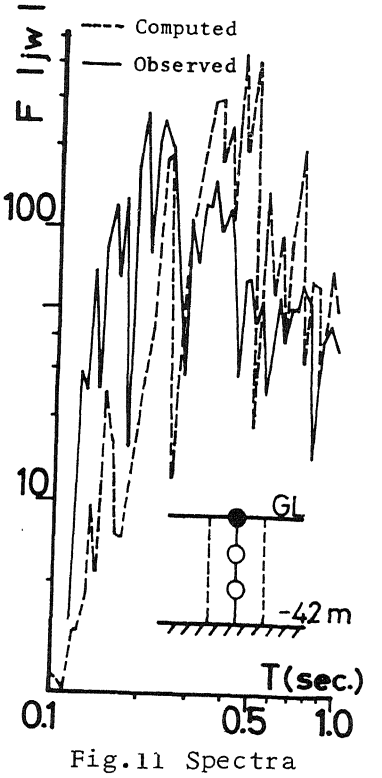

Fig.11 Spectra

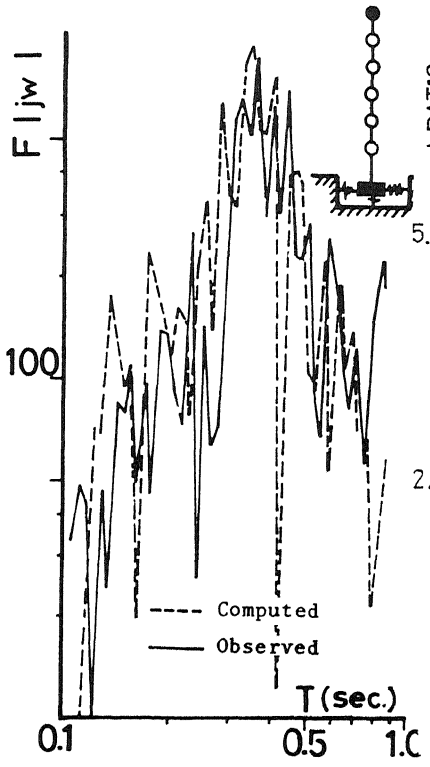

Fig.12 Spectra

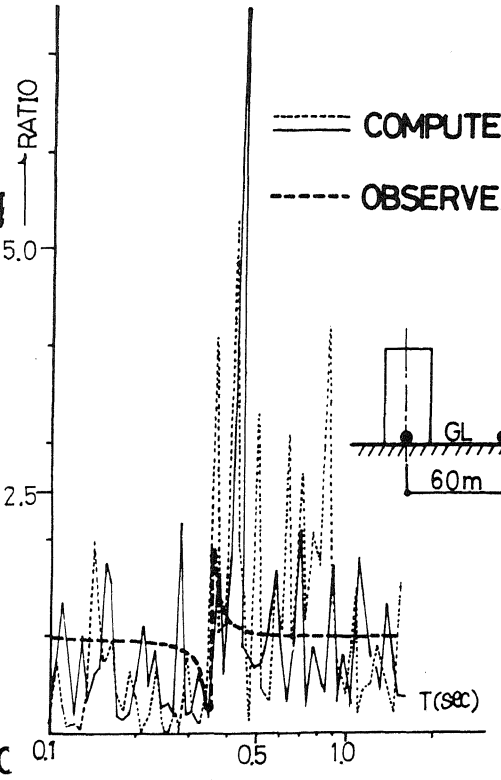

Fig.13 Spectral Ratio

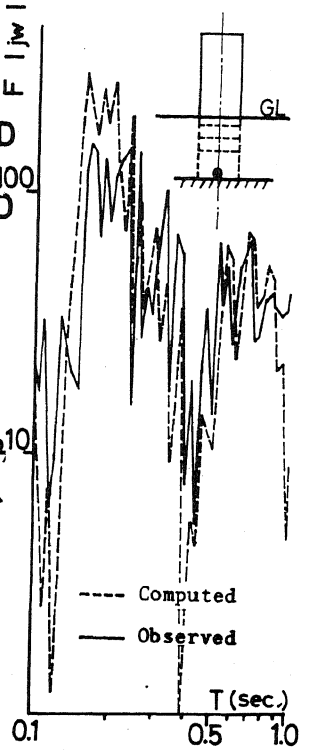

Fig.14 Spectra

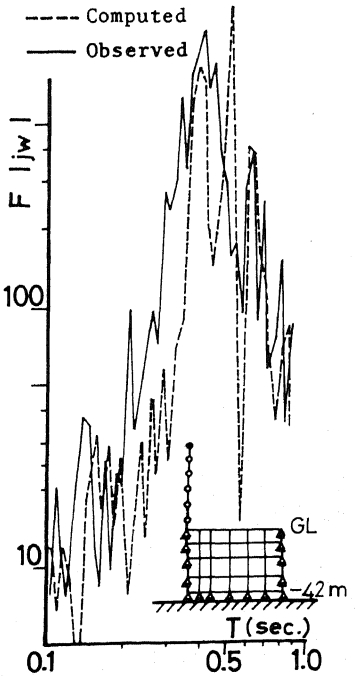

Fig.15 Spectra

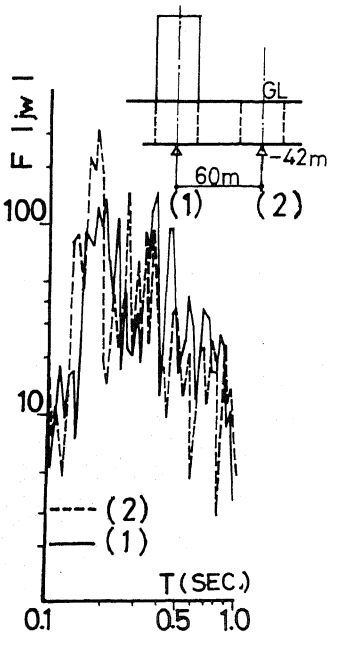

Fig.16 Spectra

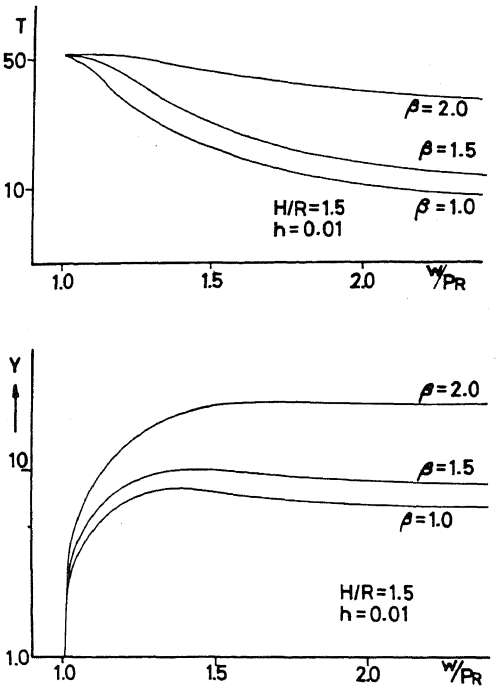

Fig.17 Maximum Magnification Curves

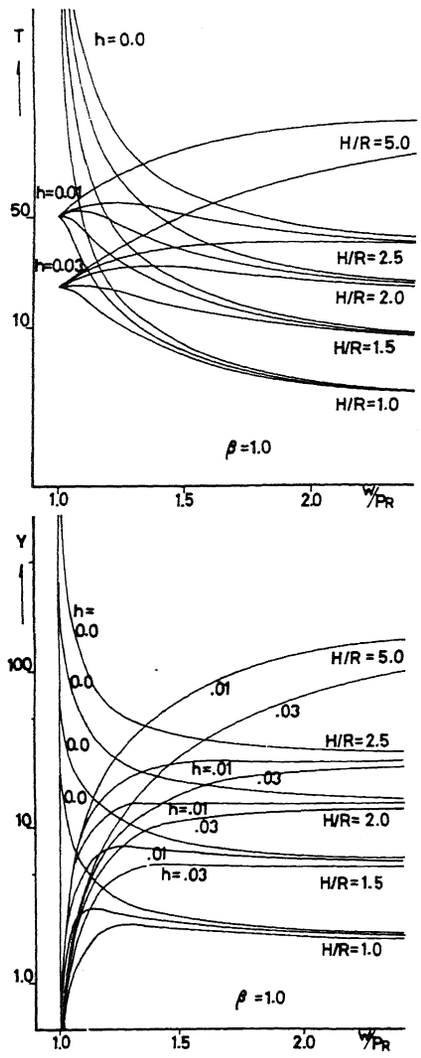

Fig.18
Maximum Magnification Curves

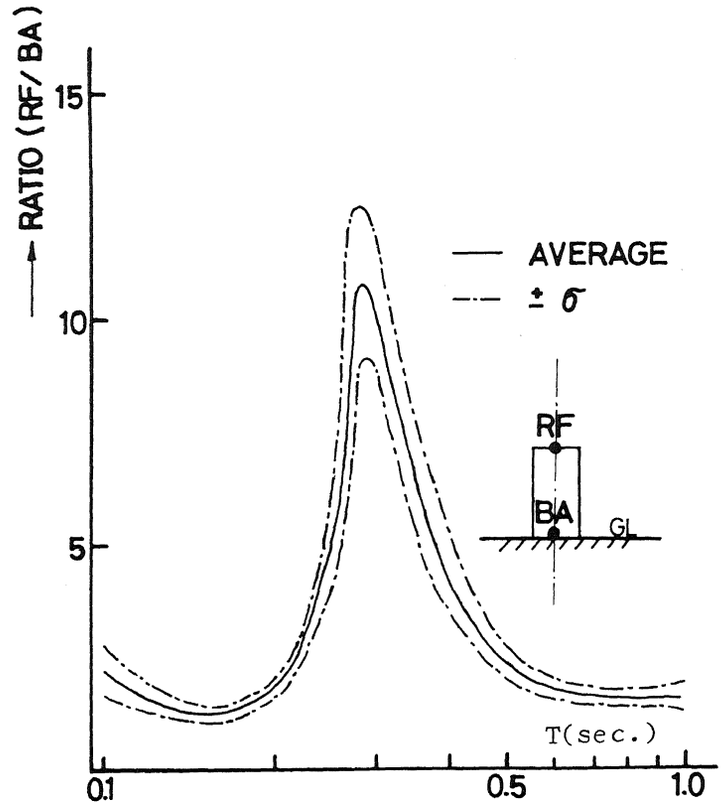

Fig.19 Variation of Spectral Ratio

Table.1 Result of Experiment and Observation

RESULTS OF VIBRATION TEST

DIRECTION	PERIOD (sec)			RATIO OF MODE SHAPE		DAMPING FACTOR
	1	2	3	ROCKING	SWAY	
LONGITUDINAL	0.35 0.10	0.33	0.31	9.2 %	11.0 %	0.08
TRANSVERSE	0.36 0.08	0.34	0.24	40.0 %	10.0 %	0.06

1: PERIOD INCLUDING ROCKING AND SWAY

2: PERIOD INCLUDING ROCKING

3: FOUDAMENTAL NATIONAL PERIOD

VALUE OF PERIODS OBTAINED BY EARTHQUAKE OBSERVATION

	LONGITUDINAL DIRECTION			TRANSVERSE DIRECTION		
	RF/BA *	S60-GL/S60-41	RF/42	RF/BA *	S60-GL/S60-GL	RF/42
1st	0.32-0.36	0.47	0.45-0.53	0.30-0.36	0.40-0.41	0.46
2nd	0.09	0.17-0.18	0.35-0.40	0.09	0.19	0.38-0.39

PERIOD INCLUDING ROCKING

ERRATA

Page	Line from the above	Error	Correction
1892nd	21	Haskel's	Haskell's
1894th	16	-41	-42
1894th	17	-42	-41
1894th	41	$\frac{1+\alpha}{4\eta}$	$\frac{1+\alpha}{4\eta}$
1894th	42	$(\frac{\omega}{p})^2$	$(\frac{\omega}{p})^2$
1894th	42	$(\frac{\omega}{p})$	$(\frac{\omega}{p})$
1899th	Fig. 19	COMPUTED	OBSERVED
1899th	Fig. 19	OBSERVED	COMPUTED
1900th	Table 1	FOUDAMENTAL	FUNDAMENTAL
1900th	Table 1	NATIONAL	NATURAL

ADDITION: Fig. 19a 1900th page

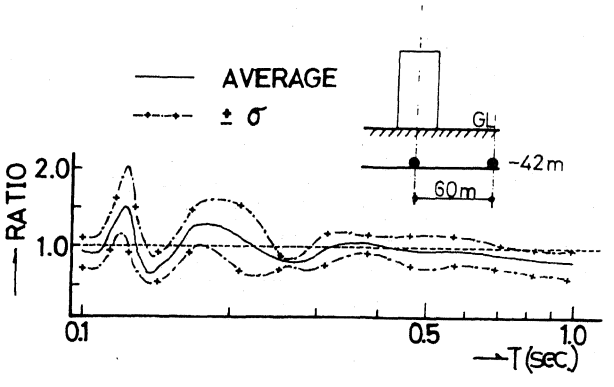

Fig. 19a