EFFECTS OF STRUCTURE-SOIL-STRUCTURE INTERACTION DURING VARIOUS EXCITATIONS

by
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SUMMARY

This paper deals with the characteristics of structure-soil-structure interaction with emphasis to the effects of some dynamic excitations. The interaction between a full-scale building and a model structure in a site is discussed on the basis of forced vibration tests, microtremor measurements and earthquake observations. An analytical model is presented and some parameteric studies based on the model are summarized. The experimental results are compared with the analytical ones. The discussion reveals two aspects of structure-soil-structure interaction; the effects of radiation waves from a structural system and energy absorption by natural mode excitation of a structural system.

INTRODUCTION

Many buildings are located on metropolitan areas where they are surrounded by a large number of other structures with various dynamic properties at short and long distances. In its situations the dynamic characteristics of a building structure are affected more or less by the existence of the others in its vicinity as structure-soil-structure interaction.

Since I. Toriumi[1)] studied analytically dynamic coupling between two rigid circular bases on an elastic halfspace, some analytical studies of structure-soil-structure interaction have been performed.[2)-6)] Field forced-vibration tests for two foundations were also carried out.[7)-8)] Nevertheless, actual phenomena of structure-soil-structure interaction during earthquakes are still indistinct.

The objective of this paper is first to clarify actual phenomena and basic characteristics of structure-soil-structure interaction by a series of experiments such as forced vibration tests, microtremors measurements and earthquake observations for a full-scale building and a model structure; second to evaluate the validity of the analytical prediction by comparison with the experimental results. Effects of several excitations on structure-soil-structure interaction are especially discussed in this study. The discussion clarifies two aspects of structure-soil-structure interaction; the one is the effects of the radiation wave from a structural system on the response of the other systems. The latter is the energy absorption by natural mode excitation of a structural system and its effects on the other systems.

OUTLINE OF SUBSOIL AND STRUCTURES

<u>Site and Subsoil</u>: A site of experiments and observations is Fuchinobe district, Kanagawa Prefecture on the west of Tokyo. Figs. 1 and 2 show view of the site and location of the structures, respectively. The subsoil is composed of a Kanto loam layer (G.L.$\sim$ G.L.-14 m), a clayey gravel layer ($\sim$ G.L. -39 m) and a clayey fine sand layer and others. According to seismic pros-

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pecting test by well-shooting method, the shear wave velocity of Kanto loam layer is about 240 m/s. The predominant frequency of the subsoil is evaluated about 5.8 Hz from the microtremors measurements.

Model Foundation/Model Building-Foundation: The simple reinforced mat foundation and model super structure were constructed in the site. They are both 4 m x 4 m with slab of 1.0 m thickness in plan. The upper concrete mass is supported by the four steel pipes and the rigidity can be varied to some extent by attaching eight braces. The forced vibration tests clarified the dynamic properties of the model shown in Tab. 1. The fundamental natural frequency of foundation soil-system is about 14 Hz. That of structure-foundation-soil-system is 5.1 Hz with the braces and 3.4 Hz without the braces.

Pilot Flat: A three-storied steel frame with two dwelling units which are situated only on the 3rd story exists at a distance of 38.5 m from the center of the model foundation. Each dwelling unit has two floors and the total height of the frame is 23.1 m. Each column of the frame is supported by a steel pile (diameter: 500 mm) at the depth of 15 m below the ground level. The dynamic properties of this structure had been ascertained by vibration test as shown in Tab. 1. The effective mass of the fundamental mode is evaluated 36.4 ton.sec^2/m (357 tons) from the tests and calculation. Comparing this structure with the model, its fundamental natural period is longer, the mass of the super structure is greater and the foundation is also larger.

In addition to the above structures, an observation cottage exists 17.4 m apart northwestward from the center of the model as shown in Fig. 2. An earthquake observation system is installed in the cottage. The total weight of the cottage with the observation facilities is roughly estimated 2 tons.

EXPERIMENTS AND EARTHQUAKE OBSERVATIONS

In order to evaluate structure-soil-structure interaction between the above structures, the following experiments were performed before and after construction of the model super structure. 1) Forced Vibration Tests: The periodic forces in the X-directon or the Y-direction were driven on the model foundation or on the roof of the model super-structure by a vibration generater. The horizontal displacements were mainly measure on the model foundation (and the roof of the model super-structure in the second stage of tests), the ground surface and the other structures such as the pilot flat and the observation cottage. The force is 2 tons in the first stage of tests, 0.1 ton or 0.2 ton in the second stage of tests. 2) Measurement of Microtremors: The displacements of the microtremor were measured at midnights. Fourier spectra of the recorded data were calculated. 3) Earthquake Observations: Seismometers were installed on the model foundation, on the model super-structure (after construction of the model super-structure) and in the ground. At some period through the experiments, an additional seismometer (X,Y,Z components) were installed on the 6th floor of the flat and some earthquakes were recorded in both systems. The location of the seismometer is shown in Fig. 3.

EXPERIMENTAL AND OBSERVATIONAL RESULTS

The discussion is restricted to some results in the X-direction of the forced vibration tests, the microtremor measurements and the earthquake observations.

Forced Vibration Tests: Figs. 4 and 5 show the results in a case that the model foundations was excited in the X-direction by a vibrator. At 2 Hz, near the fundamental natural frequency of the flat, the amplitude on the flat increases by the radiation waves from the model foundation. At the frequency of 7 Hz, the second mode of the flat was significantly excited by the radiation wave. On the other hand, the radiation wave from the model, which has the largest energy at the natural frequency of the model foundation-soil system, caused the amplitudes of the ground surface and the flat to increase at 14 Hz. The effects of the radiation wave from a system on the responses of the other systems is one phenomenon of structure-soil-structure interaction.

Fig. 6 shows the displacement responses of the model foundation forced in the X-direction and of three components of the observation cottage. The displacement of the cottage in the Y-direction was excited at 19 Hz, which denotes the natural frequency of the cottage in the same direction. It is noticed that the energy absorption caused by the vibration in natural mode of the lighter cottage are a little recognized in the responses of the model.

In order to examine the effects of vibration of the structure in the fundamental mode and of the forced position on the response of the ground surface in the case of the model structure with braces, Fig. 7 illustrates the displacements of the ground surface and the model foundation at 5.1 or 5.2 Hz before and after construction of the model super-structure. In this figure, the displacements are transformed to those per exciting force of 0.1 ton. In three types of the excitations, such as the model super-structure excitation, the model foundation excitation after construction of the model super-structure and the model foundation excitation without the model super-structure, the ratio of the foundation displacements among those three cases is about 20:4.5:1 and the ratio of the kinetic energy of the foundation is about 400:20:1. While, the kinetic energy ratio of the super-structure between the first two cases is about 32:1. From the results, it is pointed out that the radiation wave energy from the foundation mainly depends upon the energy of the super-structure.

Measurements of Microtremors: Figs. 8 and 9 show the Fourier spectra of microtremors on the model foundation and the roof of the flat after the model super-structure construction. The braces were set up on the model structure. In the spectra of the model super-structure, the responses have a large valley near the fundamental natural frequency of the flat. The phenomenon is atrributed to the energy absorption from excitation of the flat fundamental mode and is another profile of structure-soil-structure interaction.

At the second natural frequency of the flat (7 Hz), the responses of the model foundation have a keen peak. The results for this mode in microtremors are similar to those in the forced vibration tests in spite of the different excitations. It is natural that the response of the flat has a peak at the fundamental natural frequency of the model building-foundation (5.4 Hz). The phenomenon is one aspect of structure-soil-structure interaction as pointed out in the vibration tests.

Earthquake Observation: Interaction between model foundation and pilot flat; Fig. 10 shows Fourier spectral ratio (Mean ± one standard deviation) of the ground surface to the underground (G.L.-41 m) in the X-direction (EW). The result was obtained from the four observed earthquakes. For the fundamental mode of the flat, the results are similar to those of the microtremor measurements, not to the forced vibration results. Namely, the response of the ground has a large valley at 2 Hz. For the second mode of the flat, the response of the ground has a peak at 7 Hz as in the cases of the forced vibration tests and the microtremor measurements.

Interaction between model foundation-building (without braces) and pilot flat; The seismographs recorded during the East Yamanashi Earthquake (June 16th, 1976) are illustrated in Fig. 11. The maximum acceleration on the ground surface was about 180 gal (Intensity IV in J.M.A. Scale at Tokyo). Figs. 12 ~ 14 indicate the spectral ratios of the model foundation, the model super-structures and the roof of the flat normalized by the spectrum of the upperground (G.L.-41 m).

The results are similar to those of the microtremor measurements shown in Figs. 8 and 9 at all frequencies. The energy absorption at 2 Hz is also recognized in the spectral ratios of the model foundation and the model super-structure. It is noticed that the above mentioned energy absorption is another important aspect of structure-soil-structure interaction.

COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

Fig. 15 displays the analytical model for structure-soil-structure interaction[5]. The symbol M_{bj} denotes super-structure mass of j-th structural system (one-degree-of-freedom system), M_{oj} foundation mass of j-th system, λ_j damping ratio of j-th super-structure, ω_{nj} natural frequency of j-th super-structure with base fixed, r_j radius of j-th semicircular foundation, a the distance between the two structural systems. The two systems are located on an elastic halfspace and the disturbance is a plane SH wave propagating upward in the vertical direction. The detailed is omitted. In this theory the normalized responses of two structural systems depend on the eleven dimensionless parameters as follows: nondimensional frequency of SH wave; $K_{r2}=\omega r_2/\beta$, ratio of two foundation's radii; r_1/r_2, nondimensional distance between two structural systems; a/r_2, nondimensional foundation mass of j-th system; M_{oj}/M_{sj}, nondimensional structure mass of j-th system; M_{bj}/M_{sj}, damping ratio of j-th structure; λ_j, and nondimensional shear wave velocity in the ground (comparative stiffness of the soil and j-th structure); $\varepsilon_j=\pi\beta/2r_j\omega_{nj}$.

Some parametric studies based on the theory have clarified the characteristics of structure-soil-structure interaction[6]. The results are summarized in comparison with the results from a single identical system on the same ground as follows.

The responses of the foundations and the structures are different from those based on a single structure-soil-structure interaction model. In some cases, they become larger, in other cases, smaller depending on the distance and the parameters of the adjacent structure. It is noticed that the responses in contact with each other foundation are rather small compared with the other cases, especially with the cases of only a short distance and with a case of a single structural system.

The effects of the other parameters, e.g. radius and mass of foundation, mass and period of structure, on structure-soil-structure interaction were examined. The effects of the size of the foundation are more remarkable. Consequently, the response of the building that has the large-size foundation and the large structure-mass, and the long natural period becomes larger than those of a single building on the same ground. While the response of the building that has the small-size foundation and the small structure-mass, and the short natural period has an opposite tendency. This fact motivated the above-mentioned experiments and observations.

The above theory is applied to the fundamental mode of the flat (suffix:1) and the model foundation-building with braces (suffix:2) in the experimental site. The conditions correspond to those in the microtremor measurements. The values of the parameters used are as follows; $M_{o1}/M_{s1}=1.8$, $M_{b1}/M_{s1}=4.8$, $\varepsilon_1=5.70$, $\lambda_1=0.0$, $M_{o2}/M_{s2}=3.11$, $M_{b2}/M_{s2}=3.11$, $\varepsilon_2=3.62$, $\lambda_2=0.0$, $a/r_2=12.1$, $r_1/r_2=1.88$. Fig.18 shows the normalized foundation displacements and the normalized relative displacements of the super structures. The results of each structural system from a single structure-soil interaction model are shown in Figs. 16 and 17. In these figures, an abscissa indicates nondimensional frequencies, and value of $K_{r2}=1$ corresponds to 12. Hz. From these results, it is pointed out that the peak value of the model structure response is about 30 percents smaller by the existence of the pilot flat, and that the peak value of the flat is about 50 percents larger by the existence of the model structure-foundation. In the responses of each foundation, the effects of the existence of the other are observed. The energy absorption phenomina mentioned above are remarkably recognized. With regard to the fundamental mode of the flat and the model foundation-building, the analytical results agree with the spectra of the microtremors.

CONCLUDING REMARKS

From the experimental and analytical results presented, it may be concluded as follows:

1) The experiments confirmed that structure-soil-structure interaction takes place actually between the structures in earthquakes.
2) Structure-soil-structure interaction has two aspects. Namely, the one is the effect that responses of a structure is increased by the radiation waves from the other structures. The other important aspect is the phenomenon that a structure has a energy absorption capacity from the ground by exciting its own mode. In the latter case, as clarified in the experiments, the remarkable difference is brought about between the results of the forced vibration tests and either those of the microtremor measurements or those of earthquake observations.
3) The analytical results agreed with the experimental results (microtremors). The above-mentioned energy absorption is well simulated.

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Tab.1 STRUCTURES AND PROPERTIES

Properties \ Structural system	Model Foundation	Model Foundation-Building	Pilot Flat
Upper structure weight		38.4 ton	482 ton
Foundation size and weight	4M x 4M x 1M 38.4 ton	4M x 4M x 1M 38.4 ton	21.6M x 7.4M x 23.1M 136 ton (Except Steel Piles Weight)
Natural Frequency (from Vibration Test)	14Hz	3.4Hz (without braces) 5.1Hz (with braces)	X-direction 1st mode 1.6Hz 2nd mode 6.6Hz Y-direction 1st mode 1.9Hz

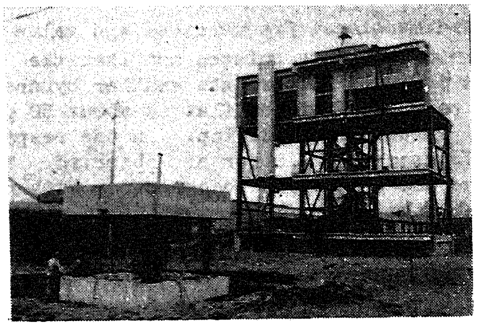

Fig.1 VIEW OF SITE

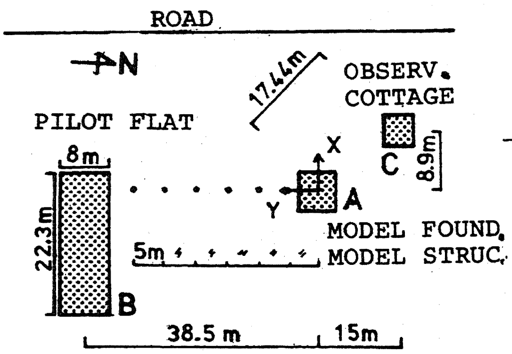

Fig.2 EXPERIMENTAL SITE

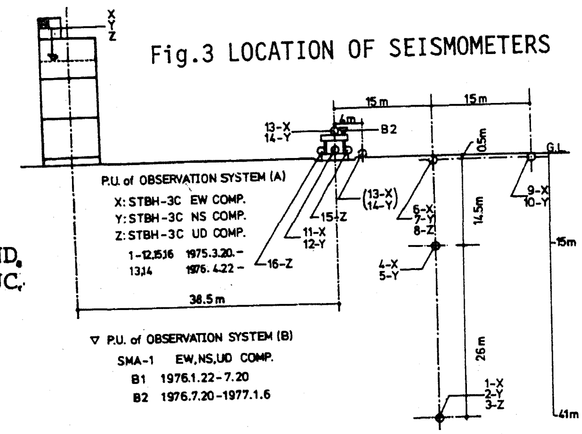

Fig.3 LOCATION OF SEISMOMETERS

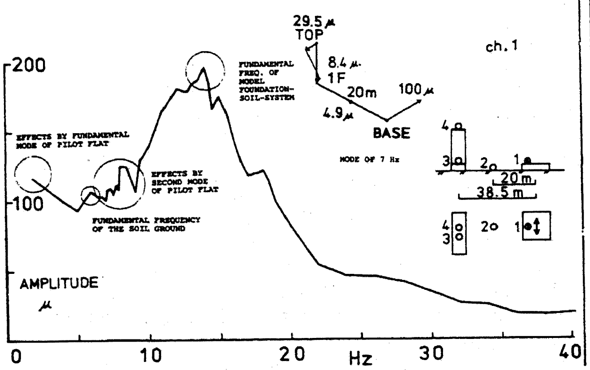

Fig.4 VIB.TEST NO1 (M.FOUND.X-DIREC.)

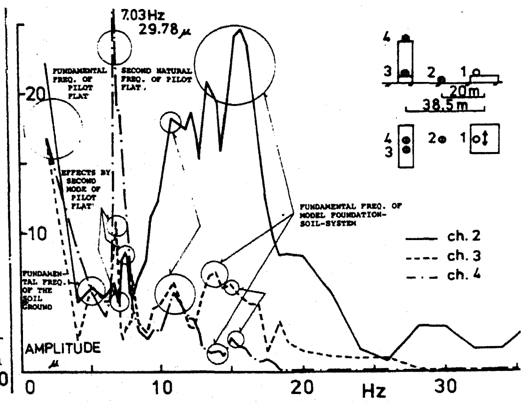

Fig.5 VIB.TEST NO1 (M.FOUND.X-DIREC.)

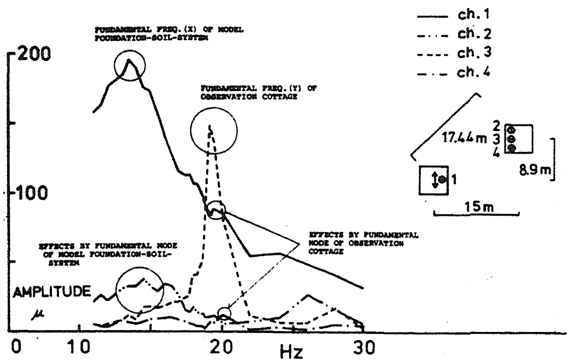

Fig.6 VIB.TEST NO2 (M.FOUND.X-DIREC.)

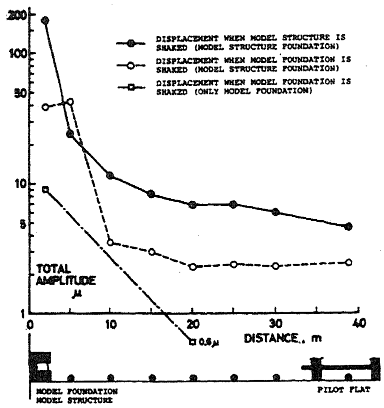

Fig.7 GROUND DISP. (X-DIREC.)

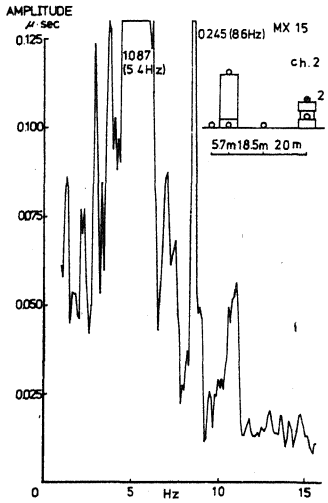

Fig.8 MICROTREMOR (M.STRC.)

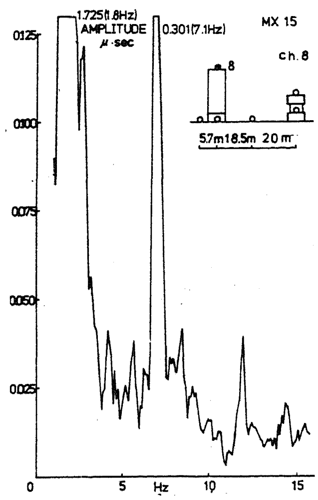

Fig.9 MICROTREMOR (FLAT)

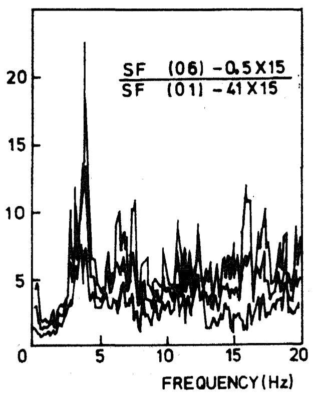

Fig.10 SPEC.RATIO (GL-0.5/GL-41)

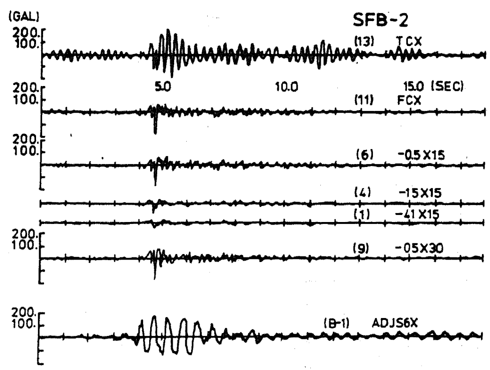

Fig.11 EAST YAMANASHI EARTHQUAKE [EW] (1976.6.16.)

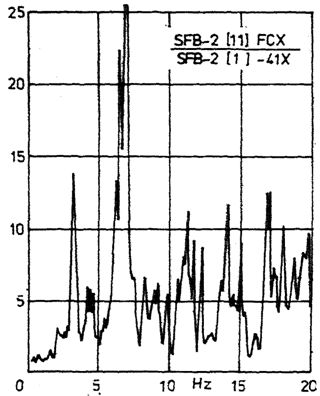

Fig.12 SPEC.RATIO (M.FOUND/GL-41)

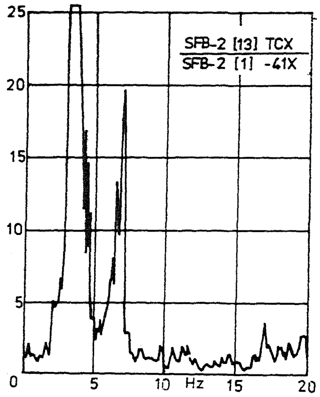

Fig.13 SPEC.RATIO (M.ST/GL-41)

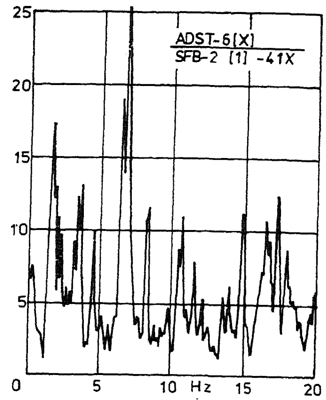

Fig.14 SPEC.RATIO (FLAT/GL-41)

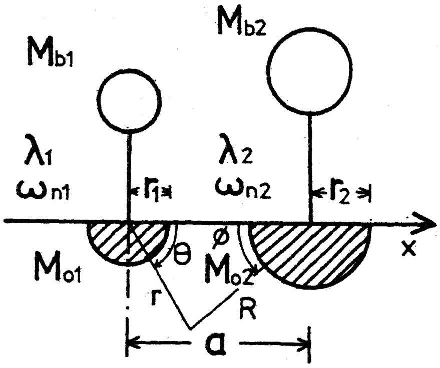

Fig.15 ANALYTICAL MODEL

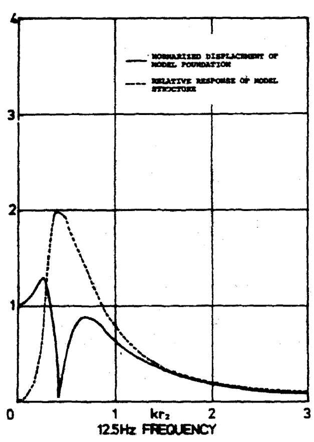

Fig.16 MODEL RESPONSE [ST-S INTERACTION]

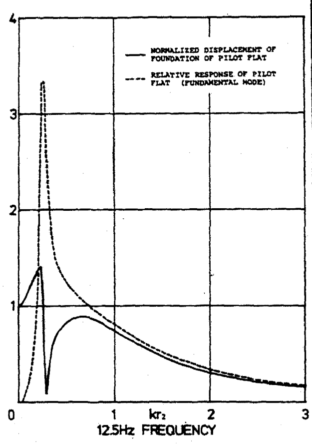

Fig.17 FLAT RESPONSE [ST-S INTERACTION]

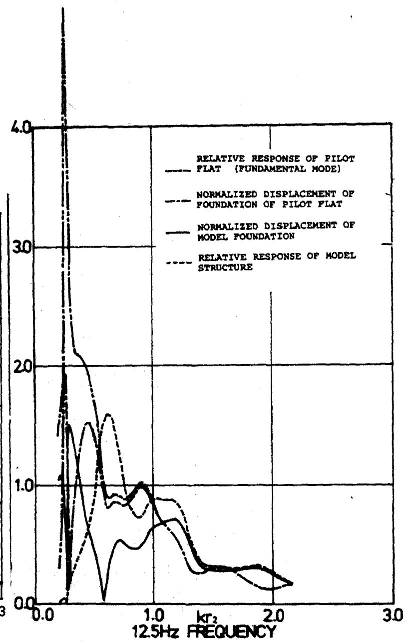

Fig.18 RESPONSE OF MODEL AND FLAT [ST-S-ST INTERACTION]