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SYNOPSIS To rationalize the aseismic design of pile foundations it is essencial to make clear the load conditions applied to piles. This paper describes 1) the results of earthquake motion measurement carried out in and around a pile-supported building, 2) the simulation using soil-pile-structure lumped mass interaction model and 3) case study of typical combination models of structure and soil. Fundamentally both the seismic loads of super-structure and the forced deformation by surrounding soil should be applied to piles as external loads. In the coupling and evaluation of these loads the dynamic interaction among soil, pile and structure plays a very important role.

INTRODUCTION

1978 Miyagi-oki Earthquake in Japan damaged many P.C. and R.C. piles and revealed that the design concept of pile foundations to lateral seismic load should be rationalized taking their earthquake motions into account. Conventional type of load condition which neglected the forced deformation by surrounding soil layers might be insufficient and unsafe in some cases. In designing pile foundations authors emphasize the necessity of applying piles seismic deformation caused by surrounding soil in addition to the seismic loads of super-structure. Two types of load condition need to be coupled not always but in accordance with the interaction effects of super-structure and surrounding soil layers.

EARTHQUAKE MOTION MEASUREMENT

Fig.1 shows the instrumentaion in and around the building, which is 7 storied P.C. apartmaent-house, 55.8m x 13.6m in plan, 18.9m high and supported by P.C. piles (400mmϕ) driven into 12m below ground surface. The ground consists mainly of sand layer. The top 4m is reclaimed and soft, but it becomes stiffer gradually according to the depth. The instrumentation is composed of two lines, which are pile-structure line and free-soil line. They have 5 and 4 measuring points with three components pick-up respectively.

Many earthquakes were observed though whose intensity are limited to weak or moderate. Through statistical processing following characteristics were made clear which reveal the interaction effect between soil and structure.

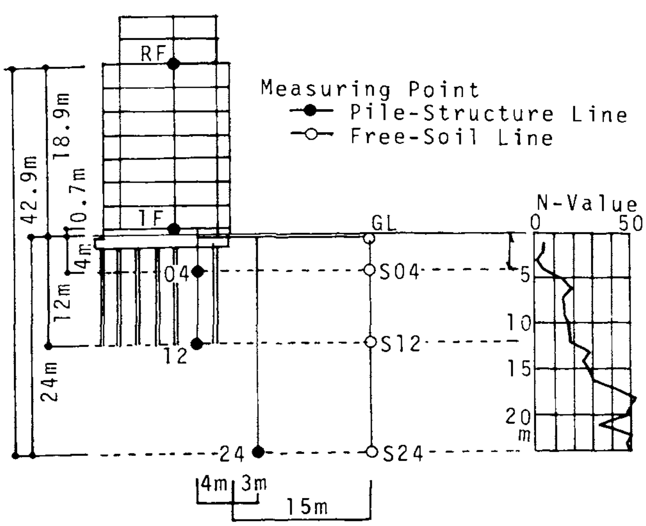

Fig.1 Instrumentation in the Building and Its Surrounding Ground

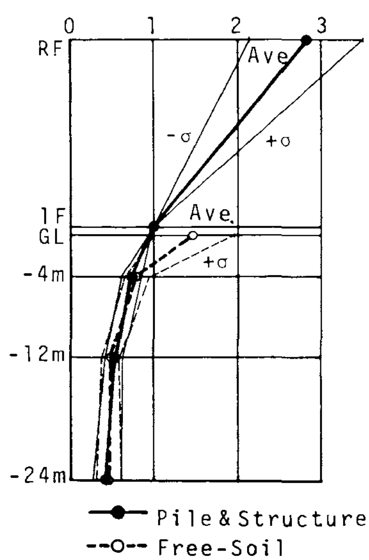

Fig.2 Maximum Acceleration Mode

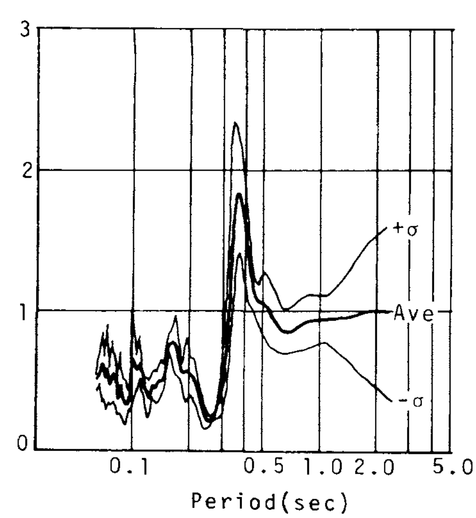

Fig.3 Fourier Amplitude Ratio 1F/GL

Fig.2 is the mode of maximum acceleration normalized by that of the 1st floor. Comparing the modes of pile-structure line and free-soil line it is clearly recognized that the amplitude of free-soil surface is about 50% larger than that of the 1st floor, but that both lines get nearly equal at deep levels. It can also be interpreted as the piles move nearly same with the soil at deep levels but the influence of super-structure is significant near the pile-top.

Fig.3 shows the Fourier amplitude ratio between the 1st floor and free-soil surface. Bordering 0.35 sec which is judged to be the primary period of the coupled system, in longer period range the amplitude of the 1st floor is greater than or equal to that of the free-soil surface, but in shorter period range it is vice-versa. It can be considered as a kind of transmission loss. The maximum acceleration ratio previously mentioned is consistent with this characteristics.

SOIL-PILE-STRUCTURE INTERACTION MODEL

To simulate the observed results lumped mass interaction model as shown in Fig.4 was adopted, which is composed of pile-structure system with near-field additive masses and free-soil system standing side-by-side. It is similar to the model Penzien et al (1964) used for the analysis of a bridge on piles, but is different in the modeling of additive soil.

In this model soil column of some area arround piles is considered to behave together with piles, and then additive masses are not imaginary but real and are connected to each other by shear springs of that area. Lateral springs transmit the forces caused by the prescribed displacement of the free-soil system to the pile-structure system. The area of additive soil column and lateral spring constants are calculated based on Mindlin(1936)'s solution.

This model turned out to be quite suitable to simulate the observed results when the volume of additive mass and damping factors are selected properly. Fig.5 shows good coincidence between the observed and simulated transfer functions by this model. The predominant modes of pile-structure system and free-soil system is combined and mixed together because of the interaction of these systems.

As shown in Fig.6 the natural periods of the coupled system vary only slightly due to the change of the volume of additive mass. This is because of the self-balancing nature of additive mass with proportional shear spring.

Modal damping factors were sought by the spectrum fitting method which fits the transfer function of the model to that observed interatively adjusting damping factors. Fig.7 shows the damping factors of free-soil column, where the results of other sites are also included. They have a conspicuous tendency of decrease in higher mode.

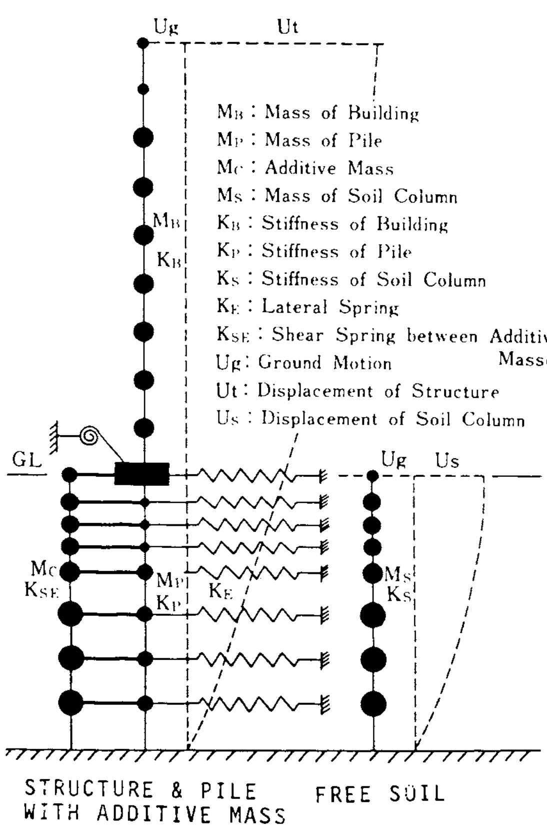

Fig.4 Soil-Pile-Structure Interaction Model

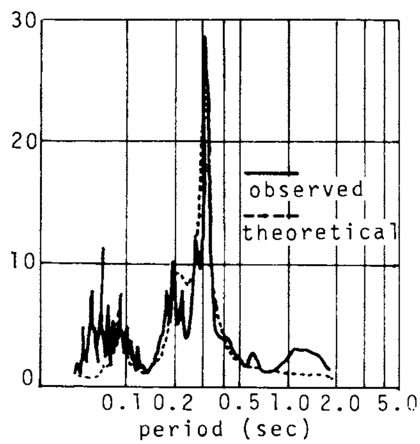

Fig.5 Transfer Function (RF/GL-12m)

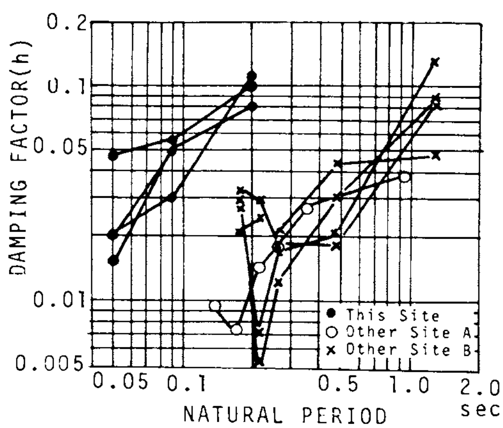

Fig.7 Modal Damping Factor of Free Soil

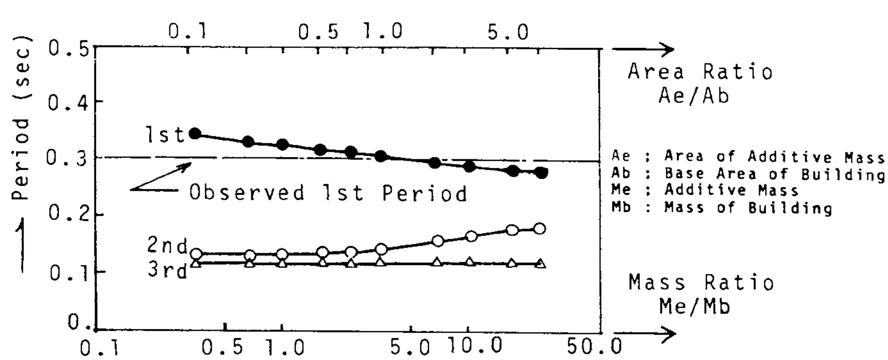

Fig.6 Variation of Natural Periods due to Additive Mass

CASE STUDY OF SOIL-PILE-STRUCTURE MODELS

To investigate the response characteristics of soil-pile-structure system typical combinations of buildings and soil conditions were chosen and analysed using the interaction model previously affirmed. The buildings are 5 storied and 10 storied which are identified in TABLE I. The soil layers are shallow 10m and deep 30m as shown in TABLE II. They are combined to each other into 4 models as shown in Fig.8, whose undamped natural periods and participation functions are shown in Fig.9. Comparing these figures following aspects can be pointed out.

1. In every model the modes of free-soil and those of pile-structure are mixed and coupled together, which represent the interaction between both systems. The coupling depends on the period characteristics of each system, then the combination of loads applied to piles are different in each case.

2. In model S-L and D-H where the primary periods of building and ground are similar the 1st and the 2nd modes show the resonative tendency causing large amplification. The 2nd modes of both models induce large bending moment at the pile-top.

TABLE I. Building Models

	Model "L"	Model "H"
Story	5	10
Primary Period	0.3 sec	0.8 sec
Plan	30m x 30m	30m x 30m
Unit Weight	1.0 t/m²	1.0 t/m²
Total Weight (Including Footing)	5850 t	10350 t
Story Height	3.0 m	3.0 m
Total Height	15.0 m	30.0 m
Pile	P.C. Pile 98-400mmφ	P.C. Pile 173-400mmφ

TABLE II. Ground Models

	Model "S"	Model "D"
Depth	10 m	30 m
Shear Wave Velocity	150 m/sec	150 m/sec
Primary Period	0.267 sec	0.800 sec
Unit Weight	1.7 t/m³	1.7 t/m³

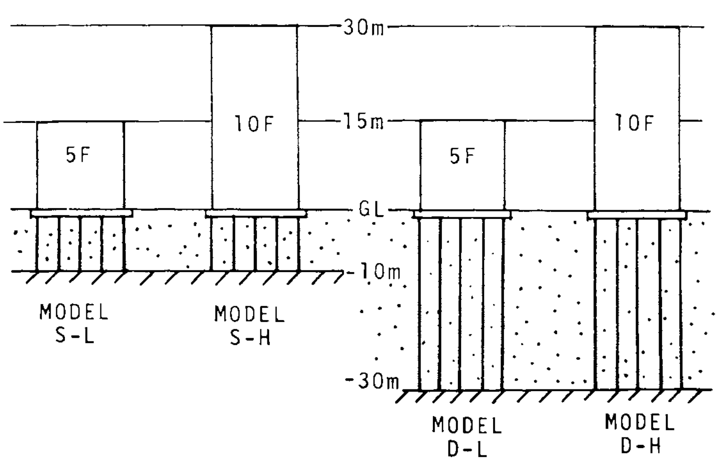

Fig.8 Typical Combination of Building & Soil Models

3. In Model S-H and D-L where the primary periods of building and ground are apart coupling does not occur in the 1st mode but in the higher mode. Except for the periods when free soil system is predominant prescribed displacement of free-soil need not be considered.

Using these four models linear earthquake response analysis was done. Input earthquake motions at the base of the models were EL CENTRO 1940 NS (U.S.A.) and HACHINOHE 1968 NS (JAPAN), whose maximum acceleration was adjusted to 100 gal. Damping factors were assumed element by element as shown in TABLE III.

Maximum response acceleration and pile moment are shown in Fig.10 and Fig.11 respectively. As is judged from the fundamental characteristics of the models, quite large amplification occured in model D-H, and higher mode caused whiplashing in model S-H.

Base shear of the building is shared by soil and piles. The ratio which is transmitted to piles is 16-18% in case of shallow layer, about 6% in case of model D-L and only 2% in case of model D-H. Bending moment becomes maximum at the pile-top because the rotation is restrained.

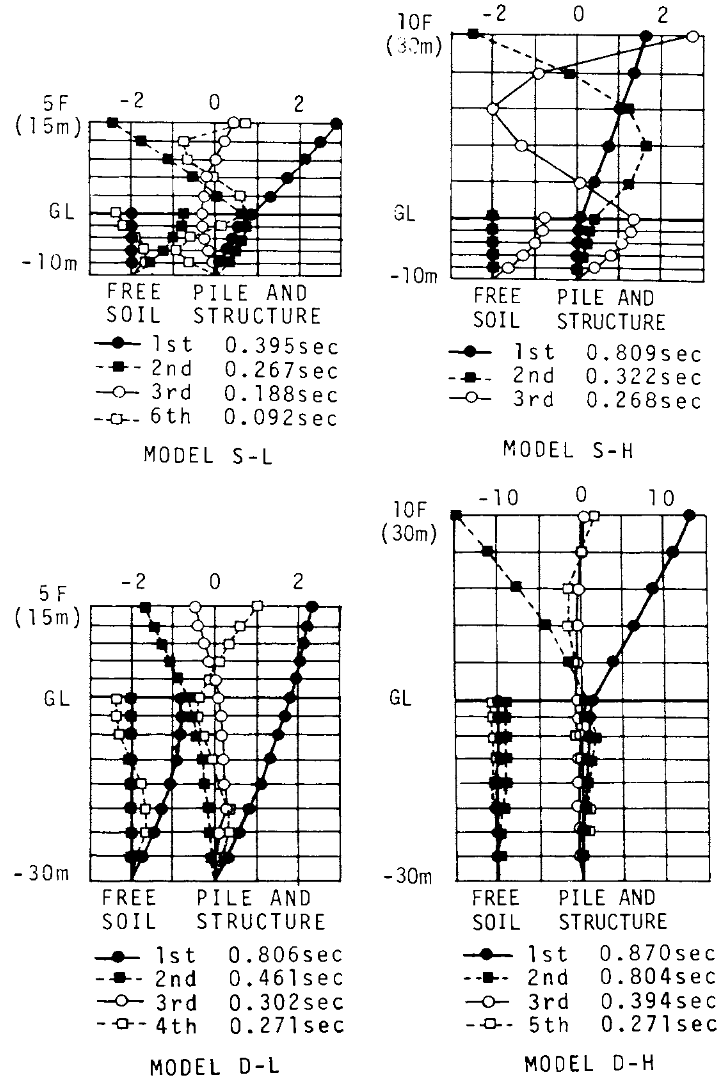

Fig.9 Natural Periods & Participation Function

It diminishes rapidly along pile axis, which is consistent with the calculated value by Chang (1937)'s formula. However the response moment is 2.5-4 times larger than the moment by Chang's formula when response pile shear is applied at the pile-top.

CONCLUSIONS

1) To rationalize the aseismic design of piles it is necessary to couple the loads transmitted from the super-structure and those caused by the prescribed displacement of surrounding soil as simply illustrated in Fig.12.

2) Dynamic interactions among soil, pile and structure should be considered on the estimation of load conditions. According to the combination of conditions of structure and soil the coupling of the two load conditions is different. Both load conditions need to be coupled not always but depending on the mode characteristics.

3) Lumped-mass interaction model including soil, pile and structure turned out to be effective for the evaluation of their behavior and load conditions.

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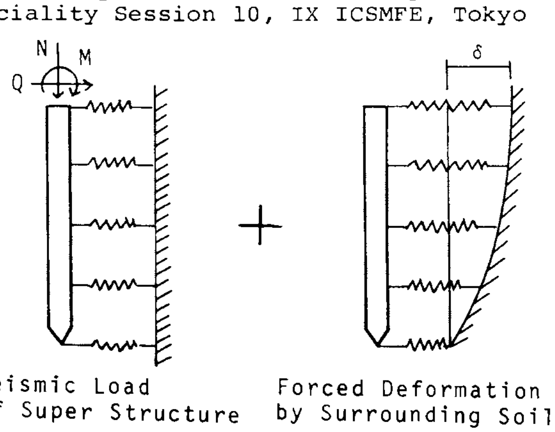

Fig.12 Load Condition Applied to a Pile

TABLE III. Element Damping Factors

Element	Damping Factor
Free Soil Additive Soil	Modal Damping Factors $h_1=8\%$, $h_2=3\%$, $h_{3\sim}=1\%$
Pile	Frequency Proportional Damping $h_1=1\%$
Building	Frequency Proportional Damping $h_1=5\%$
Rotation	$h_R=10\%$
Lateral Spring	$h_L=7\%$

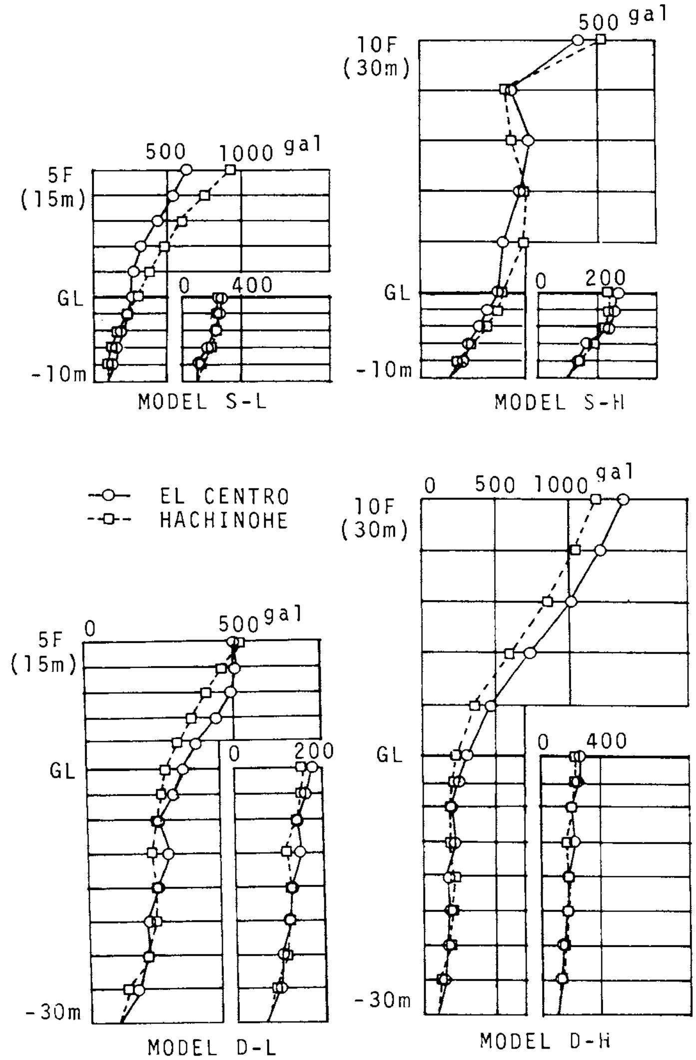

Fig.10 Maximum Response Acceleration

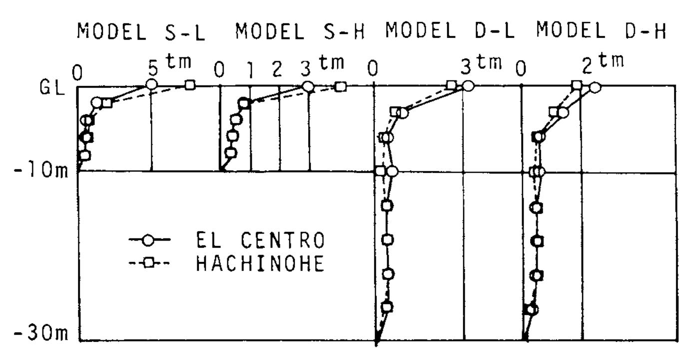

Fig.11 Maximum Pile Moment