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EXPERIMENTAL EVALUATION OF DYNAMIC CHARACTERISTICS OF LOW AND MEDIUM-RISE BUILDINGS WITH SOIL-STRUCTURE INTERACTION

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SUMMARY

Dynamic properties of low and medium-rise R.C. buildings are experimentally investigated using large amount of earthquake and ambient vibration observation data on a lot of existing buildings. The key factor is the effect of Soil-Structure Interaction (SSI) on ordinary buildings. First, ambient vibration experiments were conducted on over one hundred low-rise R.C. buildings with the same structural systems but located on different soil conditions. It was concluded that identification of dynamic characteristics of buildings is quite difficult for cases in which SSI is dominant. Next, dynamic behavior of several low and medium-rise buildings was investigated based on earthquake response observation. The transfer functions for the fixed-base and SSI included cases show a clear difference in the natural frequency and damping ratio. The loss in the effective input motion is clearly observed for buildings with large foundation. Also studied was the amplitude dependency of the estimated natural frequencies and damping ratios. In the final section, dynamic behavior of a 10-story building was studied in detail through dense measurement. Dominant rocking motion and base-floor deformation were observed. Throughout all the experimental investigations, the need to improve the knowledge on dynamic properties of ordinary buildings with SSI effect was pointed out, which may be achieved by increasing the quality and quantity of experimental studies.

INTRODUCTION

Dynamic behavior of ordinary low and medium-rise buildings has not attracted much attention despite of its complex properties derived mostly from the effect of Soil-Structure Interaction (SSI). Also the experimental studies on such buildings have not been sufficiently conducted in contrast to the large number of studies on high-rise buildings, base-isolated buildings and special facilities. This may be due to the fact that the ambient vibration tests for experimental evaluation of dynamic characteristics of low and medium-rise buildings is quite difficult (e.g. Izumi et al. 1990). Recently, experimental investigations have been highly developed through the use of high precision multi-channel measurement devices with huge data storage, and the use of more accurate analysis techniques and high speed computers. In this paper, dynamic properties of low and medium-rise buildings with SSI effect are experimentally investigated using large amount of earthquake and ambient vibration observation data on a lot of existing buildings.

Experiments in this paper have been performed mainly in Nagoya city, especially in the campus of Nagoya University. Ambient vibration tests have been conducted for over one hundred buildings in two different observation policies; one is the simple observation with a few sensors on the top, bottom and near ground of the building. Such easy and fast observation enlarge the merit of ambient vibration test for many existing buildings,

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and thus it is mainly used for detection of general vibration characteristics of buildings. However, it requires more careful analysis considering various noises, effect of spatial vibration and SSI of the building. Results of such an observation will be shown in Section 2. Another observation style is the precise one using many sensors, up to 50 channels, simultaneously. Though this is not easy to conduct for many buildings, one example on a 10-story SRC building will be given in Section 4. Seismic response observation is performed at ten low and medium-rise R.C. buildings in the campus, which are connected via the Internet (Fukuwa et al. 2000). This observation network may be a rare case with such *ordinary* buildings in such small area equipped with many seismometers. Eigenproperties and the SSI effect of the buildings under seismic excitation will be shown in Section 3, comparing with the ambient vibration test results.

AMBIENT VIBRATION EXPERIMENT OF LOW-RISE R.C. BUILDINGS

The authors have already investigated the effect of SSI for several moderate hight R.C. buildings by ambient vibration tests (Gannad et al. 1997, 1998). In the present paper, totally sixty seven 3-story elementary school buildings out of over one hundred measured low-rise R.C. buildings are newly examined. All the buildings have almost a typical plan of educational buildings, i.e., a slender rectangular with the same width. The structural system is also the same for all buildings which is consisted of 2-span reinforced concrete frames with shear walls and multi-span frames with few walls in the transverse and longitudinal directions, respectively. However, the foundation type and soil condition are different among them. Fig. 1 shows the location of the observed buildings in Nagoya city. Almost half of buildings are located on alluvium deposits. Also, almost half of them have pile foundations.

The responses were measured simultaneously at the first floor and top of the buildings as well as on the ground surface. The moving coil type sensors with natural period of 1 second were used to measure the velocity responses. For the parameter estimation, the transfer function fitting method is used, in which the dynamic properties of the building are estimated by fitting a known system whose transfer function can be matched well with the observed one (Tobita 1996). The response at the ground and the response at the first floor is considered as input for calculating the observed transfer functions, respectively. It is believed that the results of the second case can be considered as a quasi-fixed base model because the sway effect is not included. However, in this case, the effect of rocking motion is still included.

As mentioned before, the evaluation of dynamic characteristics of low-rise buildings would be difficult through conduction of ambient vibration tests. It is because a well-shaped transfer function can not be achieved except under very well-controlled conditions due to the low amplitude of vibrations and due to the remarkable effect of soil under buildings. Fig. 2 show the results of two cases which have been selected as the representatives for well and poor estimations. Using the same classification for all cases, Fig. 3 shows the statistical results based on the soil type, the type of foundation and the examined direction of buildings. Generally speaking, better performance is seen for the cases of spread foundations on stiffer soils, which indicates that the effect of SSI may be considered as one of the parameters responsible for the distortion of transfer functions.

To show the SSI effects clearly, the elastic deformation of the superstructure, the swaying and rocking motions are defined as Fig. 4. The transfer functions of these components to the response at the ground are depicted in

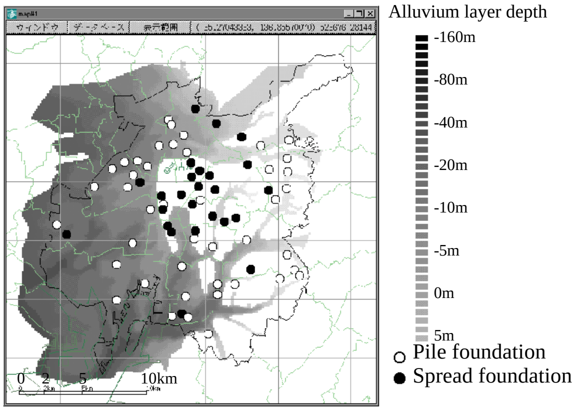


Fig.1 Soil condition in Nagoya city and *the location of investigated buildings*

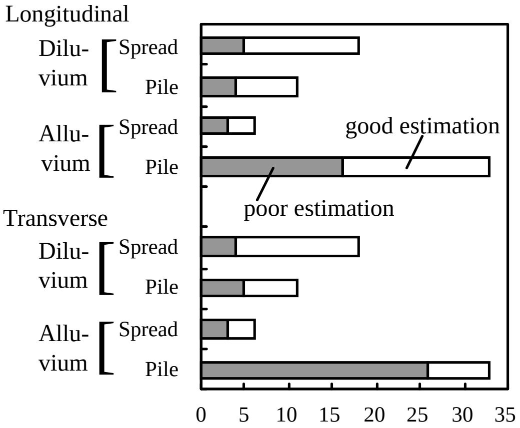
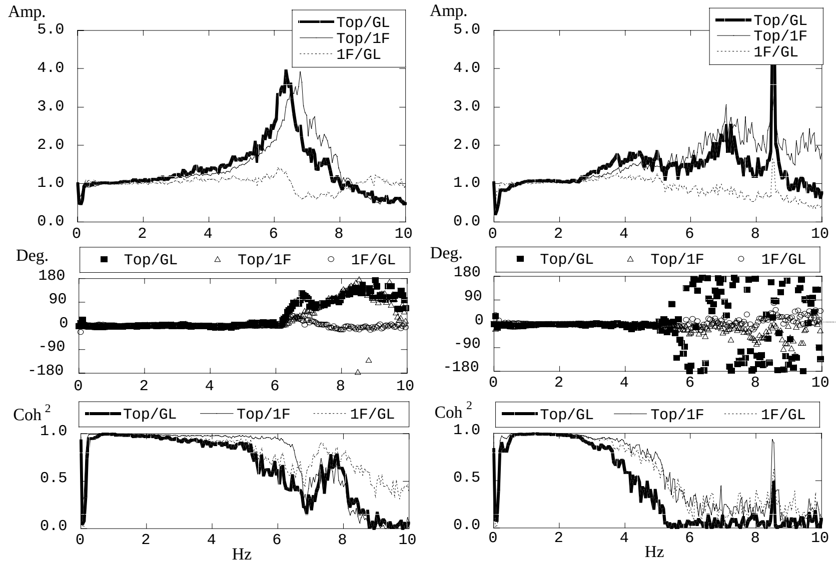


Fig.3 The quality of transfer function



(a) Building Y (good estimation) (b) Building H (poor estimation)

Fig.2 Good and poor estimations of transfer functions and coherences

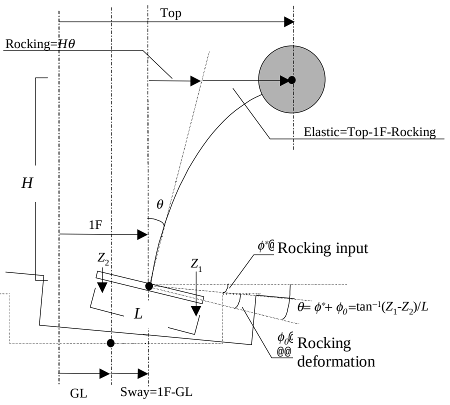
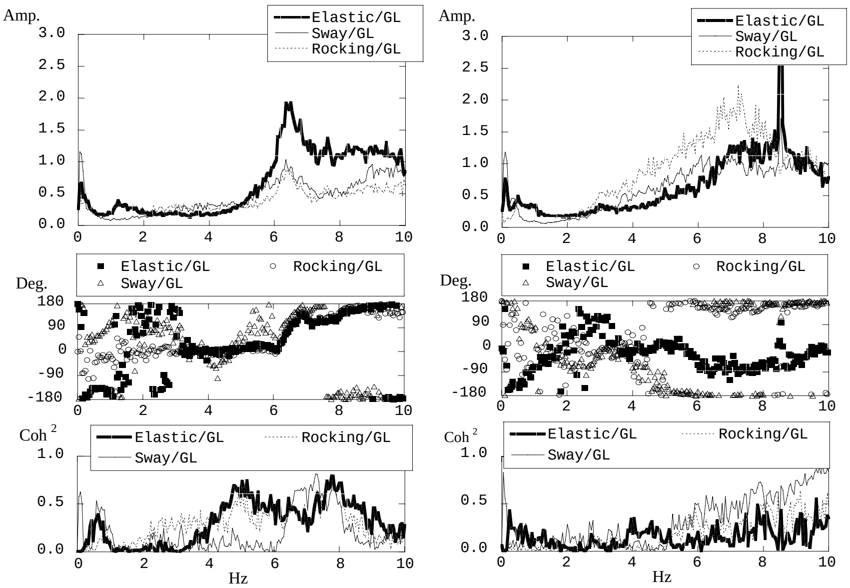


Fig.4 Model of a building



(a) Building Y (good estimation) *(b) Building H (poor estimation)*

Fig.5 Transfer functions for sway, rocking and elastic deformation

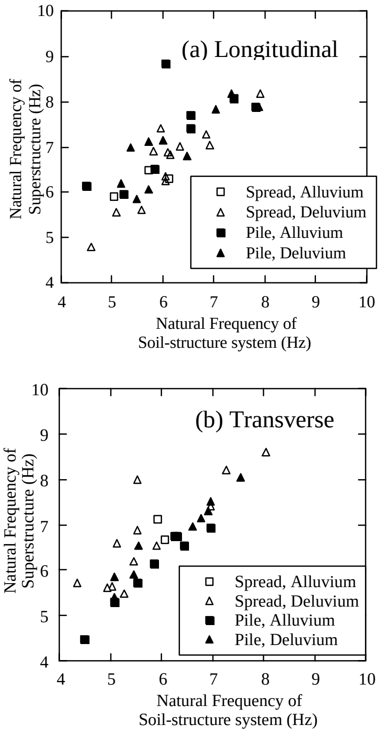
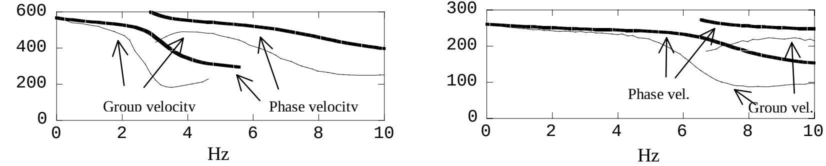


Fig.7 Natural frequency of superstructure (Top/1F) compared with those of soil-structure system (Top/GL)



(a) Building Y (good estimation) (b) Building H (poor estimation)

Fig. 5. Clear peaks of amplitudes, phase characteristics and relatively high coherences are observed at the natural frequency in the well-estimated case, however, the characteristics of vibration system is not clearly observed in the poor estimation case. Amplitudes of the swaying and rocking motions are much higher for the poor estimation case of Building H, showing the effect of SSI. Fig. 6 shows the dispersion curves of the Rayleigh waves calculated from surface layer structures at the sites. It is observed that the trough frequency of the group velocity curve, called ‘Airy phase’, exists very close to the natural frequency in the poor estimation case. The Airy phase roughly corresponds to the predominant frequency of the Rayleigh waves of the ground microtremor.

This may be showing that the most of the building response is consists of the rocking motion in the poor estimation case, which are excited by out-of-phase ground motion due to Rayleigh waves. This hypothesis requires more verification by accumulating the precise observations.

Using the idea of quasi-fixed base model, the results for the frequency of the superstructure are drawn versus the frequency of the soil-structure system in Fig. 7. Only the results of well-performed cases are shown. The results clearly show lower natural frequencies for soil-structure systems which is an explicit consequence of SSI effect.

SEISMIC RESPONSE OF LOW AND MEDIUM-RISE BUILDINGS

The vibration data from six instrumented buildings in the Higashiyama campus of Nagoya University were collected during three weak and moderate earthquakes. The collected data were then analyzed in order to study the effect of SSI on the dynamic characteristics of buildings as well as on the effective input motions. Fig. 8 shows the outline of investigated buildings which are numbered in descending order of their area. Also shown are the locations of seismometers. The information of the investigated buildings are summarized in Table 1. More detailed results on building #1, i.e., the 10-story building will be discussed in Section 4.

Fig. 9 shows the acceleration response of the buildings at roof, 1st floor and ground levels. Also shown are the Fourier spectral ratios for the two cases of top/1st floor and top/ground. It is believed that the former case may be considered as a representative for the quasi-fixed-base structure (without only swaying motion but including rocking motion) whereas the latter case includes the SSI effect. The results thus show a clear change in the natural frequency of the system due to SSI for the 6-story and the 4-story buildings. Regarding the vertical vibration of buildings, remarkable difference is seen among the response of the three buildings.

The peak acceleration and velocity at the ground level and the first floor of all buildings have been summarized in Table 2 for the case of Mar. 16, 1997 earthquake. Investigating the results reveals that there is more input motion loss for buildings with larger foundations. The loss of effective input motion is also studied through construction of Fourier spectral ratio graphs in Fig.10. The results are drawn versus nondimensional frequencies. The loss of input motion is seen clearly in the results, especially for the range of higher frequencies.

The results of natural frequencies and damping ratios for the superstructure are drawn versus the corresponding values of the soil-structure system in Fig.11. The results for natural frequencies clearly show lower values for soil-structure systems which can be interpreted as SSI effect. Also, the effect is more drastic for larger earthquakes (EQ2>EQ3>EQ1). Regarding the damping ratios, the results for building #3 are compatible with the general expectation of higher damping ratios for soil-structure systems. However, the results of building #4 show a different trend which may be due to the effect of neighboring building’s vibration through structure-soil-structure interaction. An example of the curve fitting process for the building #1 is shown in Fig.12.

Finally, Fig.13 shows the amplitude dependency of the results. The estimated natural frequencies and damping ratios for different cases with various levels of vibration amplitude are drawn in the same figure versus the peak acceleration values at top of buildings. A clear trend of lower natural frequencies for higher levels of vibration is observed. However, the results for damping ratios are almost inconclusive.

DYNAMIC BEHAVIOR OF 10-STORY BUILDING

The building #1 studied in Section 3 is studied in more detail in this section (Tobita et al. 1997, 1998b). The building as shown in Fig.14 is a 10-story Steel Reinforced Concrete (SRC) structure with irregular plan. The building is located on deep soft soil deposits and consequently has pile foundation with long piles up to 45 meters. The dynamic behavior of the building was studied through dense ambient vibration measurements. The observation points are also shown in Fig.14.

The translational and torsional mode shapes of the building are drawn in Fig.15 where the effect of building's irregularity is seen clearly. Table 3 shows the sway and rocking ratios computed based on displacements at the top story for different points of the plan. Rocking ratios even up to 50% is observed for the building at the eastern side. The ratio is 26% at the western side where the foundation width is bigger. But even at the western side, the rocking ratio is much larger than would be expected for buildings supported by pile foundations. Such large values of rocking ratio may be considered as a result of low vertical stiffness of long piles and also of softness of the underlain soil.

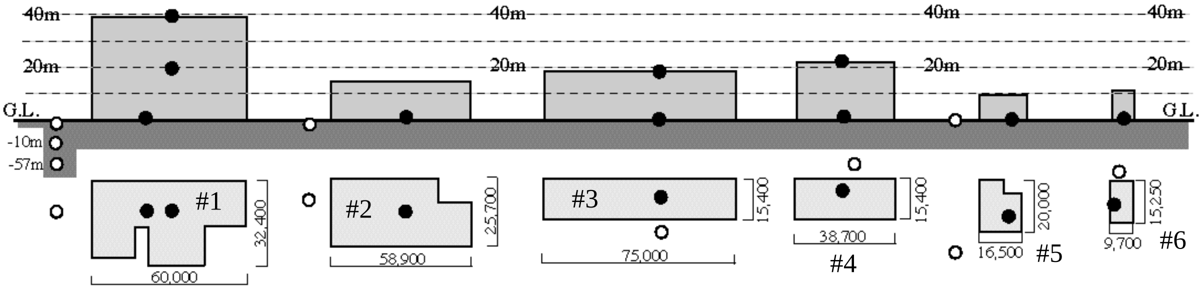


Fig.8 Plan and elevation of investigated buildings and sensors location.

Table 1 Outline of investigated buildings

No.	Structure	Floor	Height(m)	Area(m2)	Foundation type	Av. Vs (m/s)
1	SRC	10	39.3	1,541	Pile (45m)	202
2	RC	3	(12)	1,370	R.C. Pile	(315)
3	RC	4	17.9	1,155	Pile (6m)	288
4	RC	6	22.3	604	P.C. Pile (12m)	303
5	RC	2	(9)	290	Spread and R.C. Pile (5m)	291
6	RC	1	(15)	150	R.C. Pile (7m)	305

Table 2 Maximum acceleration and velocity

	Max. Acce. (cm/s2)						Max. Vel. (cm/s)					
	NS		EW		UD		NS		EW		UD	
No	G.L.	1F	G.L.	1F	G.L.	1F	G.L.	1F	G.L.	1F	G.L.	1F
1	72.1	48.4	97.2	60.6	37.0	18.1	3.95	3.85	5.81	5.42	1.80	1.59
2	54.0	52.7	63.2	49.8	34.7	37.9	2.49	4.04	4.58	3.28	1.58	1.61
3	50.3	57.3	73.5	50.0	31.4	24.1	2.87	4.02	4.51	4.05	1.81	1.93
4	44.2	42.7	55.9	58.7	38.8	20.5	2.83	3.69	4.69	4.40	1.91	1.88
5	61.2	49.1	69.7	61.3	37.5	31.1	3.79	4.40	4.50	3.86	1.73	1.63
6	54.5	61.3	74.0	80.4	57.6	51.6	3.19	4.32	5.26	4.84	1.96	1.90

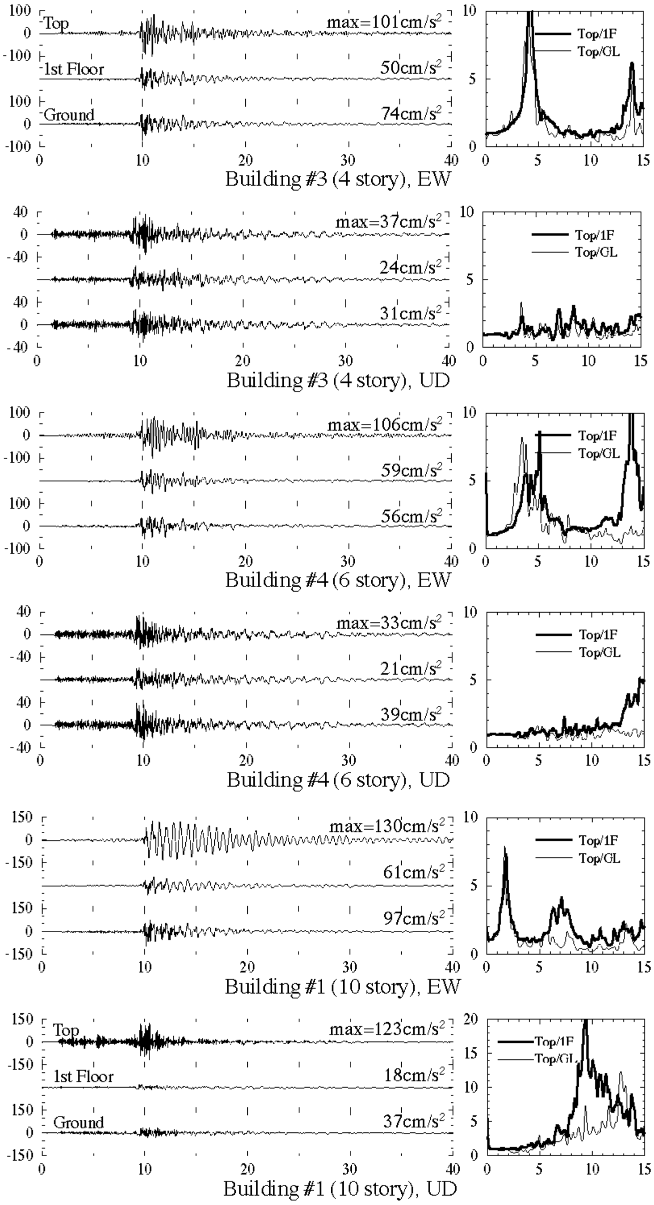


Fig.9 Response acceleration (cm/s2) during Mar. 16, 1997 earthquake, and Fourier spectral ratios (top/1st floor, top/ground).

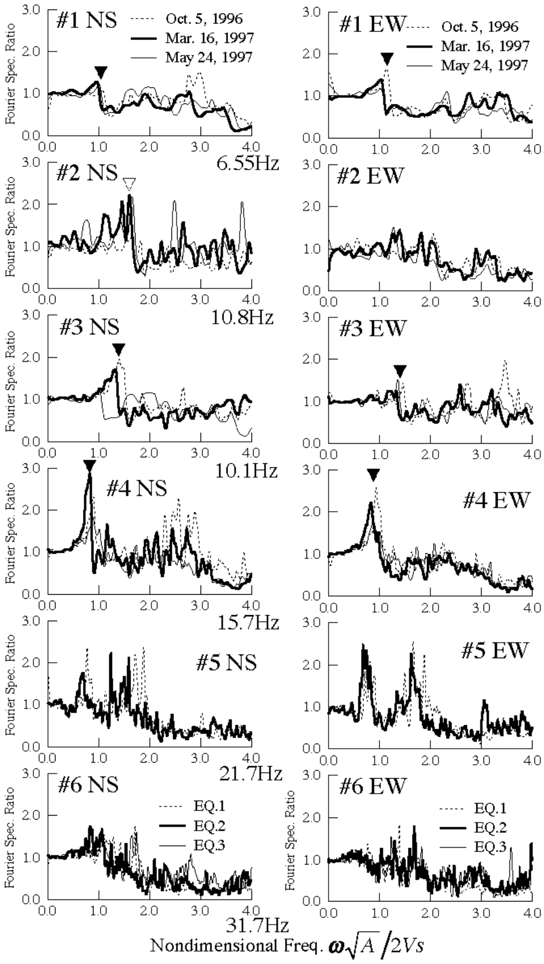


Fig.10 Fourier spectral ratio (1st floor / ground) plotted versus nondimensional frequency

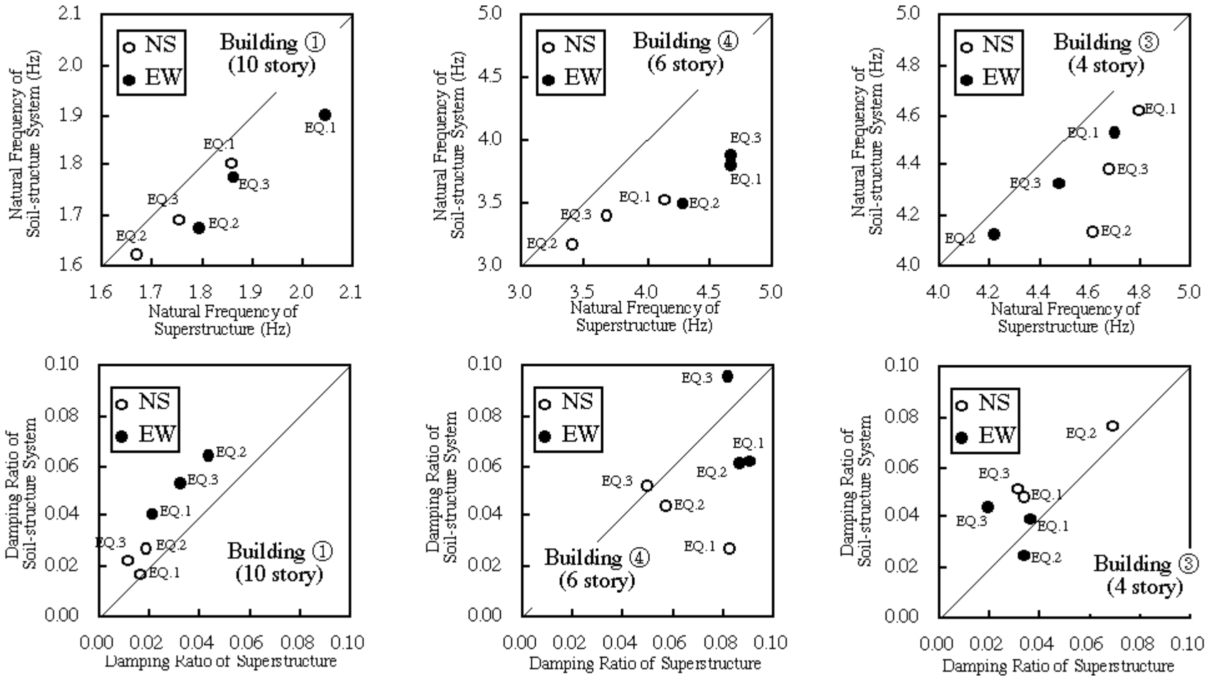


Fig. 11 Correlation between estimated parameters of superstructure and those of soil-structure system

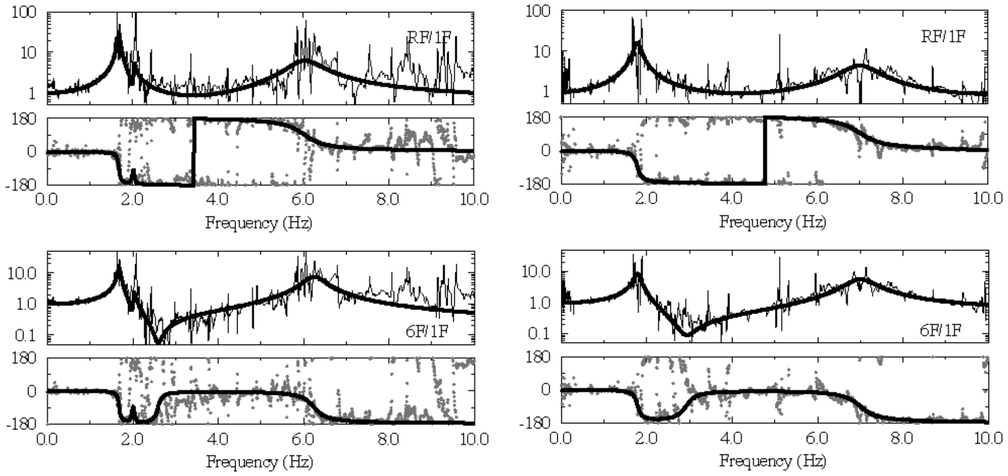


Fig.12 Transfer functions fitting for building #1 (Mar. 16, 1997 earthquake)

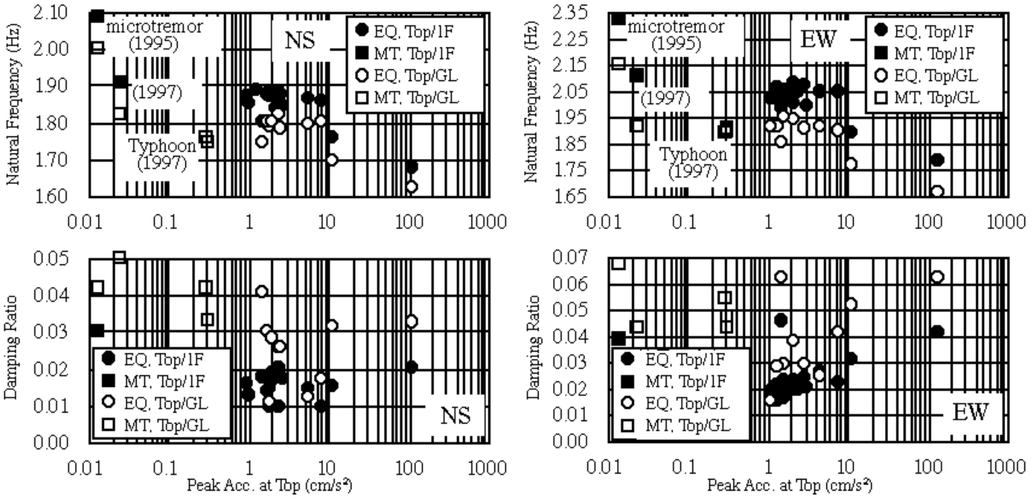


Fig.13 Amplitude-dependency of natural frequencies and damping ratios for building #1

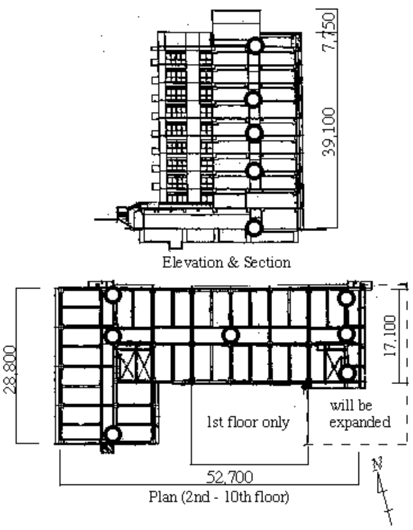


Fig.14 Outline of 10 story building and ambient vibration observation points

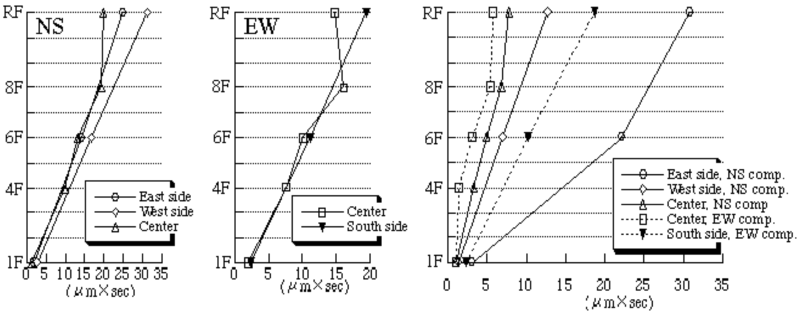
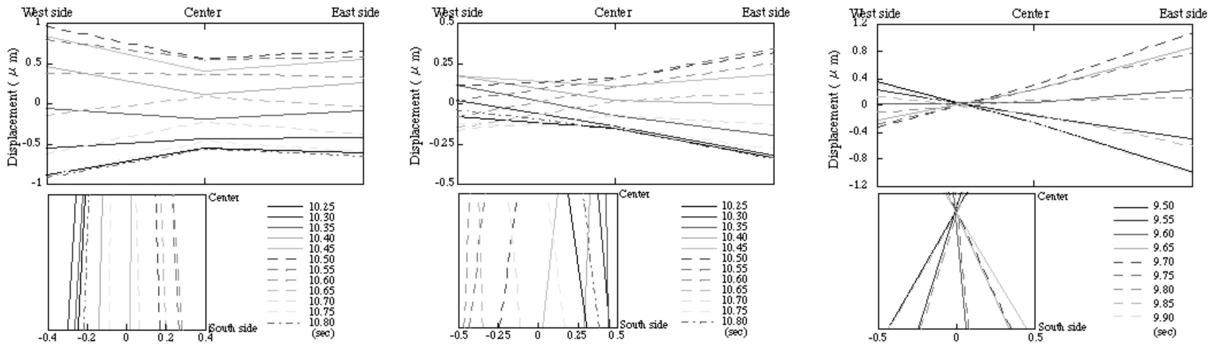


Fig.15 Mode shapes of translational and torsional modes

Table 3 Sway and rocking ratios for NS and EW directions

	West, NS comp.		Center, NS comp.		East, NS comp.		Center, EW comp.	
	Ratio	Amp.	Ratio	Amp.	Ratio	Amp.	Ratio	Amp.
	(%)	(micron sec)	(%)	(micron sec)	(%)	(micron sec)	(%)	(micron sec)
Total Top Disp.	100	31.5	100	19.7	100	24.6	100	14.6
Rocking	26	8.2			50	12.3	22	3.2
Sway	8	2.5	7	1.4	8	2.0	13	1.9
Elastic Deform.	66	20.8			48	11.8	69	10.1
Ground	2	0.6	3	0.6	3	0.6	5	0.7



(a) NS translational mode (1.82Hz)
(b) EW translational mode (1.92Hz)
(c) torsional mode (1.82Hz)

Fig.16 Horizontal vibration shapes of the top floor of translational and torsional modes

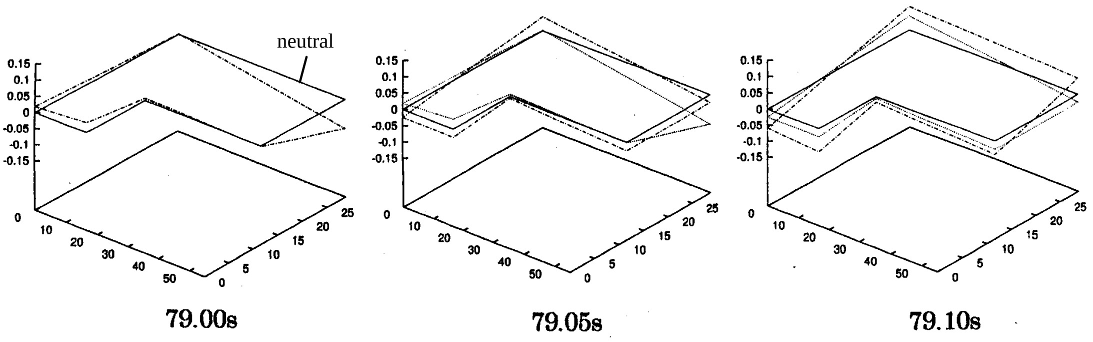


Fig.17 Out-of-plain deformation of the 1st floor (NS translational mode, 1.82Hz)

The spatial vibration shape of the building at the top floor are also presented in Fig. 16 in a different style. In-plane deformation of the top floor is observed in this figure, as the change of the angle of L-shaped plan. Deformation of the first floor slab is shown in Fig. 17. An obvious out-of-plane deformation is observed which is mainly due to different rocking motion in the two sides of the building. This complex behavior complicates the study of SSI effect on this building.

CONCLUDING REMARKS

The effect of SSI on the dynamic properties of structures was studied experimentally. As a result, the dominant effect of SSI for the cases of low and medium-rise buildings was clearly recognized. The main concluding remarks are as follows:

Ambient vibration experiments were conducted on several buildings with the same size but located on different soil conditions. It was concluded that identification of dynamic characteristics of buildings can be quite difficult for cases in which SSI is dominant.

The dynamic behavior of three buildings was studied during three low and medium size earthquakes. The loss in the effective input motion was clearly observed, especially for buildings with large foundations. Also studied was the amplitude dependency of the results which leads to lower frequencies and larger damping ratios for more severe excitations.

The dynamic behavior of a 10-story building was studied precisely through dense ambient vibration measurements. Large rocking motions were observed for the building in spite of existence of pile foundation. Different levels of rocking motion were observed for the two sides of the building due to change in the size of foundation. This leads to out of plane deformation of floors which, in turn, complicates the experimental evaluation of dynamic characteristics of the building.

Throughout all the experimental investigations, the need to improve the knowledge on dynamic properties of ordinary buildings with SSI effect was pointed out, which may be achieved by increasing the quality and quantity of experimental studies.

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