OBSERVATIONAL STUDIES ON DYNAMIC CHARACTERISTICS OF EXISTING SOIL-STRUCTURE SYSTEM

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SUMMARY

By analysing observation records of earthquakes and microtremors observed at an existing building and its surrounding subsoil, are investigeted the changes in the dynamic characteristics and the restoring force characteristics of structure system and soil-structure system with increase of response amplitude level, and the difference between them before and after undergoing large response amplitude. It is concluded that nonlinearity and hysteresis of the restoring force characteristics of the substructure, as well as the superstructure, play an important role on the earthquake response with increase of amplitude level.

INTRODUCTION

Since 1970 the authors have carried out a long term earthquake observations in an existing building, "Kimitsu-Ohwada Apartment House", and its surrounding subsoil. The main purposes of this observations are firstly to know the dynamic behavior of this building and its surrounding subsoil during actual earthquakes, secondly to establish an appropriate dynamical model for the soil-structure system and finally to check the structural soundness of this building under sever earthquake excitations. Before the start of earthquake observations, microtremor observations and forced vibration tests were carried out on this building (Refs. 1,2).

For a part of these purposes, this paper investigates: (i) the changes in the dynamic characteristics and the restoring force characteristics of structure system and soil-structure system with increase of response amplitude level; and (ii) the difference between them before and after undergoing large response amplitude. This study was attempted because 1980 Chiba-ken Chuubu earthquake of IV in JMA intensity scale here (VII in MM scale) was recorded that had the largest response amplitude of this series of observations.

For the purposes mentioned above, 2 sets of microtremor records and 16 sets of earthquake records, which have relatively large amplitude levels, are adopted. In order to investigate the state of change in dynamic characteristics, the fundamental frequencies, the damping factors and the swaying ratios are selected for analysis and the restoring force characteristics are discussed.

BUILDING, OBSERVATION RECORDS AND METHOD OF ANALYSIS

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Building and Soil

The outline of the building, "Kimitsu-Ohwada Apartment House", is shown in Figure 1 together with the soil profile and the location of instruments for earthquake observations. This is an 11 storied building with very long and narrow plan, consisted of steel frames with fireproof covering of concrete and with precast concrete panels, and located at Kimitsu City, Chiba Prefecture, on the east coast of Tokyo Bay. The base of the building is supported by steel piles reaching to sand layer 12 m below the ground surface (Ref. 1).

Observation Records

Microtremor and earthquake observation records used in this study are listed in Table 1. Microtremor observations were carried out two times in 1968 and 1982. 16 sets of earthquake records have been taken during about 10 years after the completion of the building.

As indicator for response amplitude level, peak accelerations at the 11th floor are used. Figure 2 shows peak accelerations of each earthquakes in both directions. The numbers in this figure denote the earthquake serial numbers. The maximum peak acceleration earthquake is the earthquake No.87 of the last of 16 earthquakes (1980 Chiba-ken Chuubu earthquake), which is 100 gal in the longitudinal direction and 130 gal in the transverse direction. The second maximum is the earthquake NO.27 of the middle of these earthquakes, which is 40 gal and 50 gal in each direction. Most others are small amplitude earthquakes of 10-20 gal in the longitudinal direction and 10-30 gal in the transverse direction. On the other hand, microtremor observations are 0.1-0.2 gal (5-7 μ). Then, peak accelerations of earthquake records are several ten to several hundred times comparing with microtremor records.

Method of Analysis

Fourier spectra are calculated by FFT and smoothed by Parzen type spectral window of band width 0.4 Hz for power spectra. As an example, Fourier spectral ratios are shown in Figure 3. The symbol "o" indicates spectral ratio of the 11th floor to ground surface which represents the characteristics of the soil-structure system. The fundamental frequencies are obtained from peak frequency and the damping factors are calculated by the half-power method (the so-called $1/\sqrt{2}$ method). The swaying ratios are calculated from the spectral ratios of the 1st floor to the 11th floor at the fundamental frequency. The symbol "Δ" indicates spectral ratio of the 11th floor to the 1st floor which represents the characteristics of the structure system including rocking motion. The fundamental frequencies and the damping factors of the structure system are obtained in the similar way. In the longitudinal direction, these are corresponding to the characteristics of the fixed-base structure system, because rocking motion is small.

The fundamental frequencies and the damping factors obtained here are considered to be averages over the duration time of records (20-40 sec.). The damping factors are affected by smoothing operation on spectra. However, these procedures are thought to be reasonable to investigate the relationships among records.

COMPARISON BETWEEN MICROTREMOR OBSERVATIONS EXECUTED BEFORE AND AFTER COMPLETION OF THE BUILDING

Table 2 shows the predominant frequencies at the 11th floor. These are considered to be almost same as the fundamental frequencies of the soil-structure system. In the longitudinal direction, the frequency of 3.1 Hz before the completion reduces to 2.8 Hz after the completion. In the transverse direction, 2.1 Hz also reduces to 1.9 Hz. Both reduction rates are almost equal to each other, that is, 10% in the longitudinal direction and 9% in the transverse direction. Then, if these reductions depend only on the increase of weight in the building after the completion, the increase rate of weight is thought to be approximately 20%. This seems to be reasonable judging from the condition of the building at the 1st observations which was on the way of the finish construction and was lack of the live loads. Therefore, it is estimated that the stiffnesses of the superstructure and the substructure scarcely change during this last 14 years, although the building has undergone a number of earthquakes including relatively large response amplitude earthquakes.

CHANGE IN LONGITUDINAL DIRECTION

The dynamic characteristics in the fundamental mode, evaluated from the earthquake records and the 2nd microtremor observation records, are investigated below. Since all of these are obtained after the completion of the building, the conditions of weight in building are considered to be similar in these cases.

Structure System

Figure 4 shows the state of change in the fundamental frequencies. The symbols "o" and "*" denote earthquakes (where numbers are the earthquake serial numbers) and microtremors, respectively. On the whole, the fundamental frequencies are reduced gradually with increase of amplitude level. Microtremor observations are 3.1 Hz and small response amplitude eathquakes of 10-20 gal are 2.8-3.0 Hz except for the earthquake No.41. On the other hand, the earthquake NO.27 of 40 gal is 2.6 Hz and the earthquake NO.87 of 100 gal is 2.4 Hz. While the frequency of the earthquake NO.27 shows the remarkable decrease as mentioned above, there seems no obvious difference between small response amplitude earthquakes before and after this earthquake.

Figure 5 shows the state of change in the damping factors in the fundamental mode. Microtremors are not shown, because their peak shapes of spectral ratios are remarkably asymmteric and are thought to be inadequate for the application of the half-power method. While most small response amplitude earthquakes vary within 5-7%, the earthquakes No.27 and No.87 with relatively large response amplitude are 7%.

Soil-Structure System

Figure 6 shows the state of change in the fundamental frequencies. Microtremor observations are 2.8 Hz and small response amplitude earthquakes are 2.5-2.6 Hz. On the other hand, the earthquake NO.27 is 2.3 Hz and the earthquake NO.87 is 2.1 Hz. Therefore the fundamental frequencies of the soil-structure system decrease with increase of amplitude level, as well as the structure system. There seems no remarkable difference between small response amplitude earthquakes before and after the earthquake NO.27, as well as the structure system.

Figure 7 shows the damping factors. These values are larger generally than those of the structure system as shown in Figure 5. In comparison with microtremor observations (5%) and small response amplitude earthquakes (5-9%), the earthquake NO.87 (12%) is considerably large, although the earthquake No.27 (8%) is not so large.

Figure 8 shows the state of change in swaying ratios in the fundamental mode of the soil-structure system. These values vary widely, but in general increase with response amplitude level. Small response amplitude earthquakes are 10 to 18%. Microtremor observations are 13% which corresponds with the smaller value of these earthquakes. Although the earthquake NO.27 is 11%, the earthquake NO.87 is 24% which is the largest of all swaying ratios.

CHANGE IN TRANSVERSE DIRECTION

Only the fundamental frequencies are investigated here. In the transverse direction, the fundamental frequency in the translational mode is very close to that in the torsional mode. Therefore, there are a lot of cases where the peak shapes of the spectral ratios are not adequate for the application of the half-power method.

Figure 9 shows the fundamental frequencies of the structure system including rocking motion. Microtremor observations are 2.1 Hz, most small response amplitude earthquakes of 10-30 gal are 2.0-2.1 Hz, the earthquake NO.27 of 50 gal is 1.9 Hz, and the earthquake NO.87 of 130 gal is 1.8 Hz. Figure 10 shows the fundamental frequencies of the soil-structure system. Microtremor observations, small response amplitude earthquakes are 2.0 Hz and 1.9-2.0 Hz, respectively. Both of the earthquakes NO.27 and NO.87 are 1.7 Hz. On the whole, the fundamental frequencies of both systems decrease with increase of response amplitude as well as the longitudinal direction.

Although, in the earthquake NO.27, the fundamental frequencies of the structure system including rocking motion and the soil-structure system decrease obviously comparing with small response amplitude earthquakes, there is not large difference between small response amplitude earthquakes before and after this earthquake as well as in the longitudinal direction, as shown in Figures 9 and 10.

DISCUSSION

The state of change in the fundamental frequencies is summarized in table 3 in the form of the ratio to the 2nd microtremor observations. On the whole, reduction rates of the structure system and the soil-structure system are almost equal each other in each direction, and the longitudinal direction is considarably larger than the transverse direction in each system. For example, each reduction rate of 1980 Chiba-ken Chuubu earthquake (maximum response amplitude record of all records used here) to microtremor observations (minimum response amplitude record) is 23-25% in the longitudinal direction and 12-13% in the transverse direction, respectively. Based on the results concerning with the change in the dynamic characteristics, the restoring force characteristics of each part of the superstructure and the substructure are discussed below, mainly in the longitudinal direction.

The dynamic characteristics of the structure system are considered to be affected by nonlinearity and hysteresis of the restoring force characteristics of the superstructure. With increase of response amplitude, the fundamental frequencies decrease due to nonlinearity and the damping factors increase due to hysteresis. The dynamic characteristics of the soil-structure system are also considered to be affected by nonlinearity and hysteresis of the restoring force characteristics of the substructure in addition to the superstructure. Judging from the fact that: (i) the reduction rate of the fundamental frequencies of the soil-structure system is almost equal to that of the structure system; and (ii) the swaying ratios increase with response amplitude level, nonlinearity of stiffness of the substructure is equal to or larger than that of the superstructure. Then, nonlinearity of the substructure, as well as the superstructure, is considered to play an important role on the earthquake response with increase of amplitude level.

As mentioned above in each direction of each system, there seems to be no remarkable difference between the fundamental frequencies of small response amplitude earthquakes before and after the earthquake NO.27 showing obvious reduction. This indicates that the restoring force characteristics scarcely change after undergoing nonlinearity of the stiffness. This agrees with the result derived from the comparison between microtremor observations before and after the completion of the building as mentioned above. In fact the visual cracks were not found after the earthquake No.87.

CONCLUDING REMARKS

The main results of this study can be summarized as follows:

1) With increase of the response peak acceleration level, the fundamental frequencies decrease and the damping factors increase, in the structure system and the soil-structure system.

2) These results can be explained by consideration of the restoring force characteristics. The restoring force characteristics have nonlinearity and hysteresis in the substructure and the superstructure. Then, the effect of nonlinearity and hysteresis of the substructure, as well as the superstructure, plays an important role on the earthquake response.

3) Even if the fundamental frequencies decrease during large response amplitude earthquakes, the fundamental frequencies during small response amplitude earthquakes after them almost return to the value before them, within response amplitude level in this study.

4) This shows that the restoring force characteristics scarcely change for small response amplitude.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Murakami, M., et al., "Earthquake Resistance of a Steel Frame Apartment House with Precast Concrete Panel", Proc. of 5th WCEE, 1973, Rome

[2] Ohami, K., et al., "Earthquake Observation in and around a Steel Frame Apartment House with Precast Concrete Panel", Proc. of 7th WCEE, 1980, Istanbul

Table 1. List of Observations

1968.8	1st Microtremor Observations
(1969	Completion of Building)
1970.5 I 1980.9	Earthquake Observations
1982.7	2nd Microtremor Observations

Table 2. Predominant Frequencies of Microtremor Records at the 11th Floor

Direction	1st Observations (before Completion of Building)	2nd Observations (after Completion of Building)
Longitudinal	3.1 Hz	2.8 Hz
Transverse	2.1 Hz	1.9 Hz

Table 3. Change in the Fundamental Frequencies with Response Amplitude Level in the Form of the Ratio to the 2nd Microtremor Observations

Observations	Longitudinal Direc.		Transverse Direc.	
	Structure	Soil-Structure	Structure with Rocking	Soil-Structure
Microtremors	1.00	1.00	1.00	1.00
Earthquakes of Small Response Amplitude	0.90-0.95	0.87-0.93	0.96-1.02	0.95-1.00
Earthquake No.27	0.84	0.83	0.93	0.89
Earthquake No.87	0.77	0.75	0.87	0.88

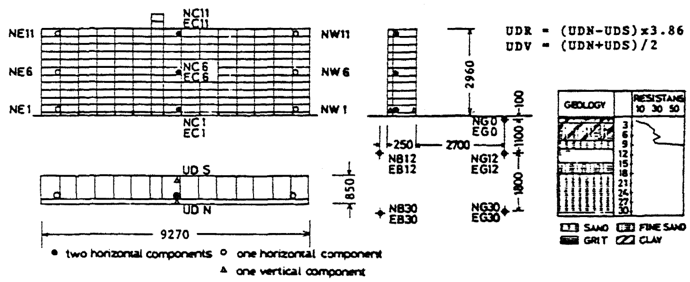

Fig. 1. Outline of Building, Soil Profile and Location of Instruments

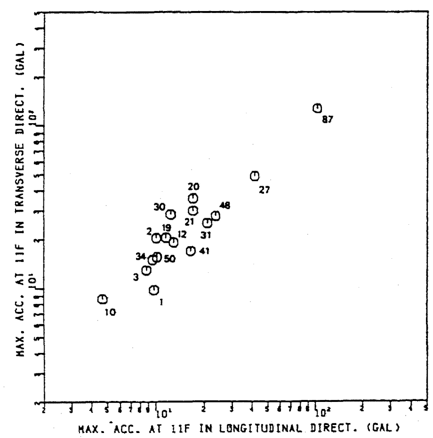

Fig. 2. Peak Accelerations of Earthquake Records at the 11th Floor

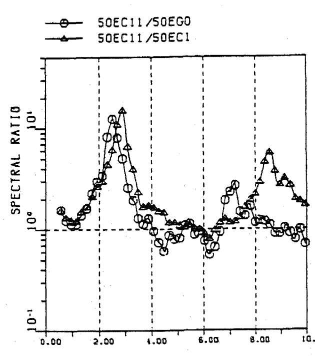

Fig. 3. Example of Spectral Ratios

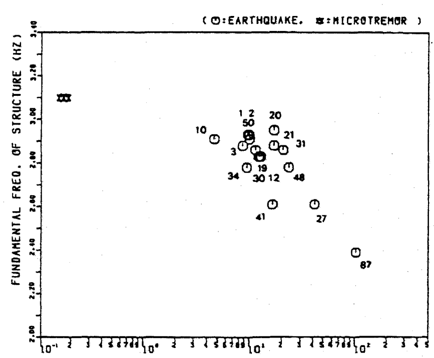

Fig. 4. Fundamental Frequencies of Structure System in the Longitudinal Direction

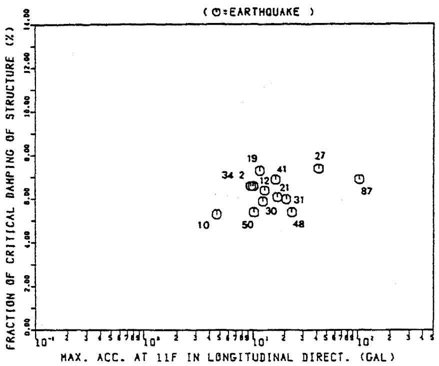

Fig. 5. Damping Factors of Structure System in the Longitudinal Direction

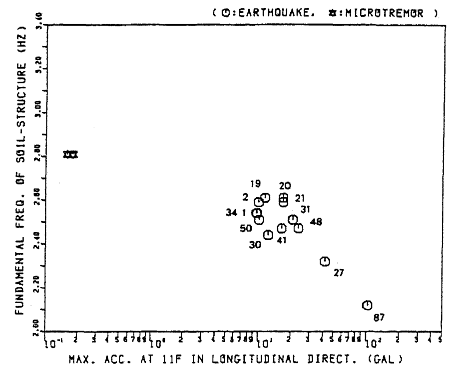

Fig. 6. Fundamental Frequencies of Soil-Structure System in the Longitudinal Direction

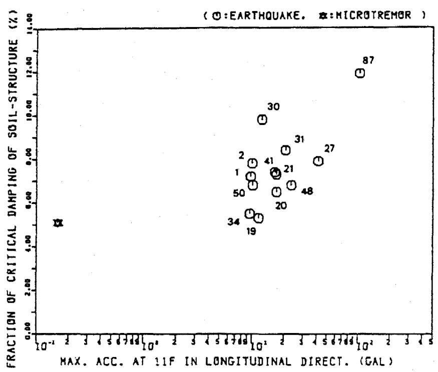

Fig. 7. Damping Factors of Soil-Structure System in the Longitudinal Direction

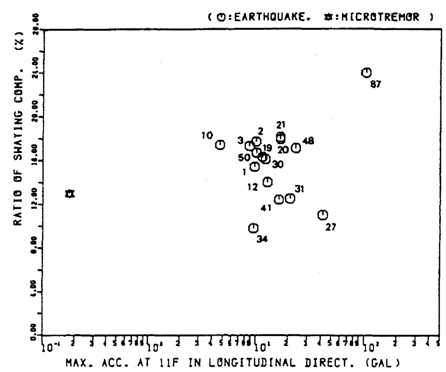

Fig. 8. Ratios of Swaying Motion to Total Motion at the 11th Floor in the Longitudinal Direction

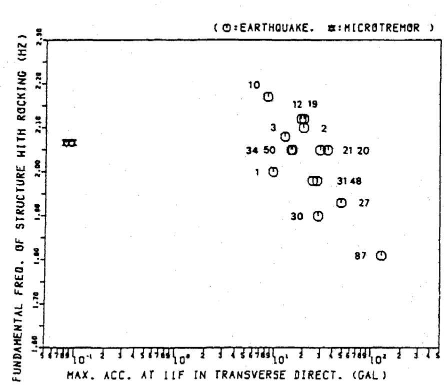

Fig. 9. Fundamental Frequencies of Structure with Rocking Motion in the Transverse Direction

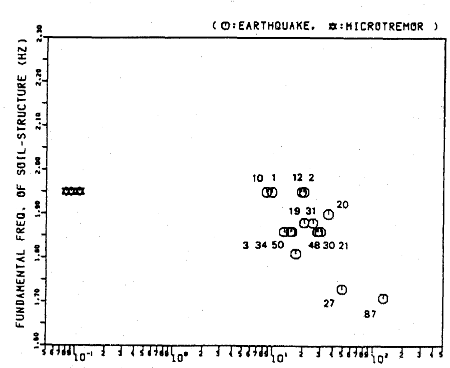

Fig.10. Fundamental Frequencies of Soil-Structure System in the Transverse Direction