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DYNAMIC CHARACTERISTICS OF A R/C BUILDING OF FIVE STORIES BASED ON MICROTREMOR MEASUREMENTS AND EARTHQUAKE OBSERVATIONS

Yasutaka IRIE[1] And Kazuya NAKAMURA[2]

SUMMARY

This paper describes the dynamic characteristics of a R/C building of five stories based on microtremor measurements and earthquake observations.

Natural frequencies of the building during earthquakes distribute from 3.9 to 4.9 Hz. These values of small earthquakes less than 5 gal are nearly equal to those in case of microtremors, and those of larger earthquakes tend to decrease gradually. The damping constants of the building during earthquakes distribute from 1.5% to 8.6% and these values are nearly equal to those in case of microtremors. Fourier spectral ratios between the fifth floor and the first floor around the natural frequency during earthquakes broadly distribute from 3.0 to 18.7, on the other hand, those in case of microtremors distribute narrow range of around 4.0. From microtremor records the soil deflection was also obtained. The swaying and the rocking ratios to the absolute displacements of building in NS direction are about 36 % and 24%, respectively, and those in EW direction are 52% and 8%, respectively. According to the above results, we can evaluate the parameters of analytical model of building and soil. Using this analytical model considering the non-linear stiffness, we can estimate the dynamic behavior of the building during strong earthquakes.

INTRODUCTION

We can not observe strong earthquakes many times, but we can record microtremors at any time and any place easily. Microtremor measurements in and around a R/C building of five stories have been carried out repeatedly since this building was founded. The earthquakes treated in this paper were mainly observed from 1995 to 1998 at the first and the fifth floor of the R/C building in three components. The number of earthquakes recorded till now are over 150. And from June 1999, one more observation site was set on the subsoil of this building. Therefore, the phenomenon of soil-building interaction can be investigated from earthquake observations and microtremor measurements. Furthermore, we try to suppose the behavior of the building during strong earthquakes in accordance with the dynamic characteristics of building in case of microtremors and small earthquakes.

First of all, we investigate the dynamic characteristics of this building and its subsoil from the microtremor measurements and earthquake observations. At the same time, the transitions of these characteristics with the time passage are investigated. And then, we investigate the dynamic behavior of the building during strong earthquakes comparing with the analytical results based on the non-linear mass-spring system. These results are useful to design buildings suffering from strong earthquakes.

[1] *Department of Architecture, Faculty of Engineering, Utsunomiya Univ., JAPAN. E-mail: iriey@cc.utsunomiya-u.ac.jp*
[2] *Department of Architecture, Faculty of Engineering, Utsunomiya Univ., JAPAN. E-mail: iriey@cc.utsunomiya-u.ac.jp*

2. OUTLINES OF SUBSOIL AND BUILDING

The observation site exists in the campus of Utsunomiya University. The soil is consists of loam of six meters thick on hard gravel as shown in Fig. 1. The spectral ratios of microtremor on soil in horizontal component to that in vertical component called H/V spectral ratios are shown in Fig. 2. From this figure, it is recognized that the predominant frequency of the soil is about 6.2 Hz. The objective building is a R/C structure of five stories, the section and the plan of which are shown in Fig. 3. Seismometers of three components are established in this building of the fifth and the first floor and also on its subsoil. Moreover, we set up seismometers for microtremor measurements as shown in Fig. 4.

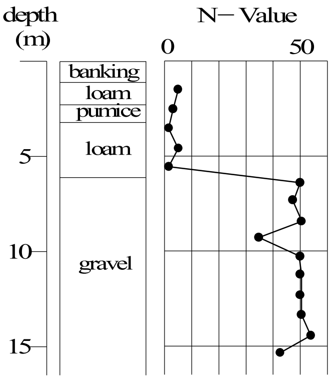

Fig.1
Soil profile

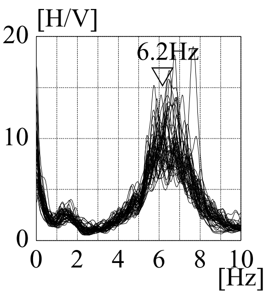

Fig.2 H/V spectral ratios of soil

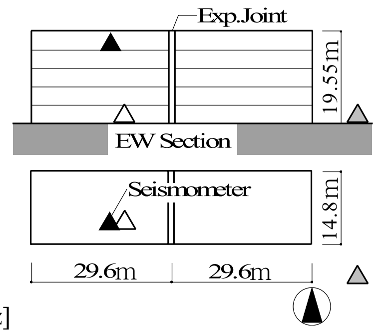

Fig.3
Outline of the building

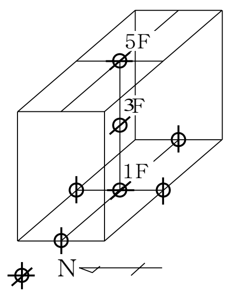

Fig.4 Location of seismometers

3. OUTLINE OF MICROTREMOR MEASUREMENTS AND EARTHQUAKE OBSERVATIONS

The number of earthquake observed from 1995 to 1999 is 152. The sensing instruments named Altus K2 made by Kinemetrics co. ltd. are acceleration type seismometer having three components. The distribution of maximum acceleration of earthquakes observed at the first floor of this building is shown in Fig. 5. The seismic intensities of most earthquakes are rather small. Therefore we adopt for analysis such earthquakes as the maximum acceleration at the first floor of the building are larger than 5 gal. The number of earthquakes adopted for analysis is 41.

The sensing instruments for microtremors are one component moving-coil velocity type seismometer having a natural period of 1.0 sec, damping constant of 0.7 sensitivity of 3 volts/kine. All of the data are recorded by digital form at sampling frequency of 100 Hz.

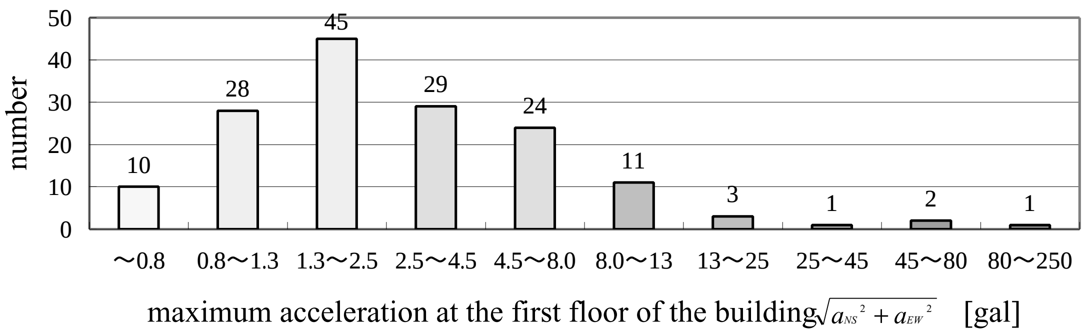

Fig.5 Distribution of seismic intensity of observed earthquakes

4. DYNAMIC CHARACTERISTICS OF A RC BUILDING OF FIVE STORIES

4.1 Natural Frequency:

Time length of one datum for analysis is 20.48 seconds. The normalization of Fourier spectra is carried out by means of Parzen's spectral window, the band width of which is 0.4 Hz. Fourier spectra of NS and EW components of microtremors at the fifth floor are shown in Fig. 6. Fourier spectral ratios of the fifth floor to the first floor and the fifth floor to the soil are shown in Fig. 7 and Fig. 8, respectively. Every line shows a spectrum and a spectral ratio obtained from one record length. In case of earthquakes similar spectra and spectral ratios are shown in Figs. 9,10 and 11. From Fig.7 and Fig.10, natural frequency of this building including rocking of foundation (fb), are 4.5 Hz in NS component and 5.4Hz in EW component. From Fig. 8 and Fig. 11, the natural frequency of this building including soil deformation (fsb), are 3.5Hz in NS component and 3.8 Hz in EW component. Next, to investigate the relation between the natural frequency (fb) and the maximum acceleration at the first floor of the building (x_{1max}), we make Fig. 12. The average results in NS and EW components obtained from microtremors are shown by star marks in this figure. A straight and dotted lines show approximate relations in NS and EW component, respectively. From this figure, natural frequencies tend to decrease gradually with larger earthquakes. It is considered that the stiffness of the building decreases because of the friction of non-structural member of the building during larger earthquakes.

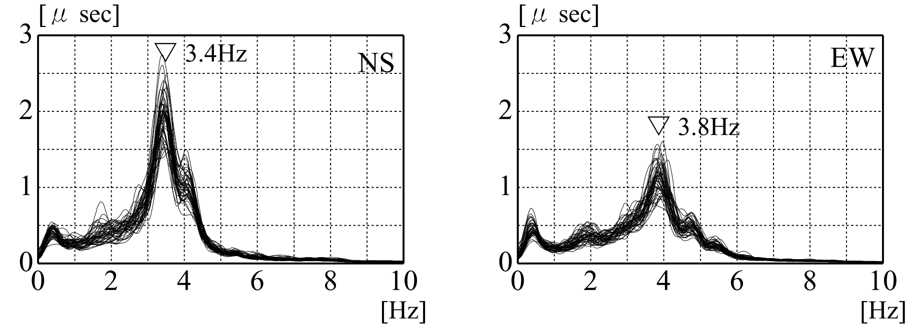

Fig.6 Fourier spectra of microtremors at the fifth floor

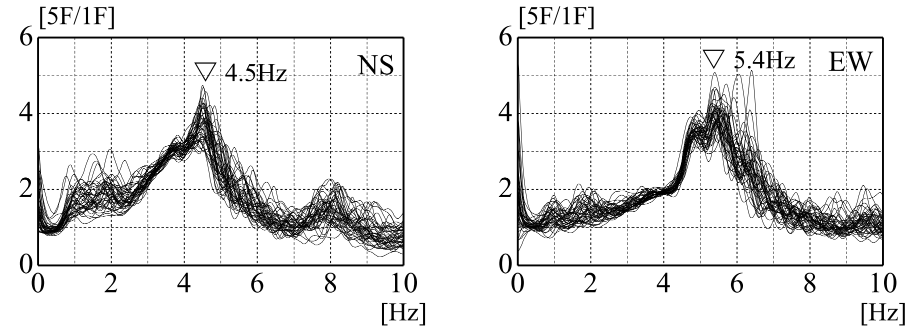

Fig.7 Fourier spectral ratios of microtremors of the fifth floor to the first floor

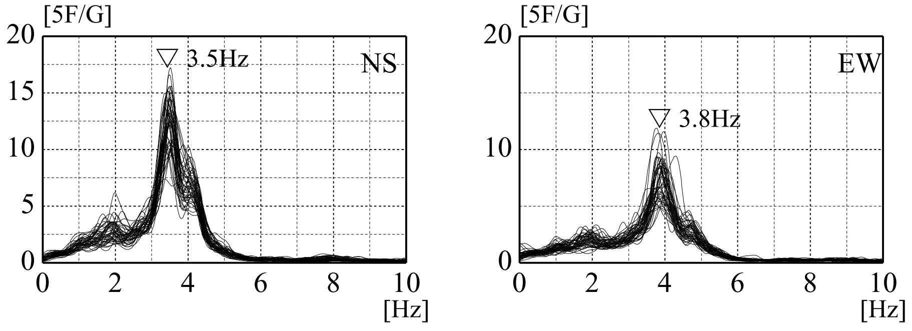

Fig.8 Fourier spectral ratios of microtremors of the fifth floor to the soil

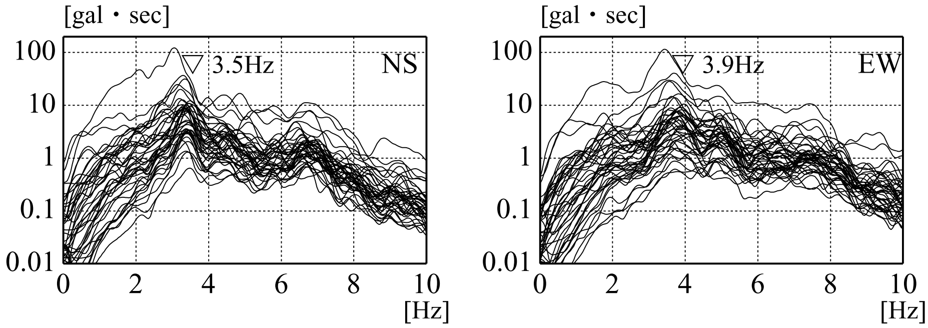

Fig.9 Fourier spectra of earthquakes at the fifth floor

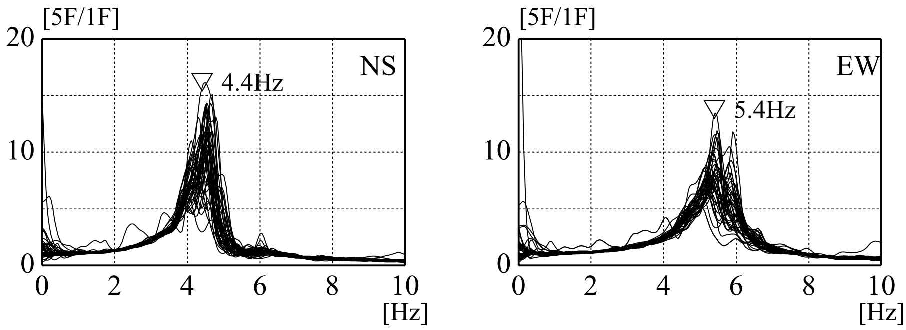

Fig.10 Fourier spectral ratios of earthquakes of the fifth floor to the first floor

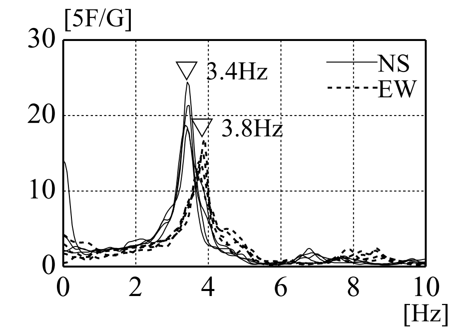

Fig.11 Fourier spectral ratio of earthquakes of the fifth floor to the soil

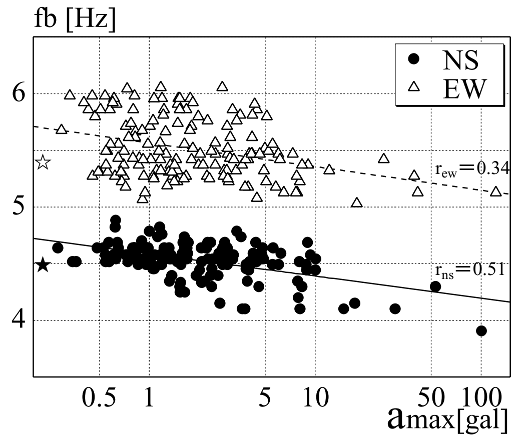

Fig.12 Natural frequencies (f_b) vs.maximum acceleration at the first floor of the building (x_{1max})

4.3 Damping Constant:

Damping constants are obtained by the RD method. To complete free waves, many data (n=7800) can be used from microtremors but a limited number (n=314) of data can be used from earthquakes because of the limited length of seismic records. So, we take a decreasing part of free waves made by RD method in case of analyzing seismic records shown in Fig.13. The relation between the damping constants and the maximum acceleration of earthquakes at the first floor of the building (x_{1max}) is shown in Fig. 14. The average damping constant of microtremors and earthquakes in NS component are 5.1 % and 3.8 %, respectively, and those in EW component are 5.6 % and 5.1 %, respectively. It could be recognized that the damping constants of small earthquakes are nearly equal to those of microtremors. Any other useful results can not be found out from this figure. Next, the relation between the damping constants and the natural frequencies (fb) are shown in Fig. 15. From this figure, any useful results can not also be found out.

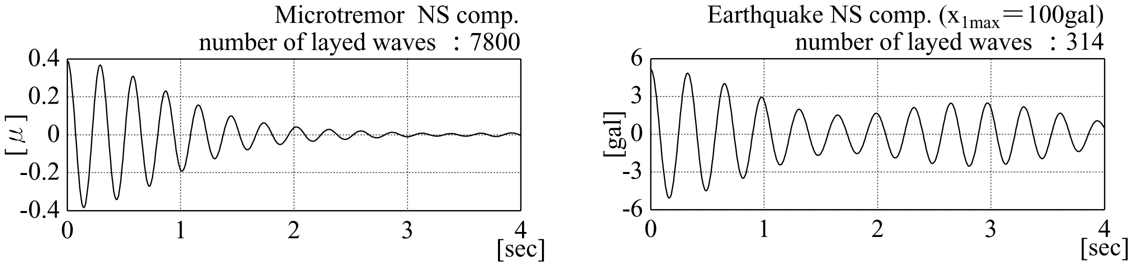

Fig.13 Free vibration wave by RD method

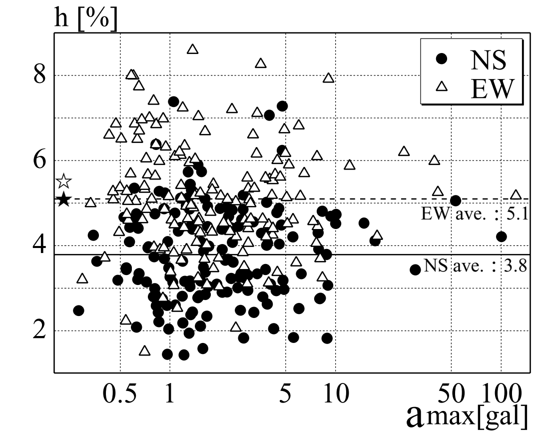

Fig.14 Damping constants vs. x_{1max}

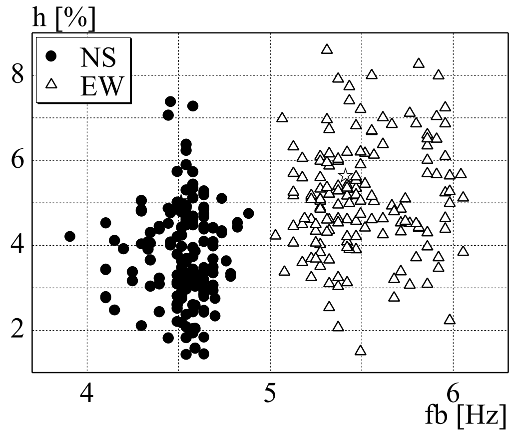

Fig.15 Damping constants vs. natural frequencies (fb)

4.3 Deformation of Soil:

To investigate the mode shape around the natural frequency, smoothing of waves are carried out. The Fourier amplitude spectra (F.A.S.) around the natural frequency (fsb) are cut out by a band pass filter. Band width of the filter is 0.5 Hz and height of it is 1.0, and both side of this rectangular filter having the cosine taper of 0.5 Hz. The smoothed waves are obtained by transforming these cut out F.A.S. to the waves of time domain. The swaying and the rocking ratios (Rs and Rr) are defined as Rs=Xb/Xt×100, Rr=Xr/Xt×100, respectively. In this definition, Xb contains both the ground motion (Xg) and the horizontal deformation of the soil (Xs) produced by the soil building interaction shown in Fig. 16. At a peak period of these smoothed waves, swaying and rocking ratios (Rs and Rr) are calculated, and time histories of these ones of 10 seconds are shown in Fig. 17. Average values of swaying and rocking ratios obtained from microtremors of about 20 minutes in NS component are 36% and 24%, respectively, and those in EW component are 52% and 8%, respectively.

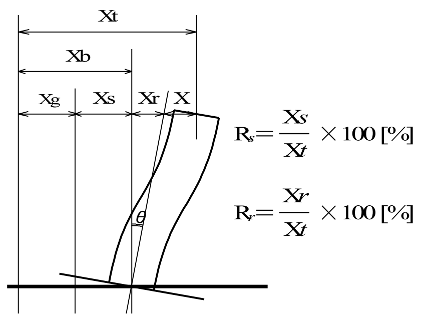

Fig.16 Definition of swaying and rocking ratios

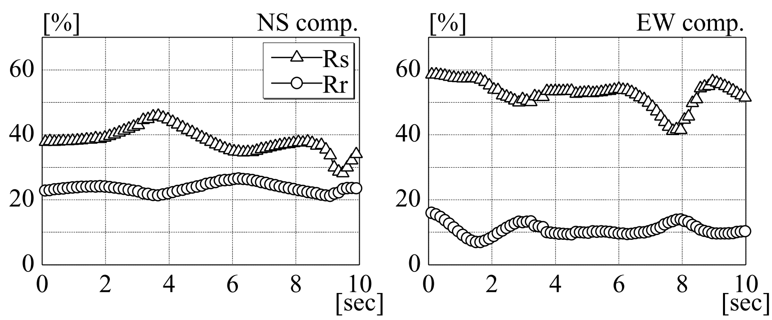

Fig.17 Time histories of swaying and rocking ratios

4.4 Amplification in the building:

The amplification of maximum acceleration between the fifth floor and the first floor corresponding to the maximum acceleration at the first floor in every component are shown by respective marks in Fig. 18. The amplification gradually decreases with the maximum acceleration at the first floor. The averages of amplification are 1.6 in NS component, 1.8 in EW component and 1.2 in vertical component. Next, Fourier spectral ratios of the fifth floor to the first floor corresponding to the maximum acceleration at the first floor in horizontal component are shown by respective marks in Fig. 19. The averages of spectral ratios in case of earthquake are 11.0 in NS component and 9.0 in EW component, these values are considerably large in comparison with the values of star marks in this figure in case of microtremors (3.9 in NS component and 4.2 in EW component).

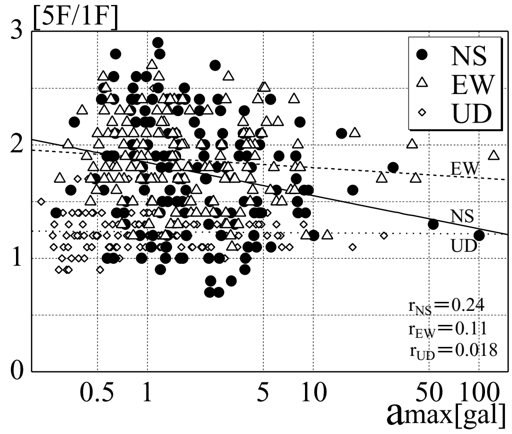

Fig.18 The amplification of maximum acceleration between the fifth and the first floor vs. x_{1max}

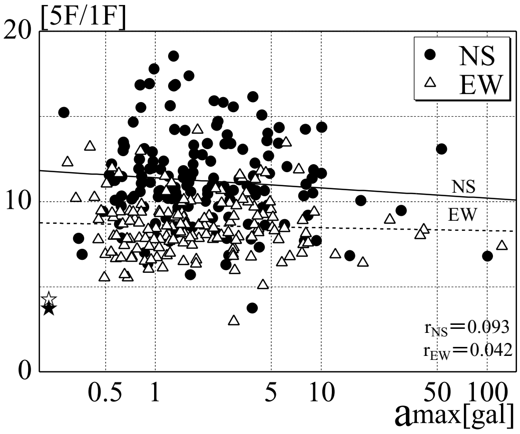

Fig.19 Fourier spectral ratios of the fifth to the first floor vs. x_{1max}

4.5 Summary of the dynamic characteristics of the building:

The dynamic characteristics of the building obtained from earthquake observations and microtremor measurements are shown in Table 1. As the microtremor measurements have been carried out many times [1], we can also investigate a transition of the dynamic characteristics of this building in Table 2. From this table, the natural frequency and the damping constant has not changed remarkably, but the rocking ratio of the foundation has decreased by about 40 % with the passage of 17 years.

Table 1 Dynamic characteristics of the building

Charcteristics / Component	Natural freq. f_b[Hz]		Damping constant [%]		Fourier spectral ratio [5/1]	
	Microtremor	Earthquake	Microtremor	Earthquake	Microtremor	Earthquake
NS	4.5	4.4 (3.9～4.9)	5.1	3.8 (1.5～7.5)	3.9	11.2 (3.8～18.7)
EW	5.4	5.4 (5.0～6.1)	5.6	5.1 (1.5～8.6)	4.2	8.6 (3.0 ～14.2)

Table 2 Transition of the dynamic characteristics of the building with time

	Natural freq. [Hz] (bldg. sys.)		Natural freq. [Hz] (soil-bldg. sys.)		Damping const. [%]		Swaying ratio [%]		Rocking ratio [%]	
	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW
1982	4.7	5.4	3.5	3.8	4.6	8.2	32.1	28.9	35.7	15.8
1985			3.4	3.8	3.8	3.5	33.0	45.2	31.0	13.6
1998	4.5	5.9	3.4	3.8	4.1	5.8	32.0	40.0	26.0	12.0
1999	4.5	5.3	3.4	3.8	5.1	5.6	35.8	51.8	23.6	8.4

5. RESPONSE ANALYSIS AND THE COMPARISON OF MEASURED AND CALCULATED RESULTS

5.1 Analytical model:

The analytical model consists of two independent mass-spring system considering soil-building interaction shown in Fig. 20. According to the above results and the size of structural members as beams, columns and walls etc., we can evaluate the parameters of analytical model of building and soil. We assume two cases about the soil. First, the equivalent stiffnesses of the soil are assumed as frequency independent linear ones proposed by Parmelee [2]. These ones are modified by considering the existence of piles. First of all, we estimate the rocking stiffness of soil (Kr) so as to coincide the peak frequency of the building (fb) obtained from the earthquake observation with one from the analysis. And then, we modified the rocking and swaying stiffnesses (Kr,Ks) to reach the satisfied agreement between observed and analyzed Fourier spectra. Second, the swaying stiffness of the soil are assumed non-linear proposed by Hardin-Drnevich[3]. The parameters employed in this analytical model are shown in Table 3 and Table 4.

The analysis is carried out by the Newmark's β method every 0.01 second.

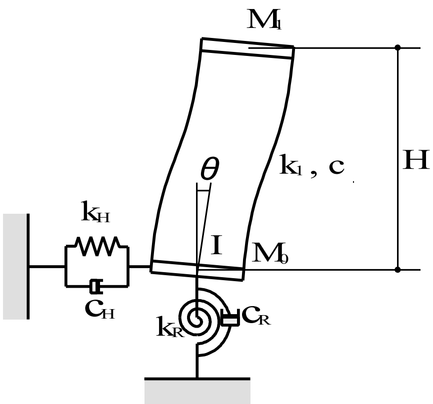

Fig.20 Analytical model

Table 3 Parameters of the analytical model

M1	2.42	[$t\cdot sec^2/cm$]
K1	2.7×10^3	[t/cm]
C	4	[$t\cdot sec/cm$]
M0	1.49	[$t\cdot sec^2/cm$]
Kh	4.4×10^3	[t/cm]
Ch	1.3×10^2	[$t\cdot sec/cm$]
I	5.4×10^6	[$t\cdot sec^2\cdot cm/rad.$]
Kr	7.1×10^9	[$t\cdot cm/rad.$]
Cr	4.7×10^6	[$t\cdot sec\cdot cm/rad.$]
H	1350	[cm]

Table 4 Soil parameters of the H D model for the swaying model

initial stiffness	$G_0=?V_s^2$	9.4×10^4 [$t/m\ sec^2$]
shear strength	$Q_u=t_{max}\cdot A$	1.1×10^4 [t]

$\rho=1.5\ t/m^3$, Vs=250 m/s , τ_{max}=2.5 kg/cm2 , A=14.8m×29.6m (see Fig. 3)

5.2 Comparison of measured and calculated results:

Observed waves on the subsoil are adopted as an incident wave of this analytical model. Response waves and it's Fourier spectra at the fifth and the first floor of the building are shown in Fig. 21 and Fig. 22, respectively. From Fig. 21, the analytical waves simulate observed ones fairly well at first sight. From Fig. 22, the peak frequencies are simulated fairly well, but the analytical peak value around 3.5 Hz of natural frequency of the soil-building system (f_{sb}) is a little small compared with the observed one even if the non-linearity of the soil is considered. The main reasons of these discrepancies are as follows; The piles are not adapted in this model. The estimation of the stiffnesses of the soil are not sufficient.

Anyway this simple analytical model can simulate the actual phenomenon fairly well. So, using this analytical model considering the non-linearity of stiffness of soil and building, we can estimate the dynamic behavior of the building during strong earthquakes.

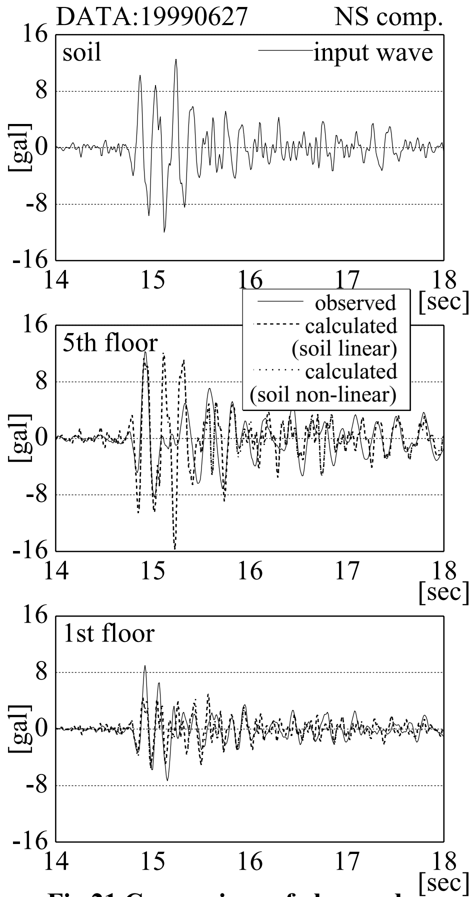

Fig.21 Comparison of observed and analytical waves

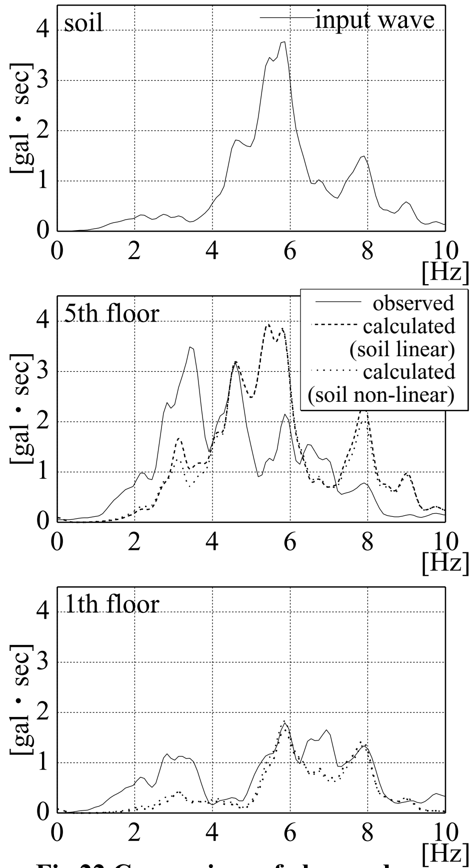

Fig.22 Comparison of observed and analytical spectrum

6.CONCLUSIONS

Main results of this study are as follows;

1. Natural frequency of the building including soil deformation of rocking tends to decrease with larger earthquakes.
2. The damping constants of small earthquakes are nearly equal to those of microtremors.
3. Average values of swaying and rocking ratios obtained from microtremors of about 20 minutes in NS component are 36 % and 24 %, respectively, and those in EW component are 52 % and 8 %, respectively. The rocking ratio has decreased by about 40 % with the passage of 17 years.
4. The averages of amplification of maximum acceleration between the fifth floor and the first floor are 1.6 in NS component, 1.8 in EW component and 1.2 in vertical component.
5. A mass-spring system considering soil-building interaction is adopted as an analytical model. A relatively good agreements are obtained between the observed and calculated waves and spectra.

7. REFERENCES

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