

# A Study on Dynamic Soil-structure Interaction Effect Based on Microtremor Measurement of Building and Surrounding Ground Surface

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Design and evaluation of building during earthquake is moved to be a performance based one. For the performance based design, behaviors of buildings are clarified more precisely based on data of earthquake motion observation. But in general buildings, the earthquake motion observation is not popular, especially, for purpose of soil structure interaction (SSI). Under a few points of accelerometers, a detailed analysis for SSI phenomena is not easy and many assumptions are needed. Here, the SSI effects of building are investigated based on a microtremor measurement. The instruments were set in the building and on the ground to evaluate the sway, rocking and torsional vibrations. The building is 7-storied residential one with flamed structure in longitudinal direction and pre-cast walled structure in transverse direction. Through transfer functions of buildings, predominant frequencies under sway, rocking mode and those of base-fixed condition are calculated. The SSI effect is remarkable in transverse direction due to predominant rocking mode. Also based on the random decrement technique, the damping factor of buildings is obtained. It is founded that the damping factors are around 5 to 6% under the microtremor level.

## INTRODUCTION

Inertial forces of superstructure, that is, base shear, inertial forces of embedment and overturning moments will be transferred to supported grounds (through piles when pile foundations). When the supported grounds are soft, the base fixed condition is not satisfied.

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The phenomena of the displacement and rocking angle of foundations by the base shear and overturning moment, so-called “soil structure interaction (SSI)” occur. The phenomena are the “inertial soil structure interaction”. On the other hand, the effect of SSI related to seismic input motions to the buildings is called the “kinematic soil structure interaction”. As a result of the horizontal and rocking motions due to the SSI, characteristics of superstructure are changed as follows;

- 1) Elongation of natural period (compared with base fixed condition)
- 2) Change of damping factor (compared with base fixed condition)

The Building Standard Law and its related enforcement and notices were revised for the direction to the performance-based design from 1998 in Japan. The calculation method of response and limit strength was provided for checking serviceability and safety of buildings. The calculation procedure is based on the response spectrum method. The acceleration response spectrum, and equivalent period and damping factor of 1st mode have to be evaluated [Midorikawa, et al., 2000]. The amplified characteristics of surface ground and SSI effects should be considered. A simplified method for incorporating SSI effects is proposed in the calculation [Iiba, 2001].

In order to complete performance-based design, it is important that not only structural characteristics and seismic behaviors of buildings but characteristics of earthquake motions to buildings have to be made clear. Especially, the SSI and earthquake motions are influenced by characteristics of surface ground. The evaluation including ground characteristics is necessary.

The paper focuses fundamental predominant frequency and damping factor of residential buildings through microtremor measurements to estimate the fundamental characteristics of the SSI phenomena. The effect of SSI on a transverse (span) direction of the residential buildings is remarkable due to many continuous walls in the direction. However, earthquake motion observations of residential buildings are not popularly conducted. The microtremor measurement is effective to evaluate the SSI effect on these buildings [Yagi, et al., 2002].

Using data measured in buildings and surrounding ground surface, transfer functions of the systems are calculated which including characteristics of sway, rocking and building modes. Based on the transfer functions, predominant frequencies of sway, rocking modes and

those of base fixed condition are compared. And the damping factors of the buildings are evaluated through the random decrement method (RDM) [Tamura, et al., 1993].

### OUTLINES OF BUILDINGS AND GROUND

A plan at ordinary floor and a section in the transverse direction of the buildings are drawn in Fig. 1. A bird-eye view of the building is presented in Photo 1. The buildings, which have 7-storied residential ones with central corridor at longitudinal direction, are constructed in a central area of Tsukuba, Japan. There are three and nine spans in transverse and longitudinal directions, respectively. A ratio of transverse to longitudinal widths is 1:3.2 and ratios of width to height in both directions are 0.46 and 1.47.

The buildings are composed of girders of reinforced concrete (RC) structure, columns of steel RC structure and floors and walls of pre-cast RC boards. The buildings are supported by the individual foundation with pre-stressed concrete piles. The site map is illustrated in Fig. 2. The same buildings called A- and B-buildings are constructed with distance of about 70 m between them. There is a main load on the north side and a load on the west.

The soil condition at the site is drawn in Fig. 3. There is a loam layer whose N values are about 5 within

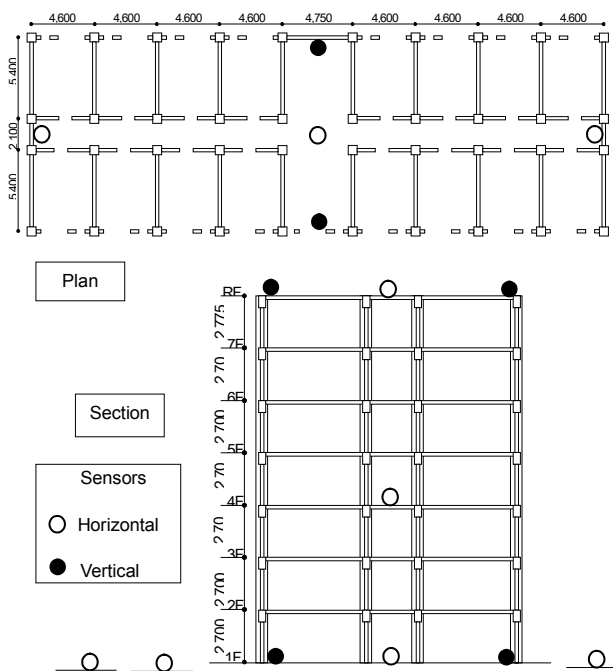


Fig. 1 Plan and section of building measured in microtremor, including the positions of velocity-type sensors in building and surrounding ground surface



Photo 1 Bird eye view of building

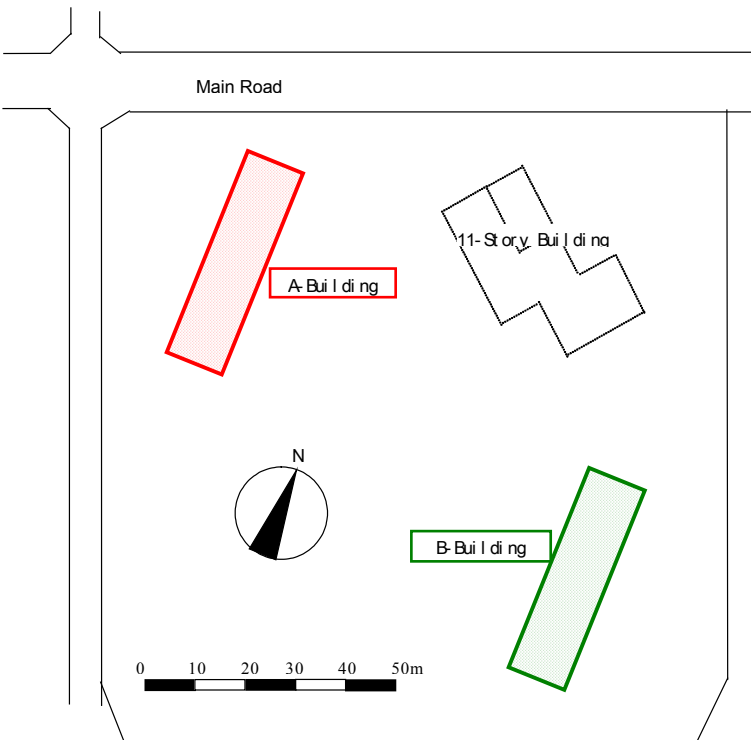


Fig. 2 Site situation of two building, which are the same geometrical and structural conditions

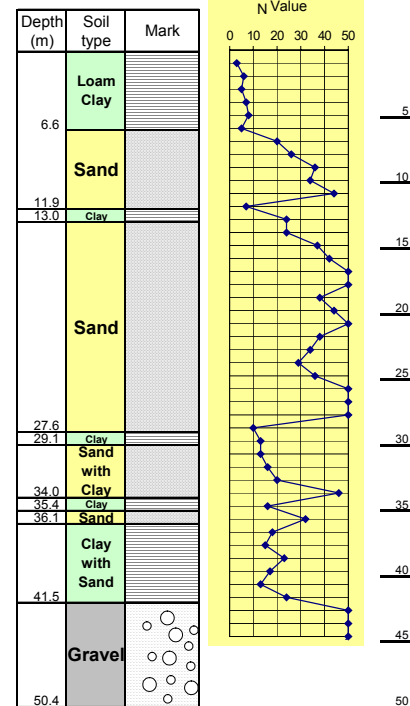


Fig. 3 Ground condition with soil types and standard penetration values (N-values)

6.6 m in depth from ground surface. The N values of following layers increase to about 20 to 40. The sandy layers between 17 to 27 m in depth have N value more than 30. The sandy and clayey layers are laminated in 28 to 41 m and in deeper depth gravel layers with more than 50 of N value can be found.

### OUTLINES OF MEASUREMENT

Sources of the vibration of buildings are in the following;

a) Microtremor

The microtremors in the buildings and on the ground surface are measured. Periods of measurement are 600 or 500 s and 7 or 8 sets of these periods are recorded. The interval of records is 0.005 s.

b) Oscillation by human bodies

The forced vibration test is carried out. 6 to 7 persons exert their forces to columns in the center at 7th floor. The forced vibration with near 1st predominant frequency and in 10 s of period is repeated at several times.

Measuring points and their marks in transverse and longitudinal directions are shown in Fig. 4. Three horizontal and two vertical sensors on the roof and 1st floor, one horizontal one on the 4th floor are set in the buildings. Three horizontal sensors are installed on the ground surface with 13m at both sides and 26m at one side far from the building. The sensor arrangements are the same in both buildings.

Types of sensors are different between buildings. Velocity transducers with servo type (VSE-15D, Tokyo Sokusin Co. Ltd.) and those with moving-coil type (Sindo Giken Co. Ltd.) are used in the A- and B-buildings, respectively. The unit of measured data is velocity.

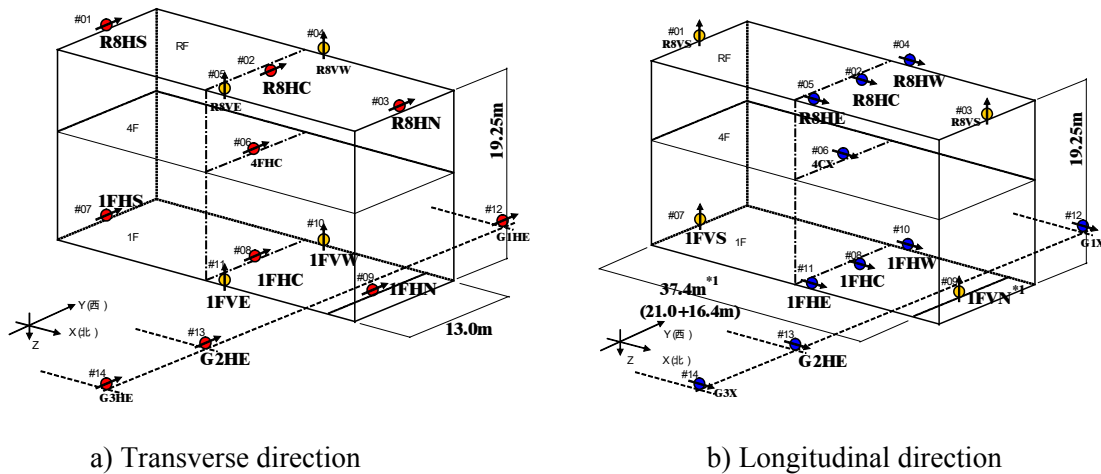


Fig. 4 Locations and marks of sensors in building and ground surfaces in longitudinal and transverse directions

## EFFECTS OF SWAY AND ROCKING ON VIBRATION CHARACTERISTICS

In order to investigate effects of the SSI on the vibration characteristics of buildings, relationships between input and response are clarified using the simplest vibration model with one mass, sway and rocking stiffness. Based on the microtremor measurement data, predominant frequencies are evaluated in transfer functions of response to input motion. The comparison of predominant frequencies between longitudinal and transverse directions and between two buildings is conducted.

### Simple Sway and Rocking Model

The vibration system with surrounding ground is assumed to be the sway and rocking model [Stewart, et al., 1998] shown in Fig. 5. Following systems are considered.

- a) Sway and rocking model (SBR-system)
- b) Rocking model (RB-system)

c) Building model with base fixed (B-system)

In each system, the relationship between input and response is presented in Table 1.

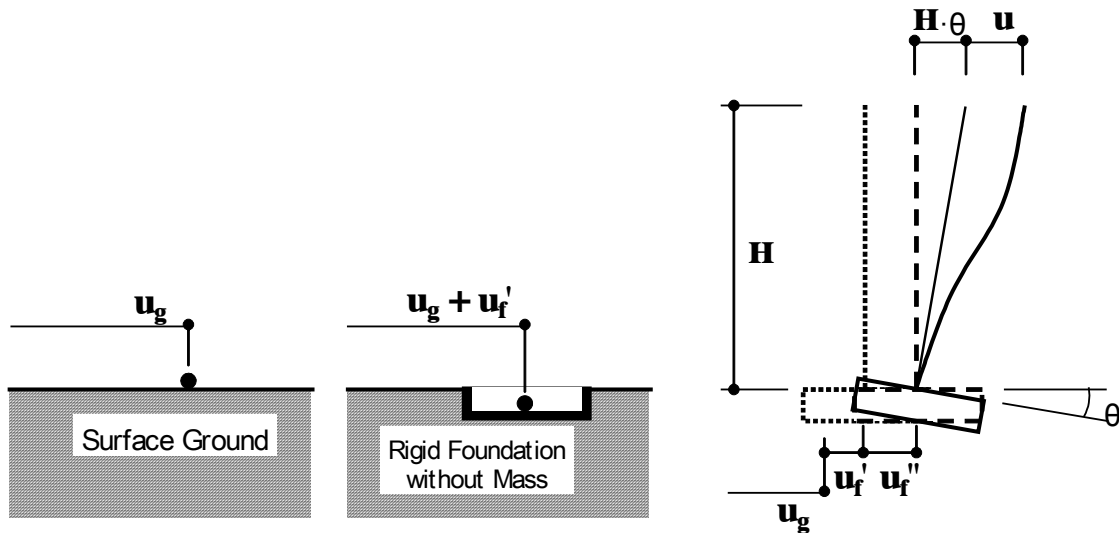


Fig. 5 Definition among displacement at ground surface, sway and rocking displacements and building displacement

Table 1 Relationship between input and response based on displacements shown in Fig. 5

System		Input	Output (Response)
1)	SRB	$u_g$	$u_g + u_f + H \cdot \theta + u$
2)	RB	$u_g + u_f$	
3)	B	$u_g + u_f + H \cdot \theta$	

$u_g$  : Free Surface Ground Motion

$u_f'$  : Foundation Input Motion

$u_f''$  : Sway

$u_f$  : 1st Floor Motion Relative to Free Surface  
( herein assumption to  $u_f = u_f' + u_f''$  )

$u$  : Top Response Relative to 1st Floor

$H$  : Height of Building

$\theta$  : Rocking Angle at 1st Floor

**Relationship between Input and Response in Measured Data**

The measurement points and arranged data in buildings and on ground surface according to relationships between input and response in Table 1 are expressed in Table 2. The measurement points and marks are referred to information in Fig. 4. The arranged data are calculated in time domain. In case that there are the plural data at the same levels, for

example, at the roof, averaged ones on the floor are used. The rocking angle at the 1st floor is obtained by vertical data on the both ends of buildings. In the longitudinal direction, though it is not clear that a rigid (uniform) rotation occurs, the displacement due to rocking is considered.

Table 2 Measurement points and arranged data in buildings and on ground surface

Input and Output for Analyzed System		Transverse Direction (A and B-building)	Longitudinal Direction (A-building)	Longitudinal Direction (B-building)
Output of SRB, RB, B $u_g+u_r+H\theta+u$		$(R8HC+(R8HN+R8HS)/2)/2$	$(R8HC+(R8HW+R8HE)/2)/2$	
Input for SRB $u_g$		G2HE		
Input for RB $u_g+u_r$		$(1FHC+(1FHN+1FHS)/2)/2$	$(1FHC+(1FHW+1FHE)/2)/2$	
Input for B $u_g+u_r+H\theta$		$(1FHC+(1FHN+1FHS)/2)/2$ $+H(1FVW-1FVE)/W$	$(1FHC+(1FHW+1FHE)/2)/2$ $+H \cdot 1FVN/W1-H \cdot 1FVS/W2$	$(1FHC+(1FHW+1FHE)/2)/2$ $+H(1FVN-1FVS)/W$
Related Height and Width	Height : H	19.25m		
	Rocking Span : W(W1+W2)	13.0m	37.4m (21.0m+16.4m)	42.0m (21.0m+21.0m)

### Calculation of predominant frequency based on transfer function

Based on the relationships between input and response, transfer functions are calculated by following equation.

$$H(\omega) = S_{io}(\omega)/S_{ii}(\omega) \quad (1)$$

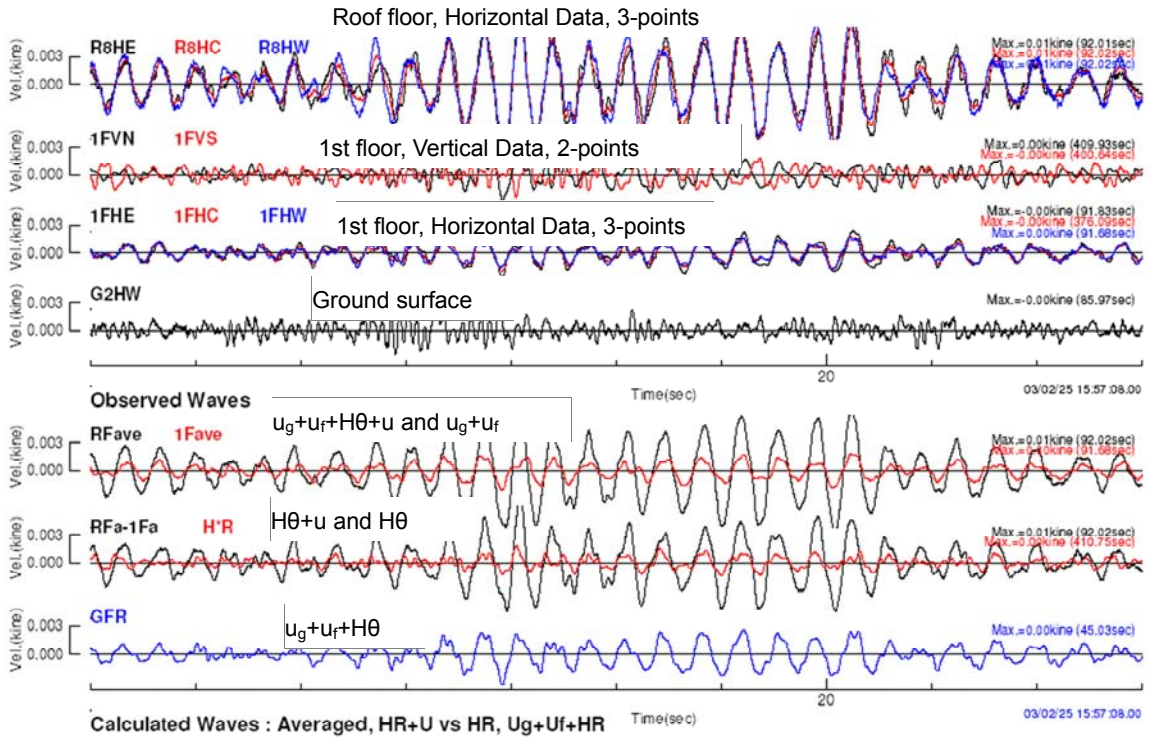
where  $S_{io}$  and  $S_{ii}$  are the cross spectrum of response and input and power spectrum of input data, respectively. The real part of the transfer functions provides the amplitude of them. The phase between response and input gives the phase difference of them.

The cross and power spectra are obtained through the Fourier spectrum converted from 8192 data of time history with interval of 0.005 s. The Fourier spectrum is calculated by moving the first data with interval of 40 s. The overlapped duration is about 50 % of analyzed one of the Fourier transform. All of the amplitudes of transfer functions obtained are averaged. The average amplitude spectra of transfer functions are smoothed by Hanning windows with eight times.

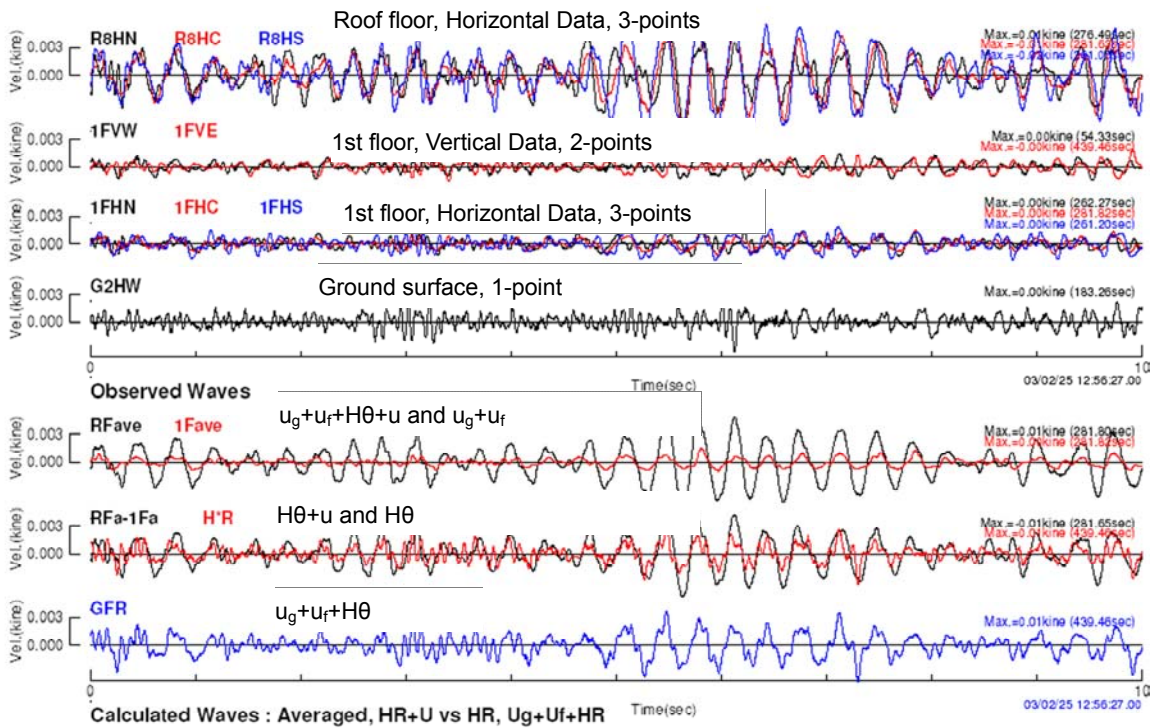
### Predominant frequency of buildings

The example of time histories (10 s) of input and responses is drawn in Fig. 6. The data at upper 4 axes are measured and another three ones are arranged.





a) Longitudinal direction



b) Transverse direction

Fig. 6 Time histories of measured and arranged data

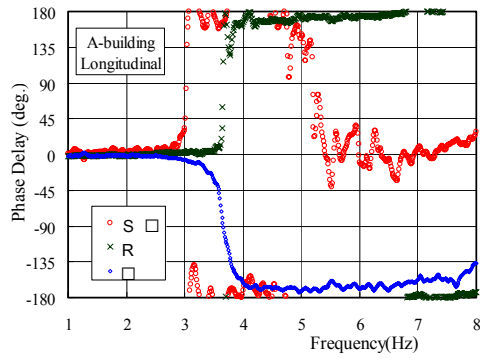
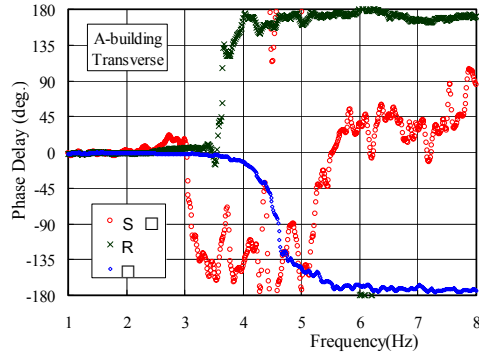
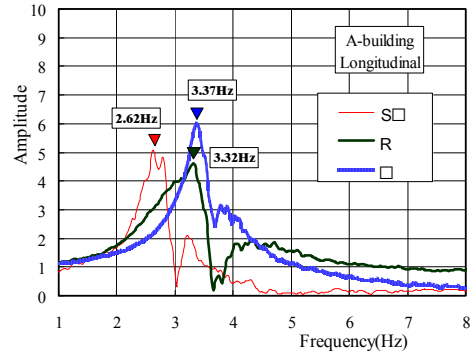
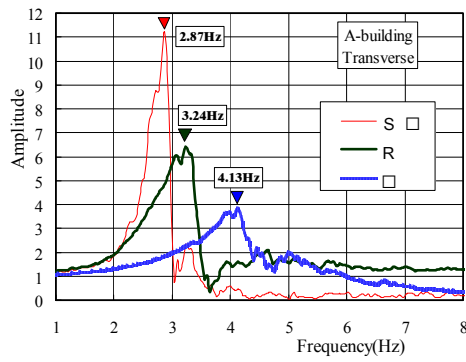


The time histories of horizontal data in the longitudinal direction at the same levels, that is, roof and 1st floors are similar to each other, because of very nearly measured points. On the other hand, in the transverse direction, a little difference of amplitude and phase are found out. Based on the transfer functions of rotational vibrations, the horizontal data seem to include torsional vibration of the buildings or phase difference of input motions. When the horizontal amplitude in the transverse direction becomes large, the phases of vertical vibrations at 1st floor are opposite and the rocking vibrations are observed. The amplitude and phase have a good correspondence of time histories between at 1st ( $u_g+u_f$ ) and roof floors ( $u_g+u_f+H\theta +u$ ). The data at 1st and roof floors have the relation between input and response in the RB system. The phase difference becomes small with large amplitude of roof floor. Compared between the data of relative response of roof to 1st floor ( $H\theta +u$ ) and the data rocking response ( $H\theta$ ), the effect of rocking vibration is remarkable and the amplitude of rocking vibration is 50-90 %of that of relative response of roof to 1st floor in the transverse direction.

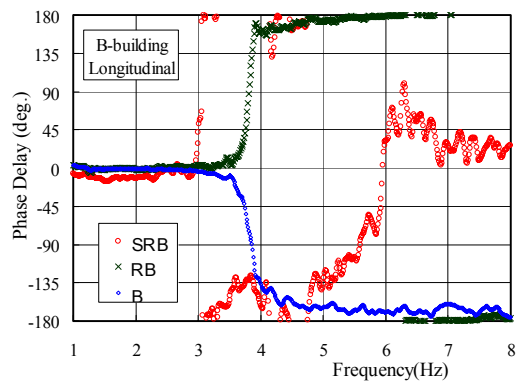
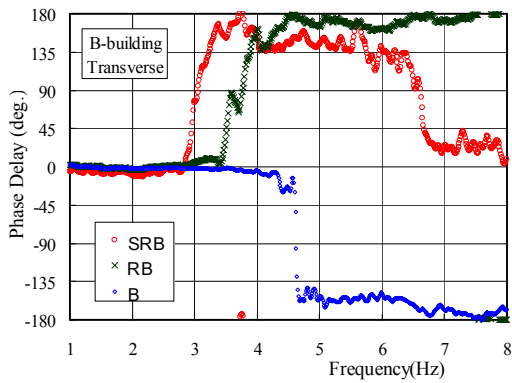
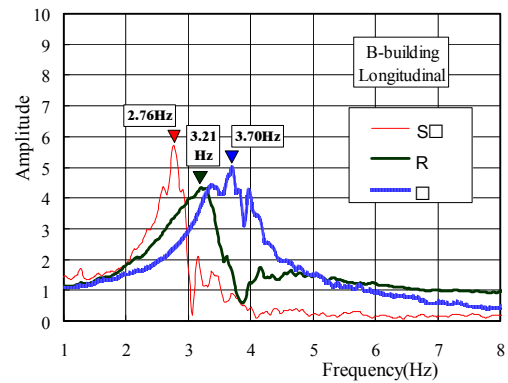
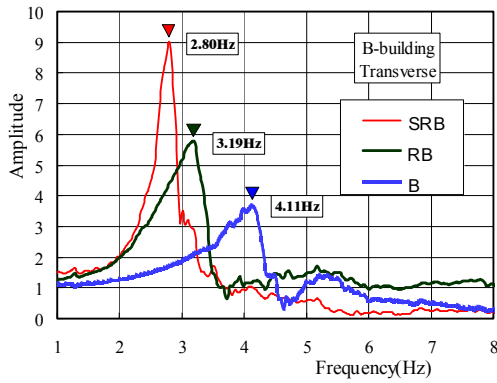
The amplitude and phase difference spectra of the transfer functions with buildings and their directions are shown in Fig. 7. The predominant frequencies obtained from amplitude spectra are presented in Table 3. The amplitude spectra have simple one simple peak like a transfer function of one-degree-of-freedom system. With comparison of amplitude at predominant frequencies in three systems, there are the relations of  $SRB > RB > B$ -systems in the transverse direction. On the other hand, the tendency is not so clear in the longitudinal direction.

Table 3 Predominant frequencies of various systems and ratios to frequency of B system

Direction	Building	System				
		SRB	RB	B	S	R
Transverse	A-building	2.87 (0.70)	3.23 (0.78)	4.13 (1.00)	6.21 (1.50)	5.21 (1.26)
	B-building	2.80 (0.68)	3.19 (0.77)	4.11 (1.00)	5.83 (1.42)	5.04 (1.22)
Longitudinal	A-building	2.62 (0.78)	3.32 (0.99)	3.37 (1.00)	4.28 (1.27)	19.57 (5.81)
	B-building	2.76 (0.75)	3.21 (0.87)	3.70 (1.00)	5.39 (1.46)	6.47 (1.75)



### A-building



### B-building

Fig. 7 Transfer functions of SRB-, RB- and B-systems

The predominant frequencies of the 1st mode in different systems have the relation of  $SRB < RB < B$ -systems in the transverse direction. In the longitudinal direction, the relation of  $SRB < RB \approx B$ -systems or  $SRB < RB \leq B$ -systems is obtained. The predominant frequencies for the sway (S) and rocking (R) systems shown in Table 3 are calculated by a system with one mass and springs in series of sway, rocking and building itself. Based on Table 3, the ratios of predominant frequencies of RB- and SRB-systems to those of B-system, which is according to base fixed condition, are 0.77 – 0.78 and 0.68 – 0.70 in the transverse direction. Compared with predominant frequencies of the S-, R-, B-systems, the frequencies of B -system are smallest. However, since the predominant frequencies of the S-, R, B - systems are similar, the effect of sway, rocking motion on the response of buildings are remarkably large.

On the other hand, the ratios of predominant frequencies of RB- and SRB-systems to those of B -system in the longitudinal direction are 0.87 – 0.99 and 0.75 – 0.78, respectively. Compared with predominant frequencies of the S-, R- and B-systems, the frequencies of B - system are smallest. In case of A-building, the predominant frequencies of the R- system are quite large and this means there is very small rocking effect, that is, the rocking motion is negligible. In the longitudinal direction, the effect of sway motion is remarkable.

The characteristics of two buildings except rocking motion in the longitudinal direction are quite similar. When the rocking angles of the 1st floor are calculated, vertical data are used. In the longitudinal direction, the distance between two vertical sensors is large and it is necessary to evaluate whether the rocking motions will be estimated by two vertical sensors and whether 1st floor is rigidly vibrating or not.

### **DAMPING FACTOR BASED ON RANDOM DECREMENT METHOD (RDM)**

To obtain the damping factors of the buildings, the RDM is applied to the observed microtremor data. Focused on the predominant frequency of fundamental vibration mode of interaction system, the damping factors are calculated with two buildings and their directions. To estimate the damping ratios of the buildings, there are methods of the 1/square root of 2, the half power, curve fitting and phase gradient, as procedures based on data in frequency domain. Here, using the data of time history, the damping factors under free vibration are obtained based on the RDM.

### Calculation Procedure by RDM

The observed data at the roof floor  $X(t)$  is assumed to be expressed to be sum of free vibration  $D(t)$  and response due to forced vibration  $R(t)$ . Through superposing time histories which are set to the maximum at time of zero, the response  $R(t)$  gradually vanishes and the response  $D(t)$  remains with superposition as shown in Fig. 8 [Tamura, 1993]. The superposed time histories  $\sum Di(t)$  will be the response of free vibration with the initial amplitude  $\sum Pi$  which is the sum of each random amplitude  $Pi$  as expressed in the following;

$$\sum Di(t) = (\sum Pi) \exp(-h\omega_0 t) \cos(\sqrt{(1-h^2)}\omega_0 t) \quad (2)$$

Where  $h$  is the damping factor and  $\omega_0$  is fundamental predominant frequency of the buildings.

The process to get the free vibration time histories by RDM is shown in Fig. 9. The horizontal data

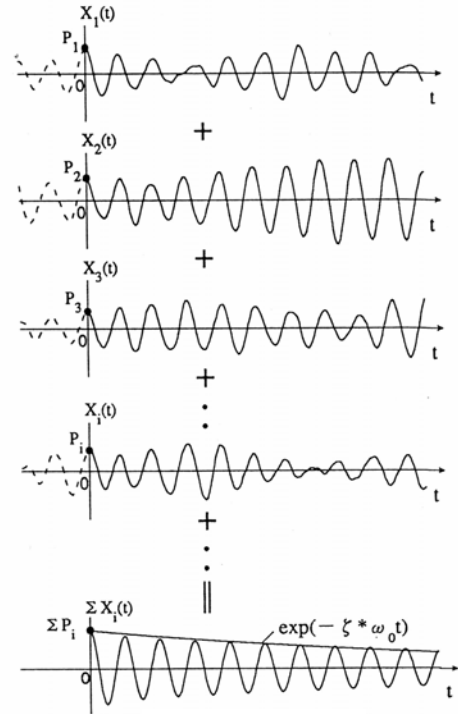


Fig. 8 Superposition of time histories based on the RDM (refer to Tamura et al.)

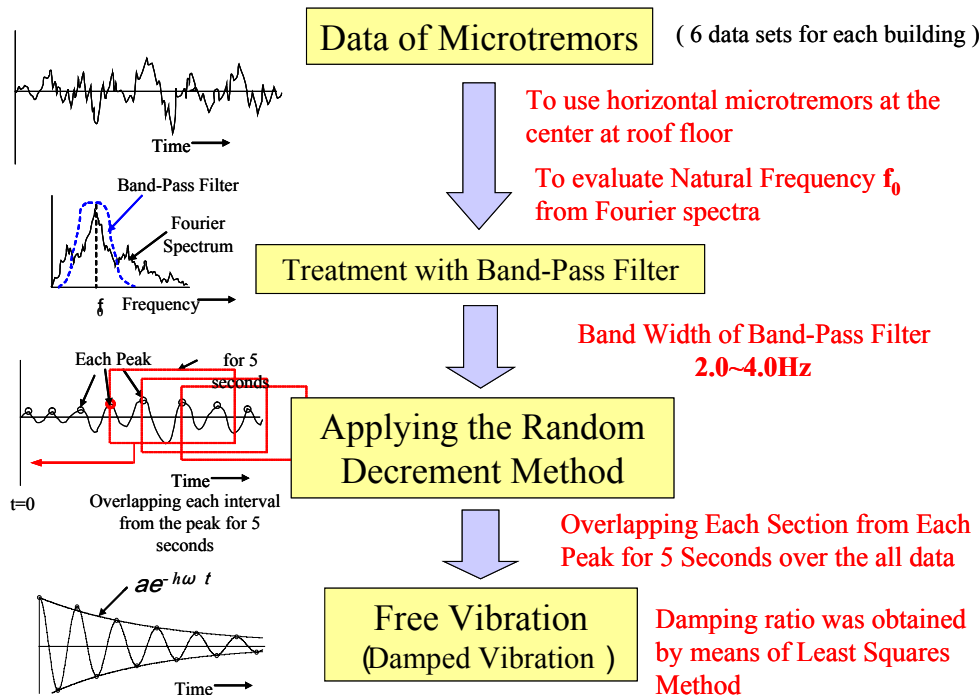


Fig. 9 Process to get the free vibration time histories by RDM

observed at the center of roof floor are used. The ensemble averages of the Fourier amplitude spectra of the time histories with buildings and their directions are drawn in Fig. 10. When the RDM is applied, the filtering with narrow frequency band called Butterworth type is conducted.

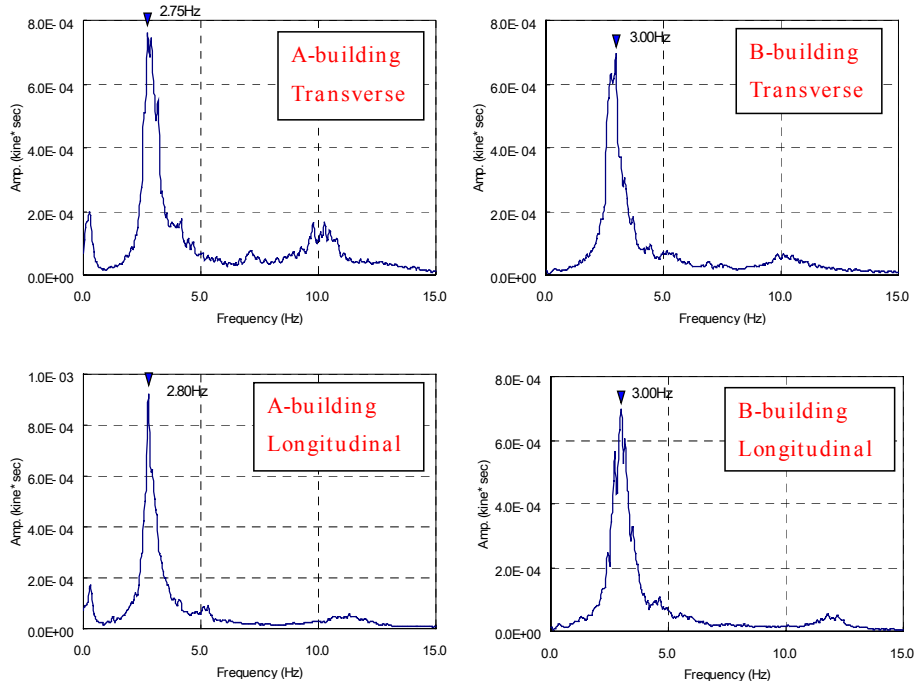


Fig. 10 Fourier amplitude spectra with buildings and their directions

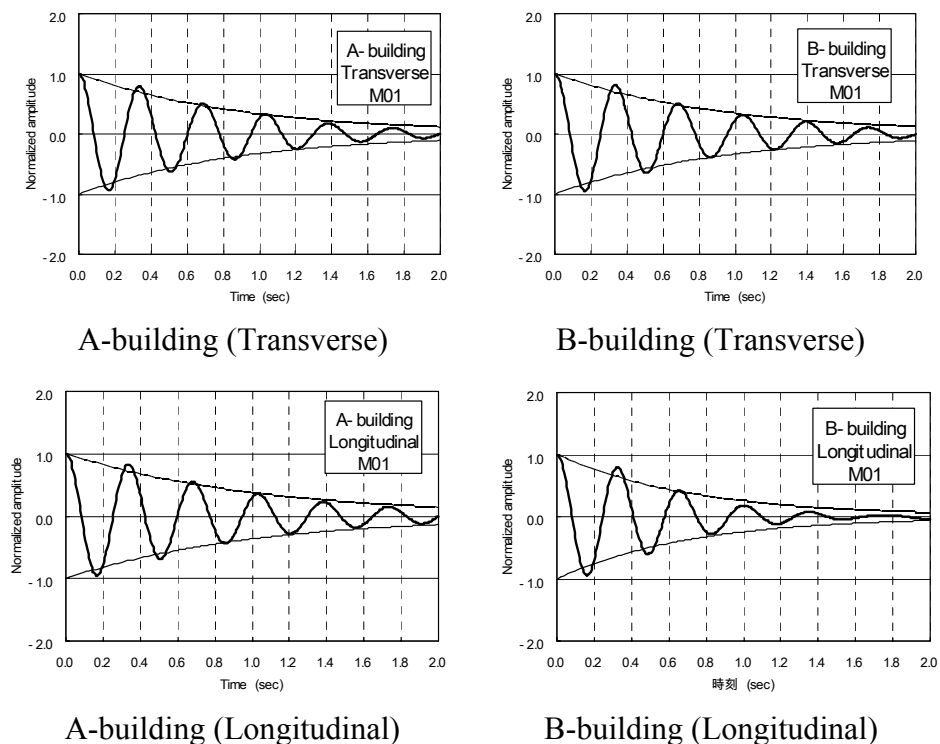


Fig. 11 Free vibration responses by RDM and envelop curves by LSM

The predominant frequency of the velocity time histories is 2.75 to 3.0 Hz. The frequency range of 2 to 4 Hz which includes the predominant frequency of buildings is kept. The filtered spectra are converted to the time histories. After the times when maximum velocities occur are set to be zero in time and the data of 5 seconds in period from that times are superposed. The total measured records are used in the RDM, the number of superposition is around 10,000 (refer to Table 4). The resulting time histories are normalized by the amplitudes at time of zero and the damping factors are obtained, applied the least square method (LSM) using 8 maximum data in time histories.

The results of free vibration response by the RDM and envelop curves by LSM with buildings and their directions are shown in Fig. 11. The envelop curves show good agreements with the free vibration response by the RDM. Table 4 summarizes whole results of damping factors. The damping ratios are not so scattered. The average damping factors are 5.5 to 6.0 % and 6.5 to 6.9 %, in the transverse and longitudinal directions, respectively.

### DAMPING FACTOR BASED ON HUMAN FORCED VIBRATION

The damping factors of the buildings are evaluated based on the data of free vibration due to force vibration of building generated by human oscillator. The time history data are arranged by band pass filter (2 to 4 Hz). Appropriate data according to the duration of free vibration in all of the filtered data are picked up as presented in Fig. 12. The data in period of 55 to 60 s are selected in this case. The damping ratios are identified through the LSM based on the data, using following equation.

Table 4 Damping factors of buildings by RDM

	A- building				B- building			
	data set	f (Hz) <sup>*1</sup>	h (%)	N <sup>*2</sup>	data set	f (Hz) <sup>*1</sup>	h (%)	N <sup>*2</sup>
Transverse	A-TM01	2.75	6.51	1801	B-TM01	3.00	5.81	1472
	A-TM02	2.95	5.97	1796	B-TM02	2.75	5.04	1478
	A-TM03	2.85	5.82	1779	B-TM03	2.90	6.17	1485
	A-TM04	2.85	5.73	1771	B-TM04	2.75	5.04	1460
	A-TM05	2.85	5.10	1777	B-TM05	2.80	5.96	1469
	A-TM06	2.90	6.67	1796	B-TM06	2.80	5.32	1468
	average	2.86	5.97	1787	average	2.83	5.56	1472
Longitudinal	A-LM01	2.80	5.57	1785	B-LM01	3.00	7.48	1524
	A-LM02	2.90	5.07	1772	B-LM02	2.80	7.75	1519
	A-LM03	2.80	7.40	1792	B-LM03	2.80	7.45	1520
	A-LM04	2.95	7.27	1833	B-LM04	2.80	5.99	1505
	A-LM05	2.85	7.51	1833	B-LM05	2.90	6.16	1495
	A-LM06	3.10	6.46	1823	B-LM06	2.90	6.31	1515
	average	2.90	6.55	1806	average	2.87	6.86	1806

\*1 natural frequency obtained by peak of Fourier spectrum

\*2 Number of overlapping for each data set

$$D = D_0 \exp(-h\omega_0 t) \cos(\sqrt{1-h^2}\omega_0 t) \quad (3)$$

Examples of time histories of observed free vibration and identified envelop curves are drawn in Fig. 13. Since the time histories of free vibration have some dependency on

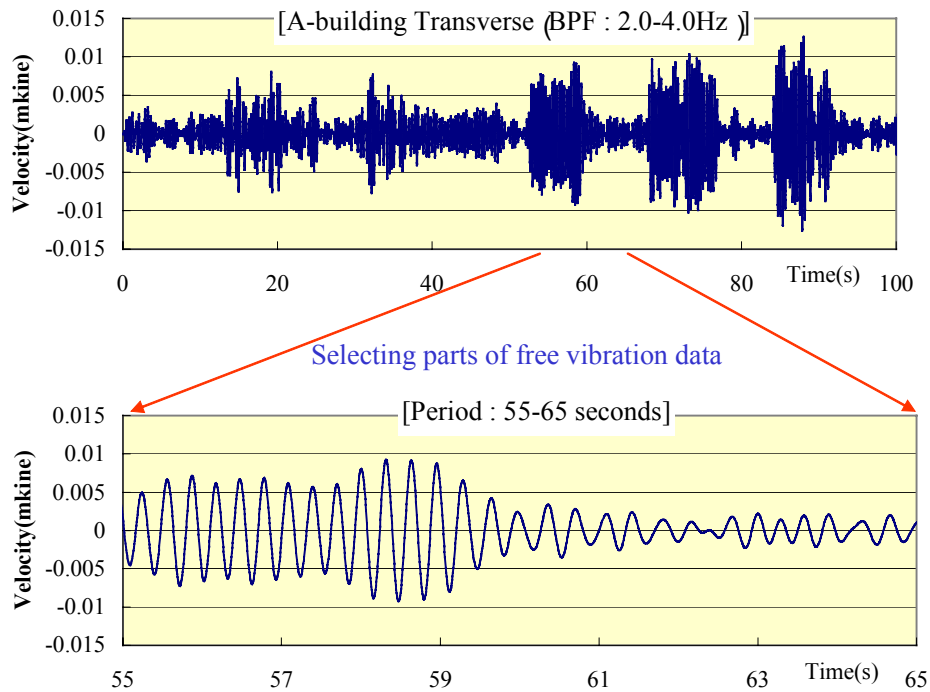


Fig. 12 Pick up of appropriate data from free vibration response

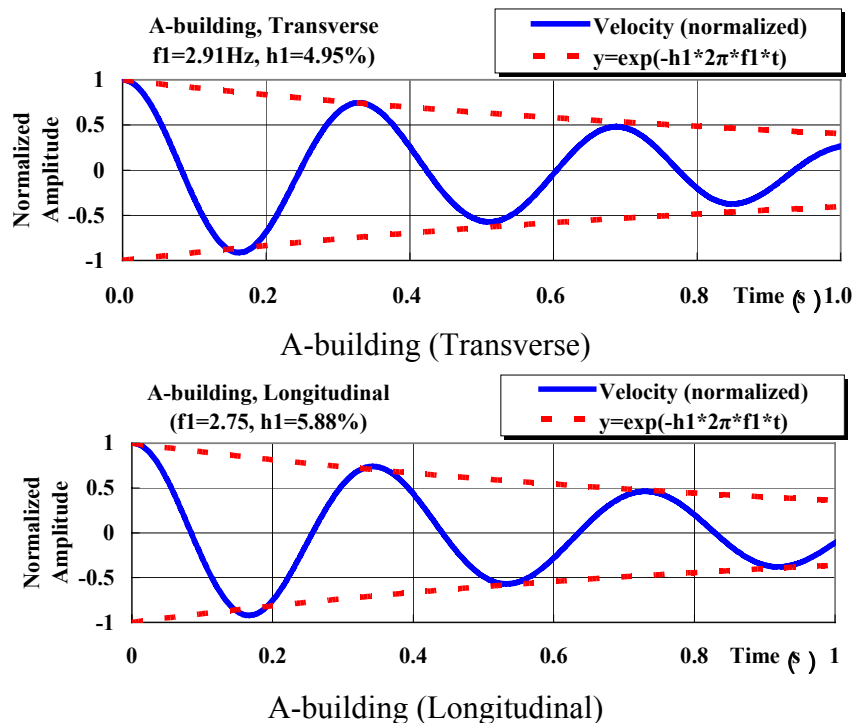


Fig. 13 Identified envelop curves of free vibration response



Table 5 Damping factors of buildings by forced vibration

	A-building		B-building	
	$f_1$ (Hz)	$h_1$ (%)	$f_1$ (Hz)	$h_1$ (%)
Transverse direction	2.91	4.95	2.75	5.66
Longitudinal direction	2.75	5.88	2.72	4.90

amplitude of vibration, identified damping ratios vary according to predominant frequency. Table 5 shows representatives of damping factors with buildings and directions. In the transverse direction, the damping factors by forced vibration are a little less than those by microtremors. In the longitudinal direction, the damping factors by forced vibration are smaller by 1 to 2 % than those by microtremors. Since the number of obtained damping factors by forced vibration is very small, the quantitative evaluation is difficult.

### CONCLUSIONS

In order to evaluate the fundamental characteristics of the SSI phenomena by means of microtremor measurements are conducted. Through several methods, fundamental predominant frequencies and damping factors of residential buildings are calculated. The fundamental predominant frequencies are obtained from the transfer functions of the systems including vibration modes of sway, rocking and buildings. The damping factors are evaluated from microtremor and forced vibration data. The damping factors based on microtremor data are got using the random decrement method (RDM).

The ratios of predominant frequencies of SSI systems to those of building with base fixed condition are 0.75 – 0.78 in longitudinal direction. Effects of sway mode on the predominant frequencies are founded. In the transverse direction, the ratios of predominant frequencies of SSI systems to those of building with base fixed condition are 0.68 – 0.70. In the transverse direction, the effects of rocking mode are remarkable.

The damping ratios by the RDM are not so scattered. The average damping factors are 5.5 to 6.0 % and 6.5 to 6.9 %, in the transverse and longitudinal directions, respectively. The damping factors by forced vibration are a little less than that by microtremors. In the longitudinal direction, the damping factors by forced vibration are smaller by 1 to 2 % than those by microtremors. Since the number of obtained damping factors by forced vibration is very small, the quantitative evaluation is difficult. More data are necessary to discuss the damping factors and the effect of radiation damping.

## ACKNOWLEDGEMENTS

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