STRUCTURE OBSERVATION &IDENTIFICATION CONSIDERING SOIL-STRUCTURE INTERACTION OF STORY STIFFNESS AND DAMPING RATIO OF 8-STORY STEEL ENCASED REINFORCE CONCRETE STRUCTURE BY MICROTREMOR

REN Jun* **Supervisor: Koichi MORITA ****
MEE08164

ABSTRACT

The author attempts to consider the effect of soil-structure interaction by identifying the dynamic parameters of an existing building. Target building is an 8-story steel encased reinforced concrete building which was constructed in 1998. In the study, an eight degree of freedom analytical model is utilized to analyze the data from microtremor measurement. Then, nonparametric and parametric techniques are employed to determine natural frequency, damping ratio and story stiffness of the structure. For these two cases, one is without considering the effect of soil-structure interaction; the other is with considering the effect of soil-structure interaction. Comparing the results of these two cases, the effect of soil-structure interaction can be confirmed. Nonparametric methods include the well known transfer function and Random Decrement method. The parametric method employed herein is the off-line system identification method ARX (Auto-Regression with eXtra input).

Keywords: Soil-Structure Interaction, Damping Ratio, Story Stiffness.

1. INTRODUCTION

System identification (SI) deals with the problem of building mathematical models of dynamic systems based on observed system data (Ljung 1999). SI not only plays the role of calibrating structural building models which could not otherwise be validated through experimentation but also implicitly aids the design of high performance and high reliability structures. Existing experimental modal analysis techniques usually require excitation and response data with a high signal-to-noise (s/n) ratio and all sources of excitation be measured and uncorrelated (Moore et al. 2007). The combination of utilizing application specific SI methods and random ambient vibration excitation to capture highly sensitive damping ratio formulates the basis for this study. The complexity of structure and soil-structure interaction is usually troublesome to obtain accurate results for their dynamical behavior. Previous studies have shown that story stiffness of the structures are commonly obtained based without considering the effect of rocking of structure. In this context, the estimation of dynamic characteristics of 8-story steel encased reinforce concrete structure is conducted with excluded soil-structure interaction. Fundamentally, the simple method to acquire dynamic properties of a target structure is microtremor observation. Based on considering the effect of rocking motion obtained from this observation, the damping ratio and story stiffness are more accurately determined by getting rid of soil-structure interaction.

* Earthquake Administration of Shaanxi Province, China.
** Department of Structural Engineering, Building Research Institute, Japan.

In order to identify the physical characteristics of a structural system, microtremor measurement has been widely used for decades. Microtremor measurement is very useful method to obtain dynamic characteristics of structural systems including the predominant natural frequencies and structural amplification factors. Based on theoretical concept, microtremor measurements with good sensor accelerometers provide the response of structural systems in terms of low frequency seismic signals. However, in the urban area where artificial noises or signals may be superimposed at measured microtremor generating unexpected amplification ratios. Moreover, microtremor measurements' amplification ratios usually provide only first or second natural frequency of structural systems. The reason is that at higher frequencies, ambient noises and signals are generally combined with microtremor signals that cause the unidentifiable amplification ratios.

2. TARGET BUILDING

The target building is Urban Disaster Prevention Research Center (UDPRC) in National Institute for Land and Infrastructure Management (NILIM) that was completed in March 1998. The eight story structure is of steel encased reinforced concrete type. The height and building area are 30.9 m and 5050 m2, respectively. The foundation is of mat type.

In this study, a portable ambient vibration monitoring system was established. The placement of the twelve available seismometers for observation was planned and reviewed. Evaluation of the soil-structure interaction required capturing the behavior between the building and external excitation. Ten horizontally oriented accelerometers were placed on the floors and pavement area adjacent the building, and two vertically oriented accelerometers were placed in the basement, as shown on the color-coded elevation and plan drawings of Figure 1. (Blue color-coded is horizontal sensor and red color-coded is vertical sensor). The regular floor plan allowed for consistent and convenient seismometer placement in the building. The advantage of having multiple sensors is the ability to adequately capture natural mode shapes of the structure. The vertical orientation of the basement level seismometers is chosen to capture any rocking behavior, an insightful descriptor of the surrounding soil stiffness. With sensors temporarily in-situ, 15-minute ambient vibration observation were performed at a sampling frequency of 100 Hz on EW and NS direction respectively. An analytical model is now developed and analyzed to deduce the expected behavior of the dynamic building/soil system.

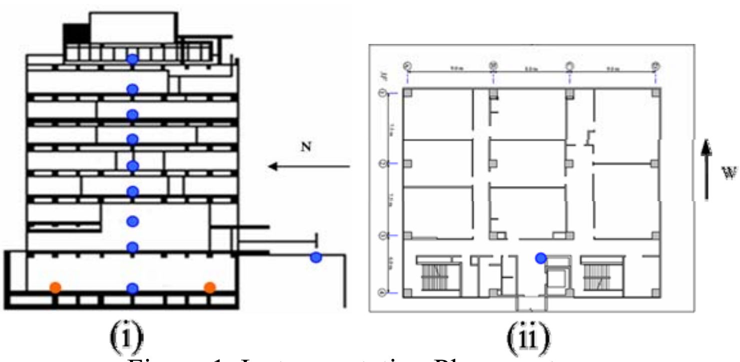


Figure 1. Instrumentation Placement
(i) Elevation, (ii) Plan

3. DATA ANALYSIS AND RESULTS

3.1. Analytical Model and Estimate of Rocking Motion

To conceptually understand the relationship between input ground motion and structure, the eight degree of freedom rocking building shown in Figure 2 was analyzed. The model includes the assumptions of rigid vertical and rocking motion. Where a_{base} is horizontal oriented accelerometer input in basement, and *Mi, ki* are concentrated story mass and story stiffness of the building respectively.

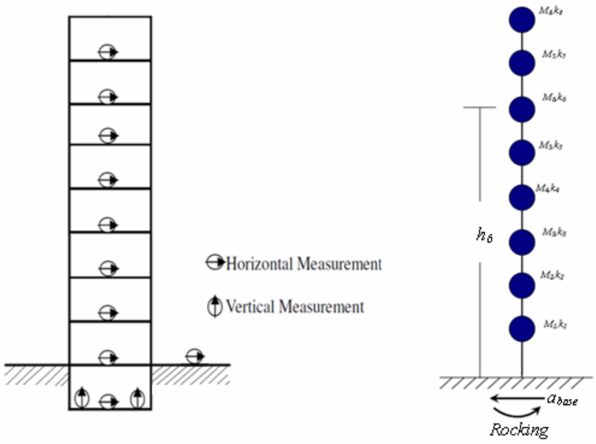
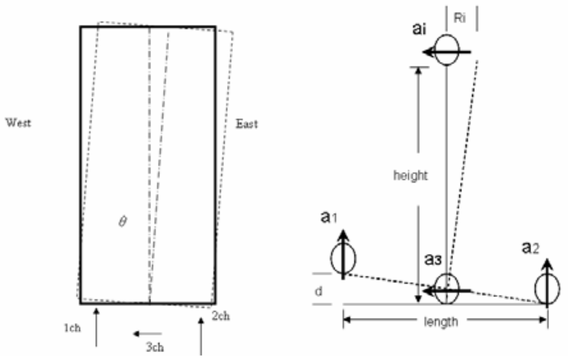


Figure 2. The vibration types considered for the building

In general, the vibration of the building consists of rocking, sway and relative displacement. Rocking motion represents the different vertical displacement of the building. Sway motion is a relative displacement between ground and the building. Relative displacement represents the lateral deformation of each story with respect to the other. In the study, the author considers the soil-structure interaction which results in rocking motion of the building.

The author tries to exclude the effect of rocking motion and identify the real story stiffness of the building from the record of microtremor observation; therefore, this model was employed to analysis the data to exclude the effect of rocking action of the building. The model was shown on Figure 3.



(i) (ii)

Figure 3. Model of rocking action
(i) Rocking action of building;
(ii) Calculated model for rocking effect

$$Ri=a_3+[(a_2-a_1)/length]*height \qquad (1)$$

where 1ch, 2ch, 3ch are three channel records of two vertical oriented accelerometers signal and one horizontal oriental accelerometers signal in basement in Figure 3(i). In the Fig 11(ii), a_1, a_2 are records of accelerometers 1 and 2 (vertical oriented); a_3 and a_i are records of accelerometers on basement and i-th story (horizontal oriented); *Ri* is rocking effect on the i-th story. Eq.(1) captures the rocking motion for each story.

3.2. Transfer function and Random Decrement method

Table 1. TF Modal Estimates on EW & NS direction

Mode	EW direction		NS direction	
	fn [Hz]	ξ [%]	f_n [Hz]	ξ [%]
1st model	1.76	3.2115	1.4289	1.7179
2nd model	5.02	2.2925	4.1911	2.1389

From the Transfer functions, the first and second natural frequencies of UDPRC are easy to find out. These frequencies as target frequencies are then used for determining the damping ratio. By Random Decrement Technique, these damping ratio for UDPRC are determined approximately in the Table 1.

3.3 Parameters Identification by using ARX Method

In this monitoring system, accelerometer data of 1-8F story are used as outputs and accelerometer of basement as input, so system identification will be based on eight concentrated lumped mass model. Parameter identification based on the ARX (Auto Regressive eXtra input) model is applied for input-output data of vibration measurements. The ARX model structure is the simple linear difference equation:

$$y(t)+a_1y(t-1)+\ldots+a_{na}y(t-na)=b_1u(t-nk)+\ldots+b_{nb}u(t-nk-nb+1) \qquad (2)$$

which relates the current output *y(t)* to a finite number of past outputs *y(t-k)* and inputs *u(t-k)*. The structure is thus entirely defined by the three integers *na, nb*, and *nk. na* is equal to the number of poles and *nb-1* is the number of zeros, while *nk* is the pure time-delay (the dead-time) in the system. From this model structure, the coefficients a_j and b_j are estimated. If A and B are expressed as,

$$A(q) = 1 + \sum_{j=1}^{n_a} a_j q^{-j}$$
$$B(q) = 1 + \sum_{j=1}^{n_b} b_j q^{-j+1-n_k} \tag{3}$$

${}_z p_j$ is the root of $A(z)=0$ and ${}_z r_j$ is the residue of a partial fraction expansion of $B(z)/A(z)$. Natural frequency f_j, damping ratio h_j and participation function βu_j are expressed as the following.

$$f_j = \frac{\sqrt{(\log|{}_z p_j|)^2 + (\arg {}_z p_j)^2}}{2\pi\Delta t} \tag{4}$$

$$h_j = \frac{-\log|{}_z p_j|}{2\pi f_j \Delta t} \tag{5}$$

$$\beta u_j = \Re\left[\frac{2\,{}_z r_j \sqrt{1-h_j^2}}{T(2\pi f_j h_j - i\,sign[\Im[{}_z p_j]]2\pi f_j(1-2h_j^2))}\right] \tag{6}$$

The measured stiffness matrix [K] is estimated from the mass-normalized measured mode shapes [Φ] ($[\Phi]^T[M][\Phi]=[I][\Lambda]$; [Φ] is determined from the participation function βu_j) and frequencies [Λ] as

$$[K] \cong ([\Phi][\Lambda]^{-1}[\Phi]^T)^{-1} \tag{7}$$

In this system identification, stiffness matrix will be obtained by Eq. (7) if eight modal properties are identified because of the assumption of eight lumped mass model. In the target building, it is difficult to identify above second modal property. Therefore, the stiffness matrix is obtained using Moore and Penrose inverse matrix (Penrose 1955) which is one of the generalized inverse matrix. Story stiffness will be estimated by multiplying [K] by a displacement vector, in which each relative story displacement is 1 from the right.

In the study, the properties of UDPRC were determined by using ARX method and the results including/excluding rocking motion were shown on Table 2, 3, 4 and 5 on EW and NS direction .

Table 2. The identified result including rocking motion on EW direction

Floor	**1F**	**2F**	**3F**	**4F**	**5F**	**6F**	**7F**	**8F**
1st natural frequency [Hz]	1.7411							
1st Damping ratio[%]	3.7364							
1st modal shape	0.0215	0.1235	0.2235	0.4668	0.5896	0.8073	0.9632	0.9221
Story stiffness [10^8N/m]	4.3766	4.331	4.0737	3.6282	2.781	1.8716	0.9176	0.2195

Table 3 The identified result excluding rocking motion on EW direction

Floor	**1F**	**2F**	**3F**	**4F**	**5F**	**6F**	**7F**	**8F**
1st natural frequency [Hz]	1.7145							
1st Damping ratio[%]	3.6859							
1st modal shape	0.0491	0.0738	0.1835	0.3275	0.3462	0.4443	0.4468	0.3424
Story stiffness [10^8N/m]	5.2882	5.0564	4.7174	3.9256	2.6931	1.642	0.6722	0.1266

Table 4. The identified result including rocking motion on NS direction

Floor	1F	2F	3F	4F	5F	6F	7F	8F
1st natural frequency [Hz]	1.4357							
1st Damping ratio[%]	2.8216							
1st modal shape	0.0764	0.1557	0.145	0.214	0.3161	0.4093	0.4527	0.4942
Story stiffness [10^8N/m]	3.3101	3.0905	2.6661	2.2991	1.807	1.1885	0.5793	0.1578

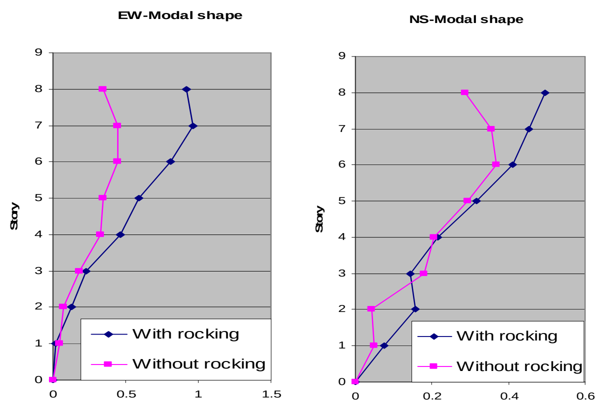
Table 5. The identified result excluding rocking motion on NS direction

Floor	1F	2F	3F	4F	5F	6F	7F	8F
1st natural frequency [Hz]	1.4042							
1st Damping ratio[%]	3.2747							
1st modal shape	0.0486	0.0422	0.1792	0.2039	0.2927	0.3682	0.3556	0.2877
Story stiffness [10^8N/m]	3.4509	3.2648	3.1073	2.4824	1.8565	1.1167	0.4517	0.0904

3.4. Comparing Two Results of Each Story Stiffness between two cases

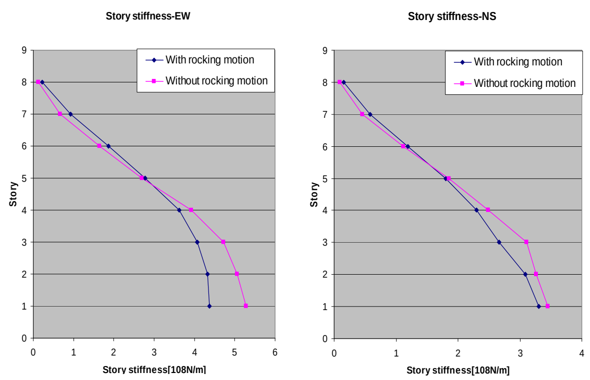
In this section, it is desirable to compare the story stiffness with including rocking motion and excluding rocking motion on these two directions. The combination of modal shape is used. For 1st modes, the modal shapes are obtained from microtremor observation by ARX method (Figure 4).

Figure 5 shows the two results of the story stiffness with including and excluding rocking motion by ARX method on EW and NS direction. An interesting phenomenon was observed that the story stiffness below the fifth floor, identified by excluding the rocking motion, increased all, but these above it decreased all. Meanwhile,



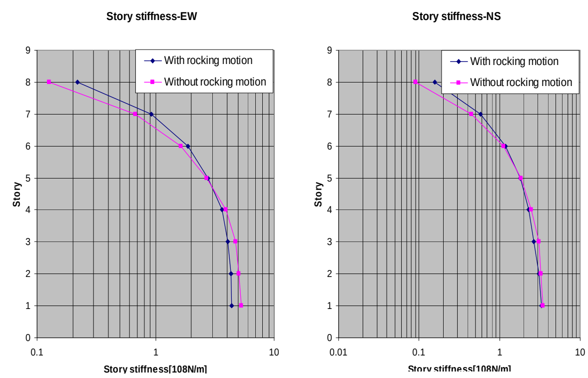
(i) (ii)

Figure 4. 1st Modal shape of UDPRC
(i) 1st Modal shape of EW direction (ii) 1st Modal shape of NS direction



(i) (ii)

Figure 5. The comparing of identified story stiffness on two directions
(i) Story stiffness on EW direction; (ii) Story stiffness on NS direction;



(i) (ii)

Figure 6. The effect of rocking motion to story stiffness on two directions
(i) Story stiffness on EW direction; (ii) Story stiffness on NS direction;

same tendency existed in EW and NS direction. In these figures, blue lines are including the rocking motion and pink lines are excluding the rocking motion.

For the further observing, these results of the story stiffness, identified in different cases, presented in logarithmic scale at X-axis (Figure 6). The bigger decreasing of the story stiffness with removing the rocking motion were found out on top floor, almost two times reduction on both direction.

4. CONCLUSIONS

In this study, damping ratio and story stiffness were estimated, and the effect of rocking motion was evaluated for UDPRC. In an effort to evaluate the soil characteristics of the surrounding soil, nonparametric and parametric techniques were employed to capture natural frequency and damping ratio for the first and second translational modes. Furthermore, the effect to story stiffness was focused on rocking motion of the building. Lastly, the rocking behavior of the UDPRC was identified. Based on previously identified results, the magnitudes of rocking motion were shown, utilizing basement to floor by using ARX method.

Results from this study can be summarized as follows:

1. The first and second natural frequencies are found to be about 1.76 Hz and 4.89 Hz on EW direction and 1.43 Hz and 4.19 Hz on NS direction, respectively. However, the third and forth natural frequencies are not able to be identified from microtremor observation.
2. From analyses results in earlier section, there is a strong belief that the effect of soil-structure interaction of UDPRC is obvious. If we have to reduce life cycle costs of a building from construction to maintenance, it is very necessary to obtain more precise structural properties of a building. Therefore, utilizing system identification with considering rocking motion from the basement to floors will produce more accurate modal parameter and stiffness estimates. The conclusions of this research would be strengthened with supplemental identification utilizing additional time and frequency domain methods. In this manner, the effect of soil-structure interaction to SI results from ambient vibration records will be better understood as well as the extent of strengths and weaknesses of equivalent stories stiffness.

AKNOWLEDGEMENT

I would like to express my sincere gratitude to my adviser Dr. Saito, T. for his continuous support, valuable suggestion and guidance during my study.

REFERENCES

Akira Mita, Structural Dynamics for Health Monitoring, Keio University (Japan), Sankeisha co., Ltd.

Douglas E. Adams, Purdue University (USA), John Wiley & Sons, Ltd.

Koyama, S., 2007, IISEE lecture note, Building Research Institute, Tsukuba, Japan.

Ljung, L. 1999, PTR Prentice Hall, Upper Saddle River, N.J..

Moore SM, et al 2007, Mechanical Systems and Signal Processing.

Morita, K., 2007, IISEE lecture note, Building Research Institute, Tsukuba, Japan.

Morita, K., 2006, SPIE 11th Annual International Symposium on NDE for Health Monitoring and Diagnostics, San Diego, USA.

Penrose, R., 1955, A Generalized Inverse for Matrices Proc. Cambridge Phil. Soc. 51, 406-413.

Schmitt, S., Jr., 2007, the East Asia and Pacific Summer Institutes Program Report.