Evaluation of Soil Stiffness Using Acceleration Response Data of the Building with Direct Embedment Foundation

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ABSTRACT: In this study, rocking stiffness evaluation method based on the measurement acceleration response data is proposed. In this method, only the acceleration response and floor plan is needed. To evaluate the rocking stiffness, the relationship between the inertia moment for rocking motion and the rocking angle is calculated. The inertia moment is calculated due to the horizontal acceleration and mass of each floor, and the rocking angle is calculated due to the vertical displacement of the basement floor. To calculate the fundamental vertical displacement, wavelet transform method is used. The calculated rocking stiffness is compared with the design value based on the building code and soil survey.

1 INTRODUCTION

The soil–structure interaction (SSI) effect is an important factor that influences the seismic response and dynamic characteristics of a building; the larger the ratio of superstructure stiffness to the stiffness of soil, the larger the SSI effect (AIJ Committee, 2003). Although soil springs can be calculated using the soil properties obtained from the field test survey and experiments before the construction of the building, it is difficult to know the real measurement of soil springs after the construction of a superstructure, especially after earthquakes occur. Some researchers studied the accuracy of soil springs proposed by current methods in the past years. For example, Tamori et al. (2004, 2005) made the microtrmor observations of 20 SRC buildings, and they used the measurement data to calculate the dynamic characteristics of the measured buildings, which were compared with those of the designed SSI model (swaying and rocking springs of soil were determined by the calculation method of response and limit strength, mass and stiffness of the superstructure were calculated according to the design standard). Their results indicated that the calculation method of response and limit strength underestimated the rocking stiffness for the buildings with direct embedment foundations. Mori et al. (2008) evaluated the soil springs of the building with a direct embedment foundation using FEM and Layered models based on the dynamic SSI analysis. However, there is rare research that evaluates the real measurement of the rocking stiffness of soil under earthquakes. This paper presents the research that tried to solve the problem.

Nowadays, a new seismic evaluation method based on the real-time residual seismic performance curve (S_a-S_d curve) is used to evaluate the seismic performance of superstructures (Kusunoki et al., 2003, Kawamura et al., 2013, Kusunoki et al., 2014). This method has been shown to be practically applicable to seismic performance evaluation of real buildings (Li et al., 2014). It is expected that the concept of the S_a-S_d curve of the single-degree-of-freedom (SDOF) model can be used to evaluate soil performance (reflected by the R_a-R_d curve of the foundation) in earthquakes.

In this paper, a simple evaluation method of rocking stiffness of the soil is proposed, which is based on the R_a-R_d curve of the foundation. The R_a-R_d curves were calculated using measurement earthquake response data of an eight-story steel-reinforced concrete (SRC) building with a direct embedment foundation.

2 CALCULATION METHOD

The superstructure of the measurement building (Figure 1(a)) can be reduced into an equivalent SDOF model, and the S_a-S_d curve (representative displacement S_d and base shear force coefficient S_a) and the equivalent mass m_e of the equivalent SDOF model (refer to Figure 1 (b)) can be calculated using the method in the reference papers (Kusunoki et al., 2014).

Generally, rocking motion mainly couples with the fundamental mode (Jennings et al., 1973). Then the representative rocking-moment coefficient R_a (Equation 1(a)) and rotation moment of the foundation M_r (Equation 1(b)) for the model in Figure 1(b) can be written as follows

$$R_a = \frac{S_a}{H_e} \tag{1}$$

$$M_r = I_e \cdot R_a \tag{2}$$

$$I_e \;\; = m_e \cdot {H_e}^2 \tag{3}$$

where the equivalent height H_e (Chopra et al., 2002) was calculated using maximum response points (u_{i1max}^f) of the fundamental mode response; see Equation (2) as follows:

$$H_e = \frac{\sum m_i{\cdot}{u_{i1\max}}^f{\cdot}h_i}{\sum m_i{\cdot}{u_{i1\max}}^f} \tag{4}$$

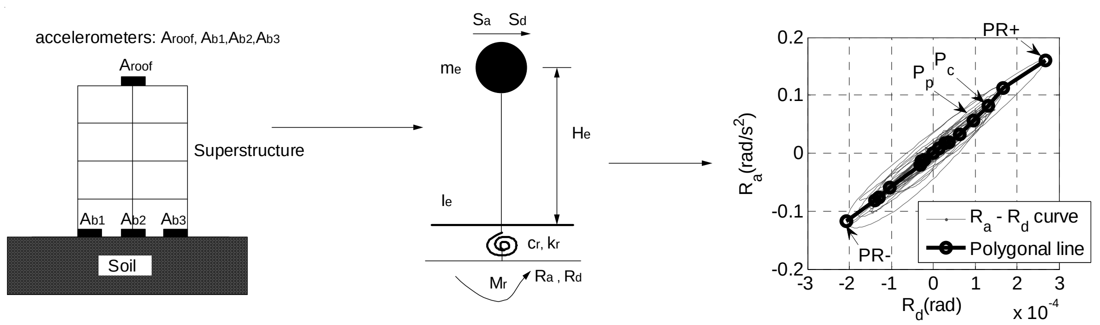
Then the dynamic equation for the rocking motion can be written as follows:

$$I_e \cdot R_a + \; c_R \cdot \; \dot{R}_d + k_r \cdot R_d = 0 \tag{5}$$

where c_R and k_R are the damping and stiffness, respectively, of the soil for the rocking motion. When the rocking motion reaches to the peak response, then damping force is zero; so Equation (3) can be rewritten as follows

$$-\frac{R_a}{R_d} = \frac{k_r}{I_e} \tag{5}$$

Then



(a) Measurement point (b) SDOF Model (c) R_a-R_d curve

Figure 1. Outline of Calculation

$$\omega_r = \sqrt{-\frac{R_a}{R_d}} \tag{6}$$

And the rocking stiffness of the soil k_r can be calculated as follows:

$$k_r = I_e \cdot \omega_r^2 \tag{7}$$

where R_d is the representative rocking angle, the calculation method was referred to the paper by LI et al. (2014). The relationship between R_a and R_d of the peak response points is simply shown in Figure 1(c), and PR+ and PR- are the maximum peak response points in R_d-R_a curve. And ω_r is the fundamental circular frequency for the rocking motion, see Equation (5).

The fundamental responses of the superstructure (used for the calculation of S_a and the rocking motion R_d) can be extracted using the wavelet transform technique (WTT) (Kusunoki et al., 2003), and the determination of the fundamental responses. Like the S_a-S_d skeleton curve(Li et al., 2014), the R_a-R_d skeleton curve can be obtained from some peak response points from a smaller response to a maximum response of the rocking motion, which can reflect the soil performance.

3 OBJECTIVE BUILDING

The research object of the paper is an eight-story SRC building (the dimensions of the superstructure are H×a×b=28×21×26, unit: m) with a base floor underground. The locations of the acceleration meters and the superstructure of the building have been discussed in previous research (Kashima et al., 2006). The foundation type is a direct embedment foundation, of which the embedment depth underground is 8.5 m.

Just as shown in Figure 2, 11 accelerometers are installed in the building and another 5 accelerometers (A01, B01, C01, N14 and A14) are located in the shallow layers of the soil surrounding the building. Each accelerometer can record 3-direction motions (x direction: E-W, y direction: N-S and z direction: vertical direction). The sampling frequency of the accelerometers is 100Hz.

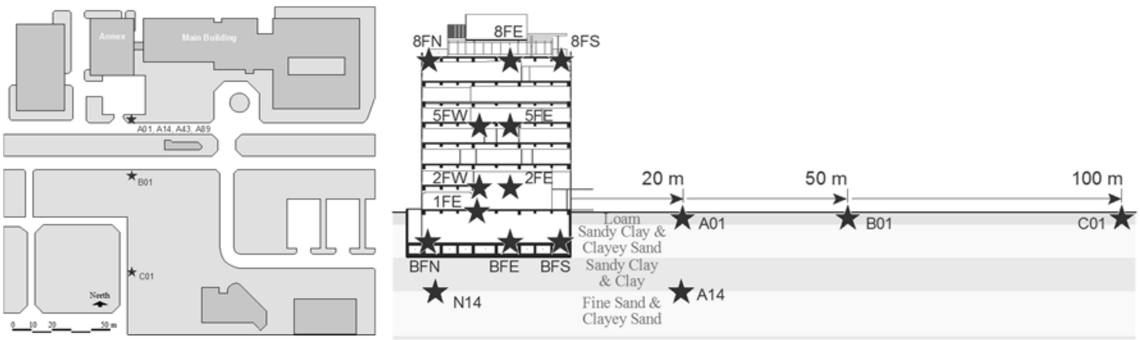


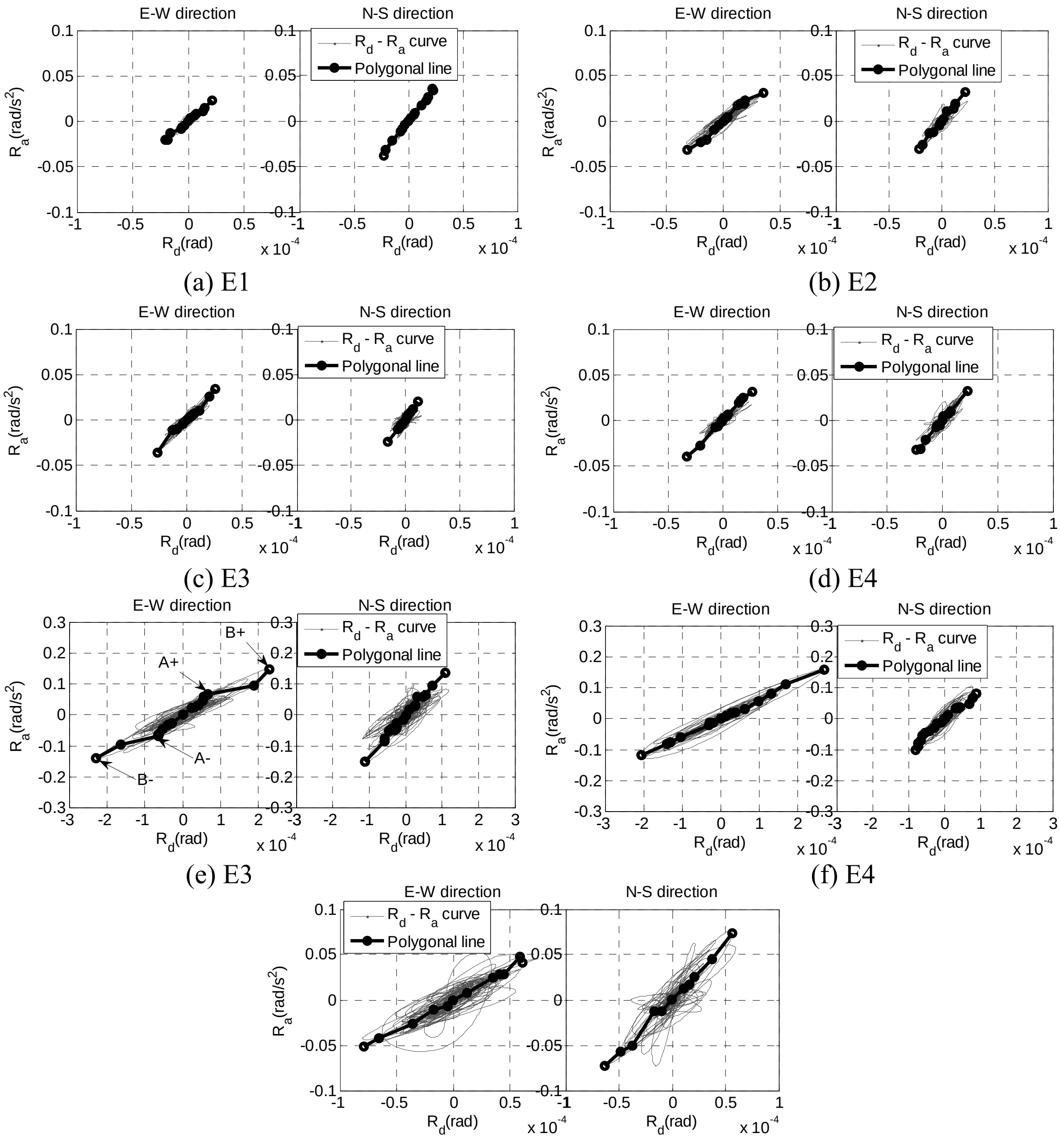
Figure 2. Measurement points of the building

Table 1.Measured earthquake data.

Time	Epicenter	Latitude	Longitude	Depth (Km)	M (Degree)	Dist. (Km)	PGA (gal)	IJMA (Degree)	Fundamental response		Number
									E-W	N-S	
2003-09-20 12:54	S Chiba Pref.	140.3033	35.2150	70	5.8	104	13.7	2.8	rank6	rank6	E1
2004-10-06 23:40	S Ibaraki Pref.	140.0917	35.9850	66	5.7	17	54.5	3.8	rank6	rank6	E2
2005-08-16 11:46	Off Miyagi Pref.	142.2783	38.1500	42	7.2	298	29.8	3.3	rank6	rank6	E3
2008-06-14 08:43	S Inland Iwate Pref.	140.8800	39.0283	8	7.2	330	26.2	3.4	rank6	rank6	E4
2011-03-11 14:46	Off Sanriku	142.8600	38.1033	24	9.0	330	279.3	5.3	rank6	rank6+rank7	E5
2011-03-11 15:15	Off Ibaraki Pref.	141.2650	36.1083	43	7.6	107	151.1	4.7	rank6	rank6	E6
2011-04-11 17:16	Hama-dori, Fukushima Pref.	140.6717	36.9450	6	7.0	105	118.1	4.6	rank6+rank7	rank6+rank7	E7

The Building has experienced more than 1,239 earthquakes since it was built in 1998. Some research on the soil stiffness in earthquakes has been obtained in past years. For example, Kashima et al. (2006) inferred that the soil stiffness (rocking stiffness and swaying stiffness) remained almost unchanged from 1998 to 2005, but the fluctuations in the results were very strong.

It is necessary to calibrate the rocking stiffness of the soil from 1998 to 2005 using earthquake response measurement data and also to check whether the rocking stiffness of the soil changed from 2006 to 2012. In the following sections, the outstanding peak response points of the R_a-R_d



(a) E1 (b) E2 (c) E3 (d) E4 (e) E3 (f) E4 (g) E7

Figure 3. Ra-Rd Curves

curves of the foundation will be used to answer these questions. In this paper, seven of the most significant earthquake records were selected from 1998 to 2012; see Table 1.

4 CALCULATION RESULTS

4.1 Study on the soil responses

As shown in Figure 4, the Polygonal Lines and the outstanding peak response points show that the soil responses were linear in most of the seven earthquakes (except E5 for the Tohoku Earthquake off the Pacific Coast in 2011). For example, the soil performance remained unchanged in Earthquakes E1–E4, E6, and E7; Earthquakes E5 showed that the soil performance decreased in the E-W direction during the earthquake (points A and B, see Figure 4(e)). The maximum peak response points could be used to calibrate the rocking stiffness of the soil in earthquakes E1–E7.

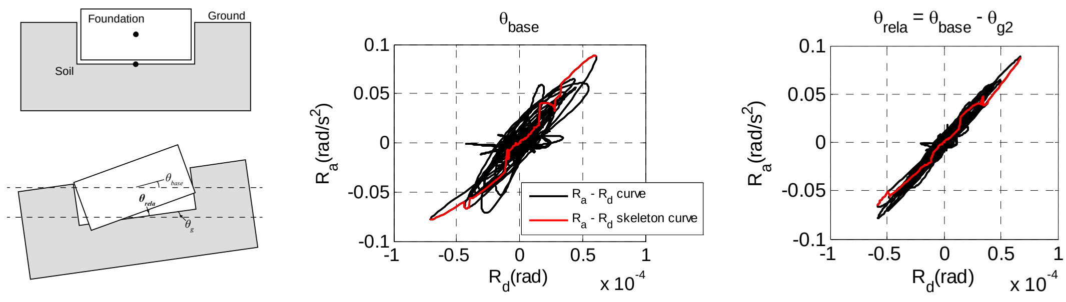
4.2 Effect of rotational Input

As for the calculation of the rocking angle θ_{base} of the building, we used the motions of the three points BFN, BFE and BFS located on the base floor. However, θ_{base} reflects the absolute rocking motion of the foundation, which contains the rotation motion of the ground. In order to get the R_a - R_d curve of the soil (reflects the relationship between the deformation of soil and the moment of the building), we should calculate the relative rotation angle θ_{rela} between the foundation and its surrounding ground, see Fig.4(a). In this case, we calculate the rotation motion of the ground for N-S direction θ_{g2} as follows,

$$\theta_{g2} = \frac{Z_{B01} - Z_{A01}}{L} \tag{8}$$

As for the influence of the θ_{g2} on the shape of the R_a-R_d curves, all the 7 earthquakes were discussed. Just as what is shown in Figure 4, when the rotation motion of the ground θ_{g2} was deleted from the rocking motion of the foundation θ_{base}, the hysteresis loops of the corresponding R_a-R_d curves would become compact and easy to understand. It can be easily concluded that the soil responses were linear during the earthquakes E1-E6. Besides, stronger rotation motion of the ground (θ_{g2}) always have larger influence on R_a-R_d curves.

After deleting (means θ_{base}-θ_{g2}) the influence of θ_{g2}, the R_a-R_d curves and R_a-R_d skeleton curves become easier to understand and analyze. Because the soil responses for the 7 earthquakes were linear, so the maximum peak response points of the R_a-R_d curves were selected to calculate the fundamental frequency (f_r=ω_r/2π), and ω_r was calculated by Equation (6). Fundamental frequency of the rocking motion of the foundation is shown in Fig.6. The fundamenal frequency is almost stable for N-S direction. But, in E-W direction, the fundamenal frequency is quite changed on E5.



(a) Response of direct foundation (b) Ra-Rd curve with ground motion (c) modified Ra-Rd curve
Figure 4. Modification result of R_a-R_d Curves

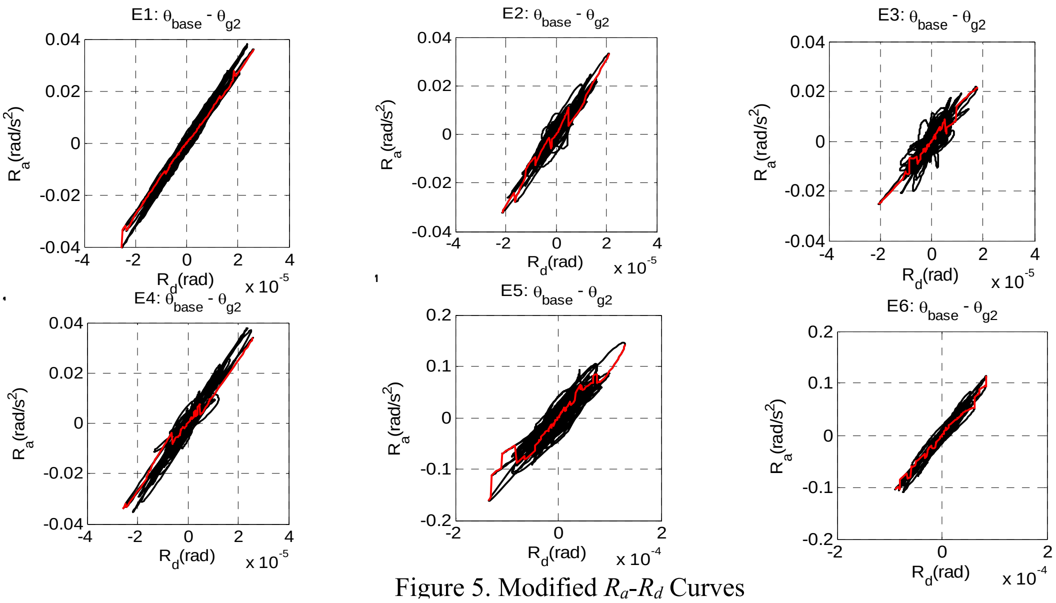
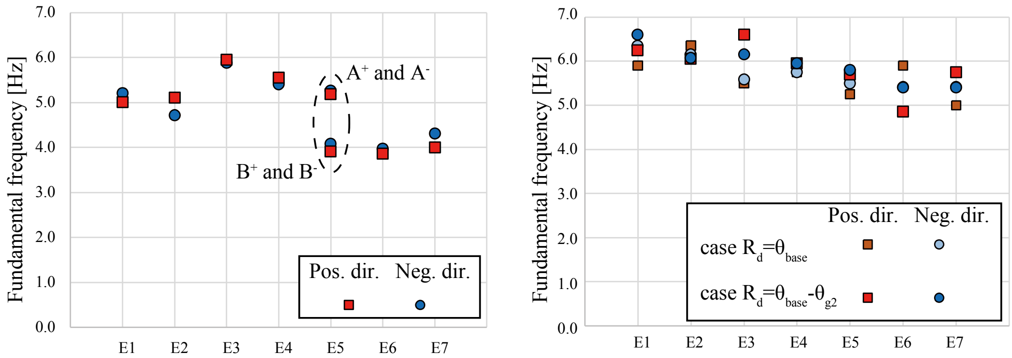


Figure 5. Modified R_a-R_d Curves



(a) E-W direction (b) N-S direction

Figure 6. Fundamental frequency of the rocking motion of the foundation

4.3 *Calculation of rocking soil stiffness*

Due to the AIJ standad (AIJ Comittee, 2003), when considering the embedment effect of the foundation in the soil, the rocking stiffness will be calculated as follows:

$$K_r = K_{rb} + K_{re} \tag{9}$$

$$\mathrm{K_{rb}}_{AIJ} = \beta_R K_{1r} \tag{10}$$

where β_R reflects the contribution of all soil layers for the total rocking stiffness, K_{1r} is the rocking stiffness for the first soil layer, and K_{re} is caused by the foundation embedment effect (reduction coefficient ξ_{re} is 0.5 under strong earthquakes).

The JARA standard (JARA, 2012) gives a method of calculating the rocking stiffness as follows:

$$\mathrm{K_{rb}}_{JARA} = I \cdot K_v = I \cdot k_{v0} \cdot \left(\frac{B_V}{0.3}\right)^{-3/4} \tag{11}$$

where k_{v0}=10/3·α·E_0, in which α is a scaling factor (as for the PS Well Logging method in this paper, earthquake condition: α= 0.2516)); and E_0 is calculated by the elastic modulus of the layered soil obtained by PS Well Logging method; $B_V=\sqrt{a \times b}$; I is the moment of inertia of the foundation mat ($I= ab^3/12$, where a and b are the size of the foundation mat).

It can be concluded that the fundamental rocking frequency ω_r ($=2\pi/T_r$, where T_r is the fundamental rocking period) of a specific SRC building is independent of different estimations of the total mass and equivalent height H_e.

As shown in Table 4 for Case 1, the rocking stiffness calculated using the measurement data is larger (1.6 times) than the designed values by the calculation method of response and limit strength. However, the real-time values are much larger (5-10 times) than those in the JARA standard, of which the vertical ground reaction force coefficient k_v was used to calculate the rocking stiffness through the model in Figure 7. For Case 2, the rocking stiffness calculated by the calculation method of response and limit strength agreed well with the results from the measurement data. It can be concluded that the estimation of the total mass has a significant influence on the calibration of the rocking stiffness of the soil.

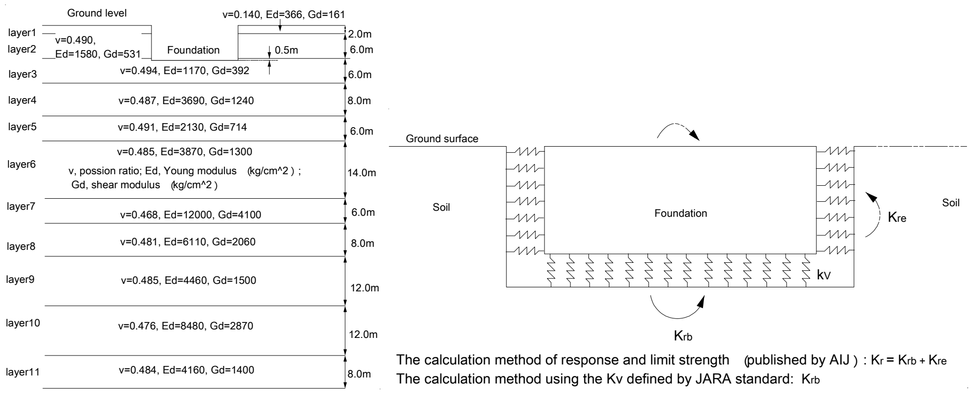


Figure 7. Soil Property and Calculation model for the rocking motion

Table 2. Calculation results of rocking stiffness

	Rocking stiffness (10^{12} N·m/rad)		
	AIJ standard	Real values	JARA standard
E–W	$0.56(K_{rb}) + 0.32(K_{re})= 0.87$	0.84 (Case 2)–1.40 (Case 1)	$K_{rb} = 0.146$
N–S	$0.82(K_{rb}) + 0.41(K_{re})= 1.23$	1.18 (Case 2)–1.97 (Case 1)	$K_{rb} = 0.225$

5 DISCUSSION AND CONCLUSIONS

A simple R_a-R_d curve of the soil for the rocking motion was presented in this paper, which can be used for the evaluation of real-time seismic performance of soil and rocking soil stiffness. In this paper, the maximum response points of the R_a-R_d curves of an eight-story SRC building in earthquakes were used to calibrate the rocking stiffness of the soil, and two conclusions can be made as follows:

(1) The Polygonal Lines restored from the R_a-R_d curves can help us understand the real-time performance changes of the soil during earthquakes. The outstanding peak response points of R_a-R_d curves are important for understanding the current properties of the soil, as the superstructure reaches its peak deformation at the same time.

(2) For the researched SRC building that has an embedment direct foundation, the calculation method of response and limit strength published by the AIJ underestimated the rocking stiffness

of the soil, and the vertical ground reaction force coefficient k_v defined by JARA standard cannot reflect the real measurement of the soil stiffness. And the estimation of the total mass has a significant influence on the calibration of the rocking stiffness.

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REFERENCES

Architecture Institute of Japan Committee, 2003, Seismic response analysis and design of buildings considering dynamic soil-structure interaction

Chopra., A. K., et al., 2002, Dynamics of structures: Theory and applications to earthquake engineering (second edition)

JApan Road Association, 2012, Specifications for highway bridges—IV edition: Substructure

Jenings, P. C., and Bielak, J., 1973, Dynamics of Building-Soil Interaction, Bulletin of the Seismological Society of America, 63(1), 9-48

Kashima, T., and Kitagawa, Y., 2006, Dynamic characteristics of a building estimated from strong motion records using evolution strategy, Journal of Structural and Construction Engineering (Transactions of AIJ), 602, 145–152

Kawamura, M., Kusunoki, K., Yamashita, M., Hattori, Y., Hinata, D., Diaz, M. A., and Tasai, A., 2013, Study of a New Method to Compute the Performance Curve of Real Structures with Acceleration Sensors in the case of SDOF System Structures, *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 78(688), 1061–1069

Kusunoki, K., Teshigawara, M., and Koide, E., 2003, Development of real-time residual seismic capacity evaluation system No 1: Outline of the evaluation method, *Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan*, *Tokai, Japan*: 961-962

Kusunoki, K., Hinata, D., Hattori, Y., and Tasai, T., 2014, Development of a new method of realtime residual seismic capacity evaluation of existing structures with accelerometers in the case of MDOF system structures, Journal of Structural and Construction Engineering (Transactions of AIJ), 79(699), 613–620

Li, L., Nakamura, A., Kashima, T., and Teshigawara, M., 2014, Earthquake damage evaluation of an 8-story steel-reinforced concrete building using Sa-Sd curves, Journal of Structural and Construction Engineering (Transactions of AIJ), 702, 1107–1116

Mori, M., Fukuwa, N., Sakai, R., and Wen, X., 2008, Effects of side and base elements of embedded spread foundations on dynamic soil-structure interaction and conventional estimation methods for soil springs by composing the impedance of each element, Journal of Structural and Construction Engineering (Transactions of AIJ), 626, 535–542

Tamori, S., and Iiba, M., 2004, Study on accuracy of sway and rocking springs in soil-structure interaction proposed by the calculation method of response and limit strength—Evaluation with predominant frequency and mode, AIJ Hokuriku Research Reports, 47, 80–83

Tamori, S., and Iiba, M., 2005, Study on accuracy of sway and rocking springs in soil-structure interaction proposed by the calculation method of response and limit strength—Evaluation with predominant frequency and mode, AIJ Hokuriku Research Reports, 48, 157–160