EVALUATION OF SOIL STIFFNESS USING PERFORMANCE CURVES OF AN EIGHT-STORY STEEL-REINFORCED CONCRETE BUILDING WITH EMBEDDED SPREAD FOUNDATION

根入れがある直接基礎のSRC建物の建物性能曲線による地盤の地盤剛性評価

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In this paper, a simple evaluation method of soil stiffness is presented based on the $R_a - R_d$ curve (which reflects the relationship between the rotation angle and the rotation moment of the foundation). Earthquake response records were used to obtain $R_a - R_d$ curves. This study analyzed the $R_a - R_d$ curves of the researched Steel-Reinforced Concrete (SRC) building (with an embedment spread foundation) for seven strong earthquakes that occurred in Japan between 1998 and 2012. And the real measurements of rocking stiffness of the soil were calculated using maximum peak response points of the $R_a - R_d$ curves. The results demonstrated that for the researched SRC building under the condition of strong earthquakes, the calculation method of response and limit strength (published by the Architecture Institute of Japan) underestimated the rocking stiffness of the soil and the method using vertical ground reaction force coefficient $k_v$ estimated in the JARA (Japan Road Association) standard cannot reflect the real measurements of the rocking stiffness of the soil.

Keywords: Rocking stiffness of the soil, Embedment Spread foundation, Performance curve, Steel-reinforced concrete (SRC) building, Strong earthquake records, Wavelet transform technique

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 effect1). 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 and Iiba2-3) made the microtremor 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 embedment spread foundations. Mori and Fukuwa et al4) evaluated the soil springs of the building with an embedment spread 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 superstructures5-7). This method has been shown to be practically applicable to seismic performance evaluation of real buildings8). 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 an embedded spread foundation (i.e., the underground soil is layered).

2. The Proposed Method for $R_a - R_d$ curve

2.1 $R_a - R_d$ curve

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 $S_d$) 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.

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

$$R_a = \frac{S_a}{S_d}$$  \hspace{1cm} (1a)

$$M_e = I_e \cdot R_a$$  \hspace{1cm} (1b)

$$I_e = m_e \cdot H_e^2$$  \hspace{1cm} (1c)

where the equivalent height $H_e$ (Chopra et al.) was calculated using maximum response points ($u_{t_{max}}$) of the fundamental mode response; see Equation (2) as follows:

$$H_e = \frac{\sum m_i u_{t_{max}} / u_i}{\sum m_i}$$  \hspace{1cm} (2)

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

$$I_e \cdot R_a + c_e \cdot \ddot{R}_a + k_e \cdot R_a = 0$$  \hspace{1cm} (3)

where $c_e$ and $k_e$ 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

$$-\frac{R_a}{R_a} = \frac{R_a}{R_a}$$  \hspace{1cm} (4)

Then

$$\omega_e = \sqrt{-\frac{R_a}{R_a}}$$  \hspace{1cm} (5)

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

$$k_e = I_e \cdot \omega_e^2$$  \hspace{1cm} (6)

where $R_a$ is the representative rocking angle, the calculation method was referred to the paper by Ligang Li et al. 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 $R_a - R_d$ curve. And $\omega_e$ 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 $R_a$) can be extracted using the wavelet transform technique (WTT, the 'Original' data $D$ can be decomposed into a number of components $d_1, d_2, \ldots, d_i, \ldots, d_n, I_0$; the components $d_1 \sim d_n$ are corresponding to the terms $\text{Rank}1, \text{Rank}2, \ldots, \text{Rank} N$ respectively; for a specific component $d_i$, the frequency range is $f/2^{i+1} \sim f/2^i$, where $f$ is the sampling frequency and $f = 100Hz$ in this paper), and the determination of the fundamental responses (Rank 6 includes the fundamental response through comparing the Fourier spectrum of each component, namely each Rank) is shown in Figure 2(a).

2.2 Polygonal Line restored from the $R_a - R_d$ curve

Like the $S_a - S_d$ skeleton curve, 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. However, outstanding peak response points (defined in Step 4) of the $R_a - R_d$ curve can avoid the influence of damping force (exists in the $R_a - R_d$ skeleton curve). If those points can be used to restore a simple Polygonal Line, then the linearity and nonlinearity of the soil response can be observed directly through Polygonal Line, as
shown in Figure 2(c) (bold line): it can be found that soil response in E-W direction of the researched building in the earthquake 2011/03/11/15:15 was almost linear. From this perspective, a series of proposed procedures of using the Polygonal Lines to evaluate the soil performance was obtained as follows:

Step 1: Accumulate the earthquake response data of the building and extract the fundamental response using the WTT technique. \( R_d \), the representative rocking angle can also be extracted.

Step 2: The reference point is located at the ground level. Then calculate \( S_a, S_d \) and the properties of the SDOF model \( (m_a, h_a) \). Peak response points (for example, points \( Q_1 \) and \( Q_2 \) of \( S_d \) in Figure 2(b)) in \( S_a - S_d \) skeleton curve will be got in this step.

Step 3: Calculate \( R_a \), the representative rocking-moment coefficient (Equation 1(a)); then, the \( R_a - R_d \) curve (fine line in Figure 2(c)) can be obtained.

Step 4: Find the outstanding peak response points of the \( R_a - R_d \) curve, which should satisfy three conditions at the same time: (1) these points should be corresponding to the peak response points in the \( S_a - S_d \) skeleton curve (for example, points \( P_1 \) to \( Q_1 \) and \( P_2 \) to \( Q_2 \) in Figure 2(b)); (2) \( R_d \) is larger than \( 1 \times 10^6 \) rad; (3) \( R_d \) of the current peak response point (for example point \( P_1 \) in Figure 2(b)) is larger than that of the previous one (for example point \( P_2 \) in Figure 2(b)).

Step 5: Outstanding peak response points (defined in step 4) of the \( R_a - R_d \) curve will be connected to restore a simple Polygonal Line (bold line in Figure 2(c)).

In this paper, we used Polygonal Line to judge the linearity and nonlinearity of the soil response: and the maximum peak response points (PR+ and PR− in Figure 1(c)) were used to calculate rocking stiffness of the soil.

3. Research object

The research object of the paper is an eight-story SRC building (Building Research Institute BRI Annex Building: the dimensions of the superstructure are \( H \times A \times B = 28 \times 21 \times 26 \), 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\(^\text{11}\), and the outline of the building and soil property are shown in Figure 3. The foundation type is an embedment spread foundation, of which the embedment depth underground is 8.5 m. The soil properties of each soil layer under the building were surveyed using the PS logging method, and the results of the soil properties are summarized in Figure 3(b).

The BRI Annex 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 and Kitagawa\(^\text{13}\) inferred that the soil stiffness
4.1 Study on the soil responses

The calculation method for the Polygonal Lines and the outstanding peak response points were previously introduced in Sections 2.1 and 2.2. Using the Polygonal Lines, soil responses of the 7 strong earthquakes were analyzed in this part.

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 Fundamental rocking period

According to the analysis in Section 4.1, the maximum peak response points of \( R_a - R_d \) curves could be used to calculate the fundamental natural frequency of the rocking motion (Eq. (5)).

Then the fundamental natural periods for the rocking motion in the seven earthquakes are summarized in Figure 5.

As shown in Figure 5, in the E–W direction, the fundamental natural periods for the rocking motion of Earthquakes E1–E4 (and the points A+ and A– in earthquake E5) were almost stable. The period was approximately 0.17–0.20 s, whereas for Earthquakes E5 (points B+ and B–)–E7, the period was approximately 0.25 s. In the N–S direction, the fundamental periods of the rocking motion for the seven earthquakes were
approximately 0.15–0.18 s.

4.3 Influence of mass uncertainty on $R_a - R_d$ curve

To calibrate the rocking stiffness, the core problem is how to determine the total mass of the building. Therefore, in this paper, two cases (Cases 1 and 2; see Table 2) were studied and could be used as the approximation values of the total mass.

For Case 1 (the upper limit), the masses of each floor were taken from the design document (the combination of the live loads and dead loads for each structural element and the different function rooms), which were calculated based on design standards. For Case 2 (the lower limit), mass density is approximately $0.8 \times 10^3$ kg/m$^2$ for the SRC office building$^{12}$. This value will be used for the calculation $m_i = A_i \times \rho$, where $A_i$ is the area of the $i$-th floor, and $\rho$ is the mass density $0.8 \times 10^3$ kg/m$^2$. The mass distribution is summarized in Table 2.

As shown in Figures 6 and 7, the equivalent height of the
SDOF model $H$, (approximately 18.4–18.8 m, with a ratio $H_s/H$ of approximately 0.66) and the equivalent mass ratio $M/M_{total}$ (approximately 0.72–0.75) are the same for the seven earthquakes in the two cases (Cases 1 and 2). This means that the influence of the absolute value of the total mass of the superstructure on the $R_g - R_d$ curves is little because the mass distributions (mass ratio) in Cases 1 and 2 are almost the same (a little different): see Table 2.

4.4 Current calculation methods of rocking stiffness of soil

4.4.1 Calculation method of response and limit strength (published by AIJ) $^1$ $^{13}$

The rocking stiffness for the vertical direction is calculated as follows

$$K_{rv} = \beta_R K_{rv}$$  \hspace{1cm} (7)

Where $\beta_R$ reflects the contribution of all soil layers for the total rocking stiffness, $K_{rv}$ is the rocking stiffness for the first soil layer, and the calculation model is shown in Figure 8.

$$\beta_R = \frac{u}{\sum u_i}$$ \hspace{1cm} (8)

$$K_{rv} = \frac{E_s r_v^2}{3 (1 - v_s^2)}$$ \hspace{1cm} (9)

Where

$$u_i = \left( \frac{E_s}{E_r} \right)^{\frac{1}{2}} \left( \frac{r_i}{r_v} \right)^{\frac{3}{2}} \quad (i=1, \ldots, n - 1)$$ \hspace{1cm} (10)

$$u_n = \left( \frac{E_s}{E_r} \right)^{\frac{1}{2}} \left( \frac{r_n - r_v}{r_v} \right)^{\frac{3}{2}}$$ \hspace{1cm} (11)

$$r_{ro} = \frac{\pi}{72} \left( 1 - \bar{v}^2 \right) r_{ro}$$ \hspace{1cm} (12)

When considering the embedment effect of the foundation in the soil, the rocking stiffness will be calculated as follows$^{13}$:

$$K_v = K_{rv} + K_{re}$$ \hspace{1cm} (13)

$$K_{re} = K_{rv} \left[ 2.3 \cdot \frac{\nu_{re}}{r_{re}} + 0.5 \cdot \left( \frac{\nu_{re}}{r_{re}} \right)^3 \right] G_{re}$$ \hspace{1cm} (14)

Where $K_{rv}$ is caused by the foundation embedment effect (reduction coefficient $\nu_{re}$ is 0.5 under strong earthquakes): $D_e$ is the embedment depth of the foundation, $G_{re}$ and $G_{ab}$ can be calculated as follows (see Figure 9),

$$G_{re} = \frac{r_n - r_v}{r_v} \frac{E_s}{E_r}$$ \hspace{1cm} (15)

$$G_{ab} = \frac{(1 - \bar{v}) G_{ou}}{r_{ro}}$$ \hspace{1cm} (16)

Where $K_{ab}$ is the horizontal soil stiffness, and the detailed calculation procedure can be found in the same document$^{13}$.

4.4.2 Calculation method based on JARA standard $^{14}$

The JARA standard gives a method of calculating the vertical ground reaction force coefficient $k_p$ as follows:

$$k_p = k_p \cdot \left( \frac{H_s}{H} \right)^{-3/4}$$ \hspace{1cm} (17)

where $k_p = 10/3 \cdot E_s$, in which $a$ is a scaling factor (as for the PS Well Logging method in this paper, earthquake condition: $a = 0.25^{15}$) and $E_s$ is calculated by the elastic modulus of the layered soil obtained by PS Logging method: $B_e = \sqrt{\mu} \times K_e$ (size of the foundation mat).

Because the soil responses during the earthquakes were linear, see Figure 4: the rocking stiffness ($k_{rv}$), see Figure 9) can be calculated as follows:

$$k_{rv} = k_c \cdot l$$ \hspace{1cm} (18)

where $l$ is the moment of inertia of the foundation mat ($l = ab^3/12$, unit: m$^4$; where $a$ and $b$ are the size of the foundation mat, unit: m).

4.5 Calibration of rocking soil stiffness

The previous analysis (section 4.2) showed that the fundamental natural period $T_r$ (corresponding to the rocking motion) 0.19 s (mean value in the E–W direction) and 0.16 s (mean value in the N–S direction) remained almost stable in Earthquakes E1 (2003–E4 (2008) and the points A+ and A- in earthquake E5). In this section, the five earthquakes are used to calibrate the rocking stiffness of the soil.

Based on the analysis in section 4.3, it can be concluded that the fundamental rocking frequency $\omega_r = 2\pi/T_r$, where $T_r$ is the fundamental rocking period of a specific SRC building is
independent of different estimations of the total mass (and even when mass distributions are a little different; see Table 2) and equivalent height \( H_e \). According to Equation (6), the moment of inertia \( I_e \) (corresponding to \( M_{\text{total}} \) and \( H_e \)) determines the value of the rocking stiffness when \( \omega_e \) is fixed. Therefore, a range of total mass \( (M_{\text{total}} \text{ for Case 2, } M_{\text{total}} \text{ for Case 1}) \) was set up to calibrate the rocking stiffness. Then, the rocking stiffness was calculated and summarized in Table 3.

Table 2 Masses, areas, and heights of superstructure

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<tr>
<th>Floor</th>
<th>( h_i ) (m)</th>
<th>Mass ( m_i ) (mass ratio: ( m_i/M_{\text{total}} )) (unit: ( 10^4 ) kg)</th>
<th>Area ( A_i ) (m²)</th>
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Table 3 Comparison of the rocking stiffness of the soil

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<th>Floor</th>
<th>( M_{\text{total}} ) (kg): Case 1, 5.12 ( \times 10^8 ) kg; Case 2, 3.07 ( \times 10^8 ) kg</th>
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As shown in Table 3 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 9. 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.

In conclusion, the rocking stiffness calculated by the calculation method of response and limit strength is not accurate and needs to be improved; and the vertical ground reaction force coefficient \( k_v \) defined by JARA standard cannot reflect the real measurement of the soil stiffness. The total mass of the superstructure is a significant factor to determine the value of the rocking stiffness.

5. Conclusions and discussion

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 spread foundation, the calculation method of response and limit strength published by the AIJ underestimated the rocking stiffness of the soil. The vertical ground reaction force coefficient \( k_v \) defined by JARA standard cannot reflect the real measurement of the soil stiffness: one important reason is because of the definition of the scaling factor \( \alpha \) in section 4.4.2, which does not completely consider the influence of the different strain levels in the current design methods\(^{11}\). For the large strain levels under strong earthquakes in this research, scaling factor \( \alpha \approx 0.25 \) may be too small.

Besides, the estimation of the total mass has a significant influence on the calibration of the rocking stiffness. However, the fundamental rocking period increased to approximately 0.25 s after Earthquake E5 (the Tohoku Earthquake off the Pacific Coast in 2011) in the E–W direction, whereas almost no changes of the fundamental rocking period took place in the N–S direction: see Figure 5. It is necessary to make further research on that phenomenon in the future.

Besides, as for the embedment spread foundation in the paper, it is impossible to know how much influence of the embedment effect (exists in the sides of foundation) on the total rocking stiffness of soil under earthquake condition. We need to make further research on that point to evaluate the vertical soil stiffness under the foundation.

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References


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和文要約
1. はじめに
地震と建物の動的相互作用（以下 SSI）は、建物の動的応答を評価するうえで重要な要素である。地盤のパネル特性の評価は、解析的検討を中心に行われている。田守らは、20種のSRC建物の常時微動観測記録と、地盤調査から算出した地盤パネル特性を用いたSSIモデルの解析結果を比較し、従来の評価方法を用いた場合には、埋め込み直後の地盤のロックング剛性を過小評価することを示している。しかし、比較的大きな地震応答時の地盤のパネル特性についての報告例は少なく、データの蓄積が望まれている。

2. ロックングモーメント−回転角関係の評価方法
一般的に、ロックング挙動は上部構造の主要なモード応答と連動すると考えられる。代表的なロックングモーメント係数は、上部構造の代表加速度Sから算出される軸傾斜モーメントから算定される（式(1))。また、回転性の運動方向（式(3))より、速度に比例する粘性減衰を0とする点では、その傾きがロックングパネル剛性を表すと考えられる。すなわち、ロックングモーメント−回転角関係（以降、R-R関係）を算出し、速度が0となる、回転角やモーメントの方向が変わる点での傾きを評価することで、ロックングパネル剛性を算出することができる。そこで、地震記録に基づき、次の手順でロックング剛性を評価する。
1) ワーベレット変換を用いて、地震観測記録から主要な応答を抽出する。基準階の上下動から、ロックング回転角Rを算出する。
2) 上部構造の代表加速度Sから、ロックングモーメント係数Rを算出する。
3) 上部構造の代表加速度Sから、ロックングモーメント係数Rを算出する。
4) R-R関係から、速度0となる点（ピーク点）を抽出する。ただし、対象とするピーク点は前ステップのピーク点よりも応答の大きなものとする。
5) 抽出したピーク点を用いて、ロックング剛性を算出する。
3. 対象建物
対象建物は、8階建てのSRC造建物である。基礎は、地下階の埋め込み部を有する直接基礎である。PS検層による地盤調査結果を図30に示す。対象建物は、1998年の建設当時から計1239波の地震記録が得られているが、本論文では、特に応答の大きい7波の観測記録を用いて検討を行う。
4. ロックング剛性の評価
NS方向およびEW方向それぞれのR-R関係を算定した結果を図4に示す。地震記録E5を除くと、R-R関係は概ね線形となっている。一方、地震記録E5では、EW方向において、ロックング剛性の低下が確認される。
R-R関係の傾き（ロックング周期）の時刻系列的变化を図5に示す。図5より、EW方向では、地震記録E5において、ロックング周期が0.20secから0.25secに伸びていることが確認できる。
R-R関係の傾き（ロックング周期）からロックング剛性を算出するためには、上部構造の層間荷重を適切に評価する必要がある。