STUDY ON THE RATIONALIZATION OF FOUNDATION INPUT MOTION IN JAPAN'S PERFORMANCE-BASED BUILDING CODE

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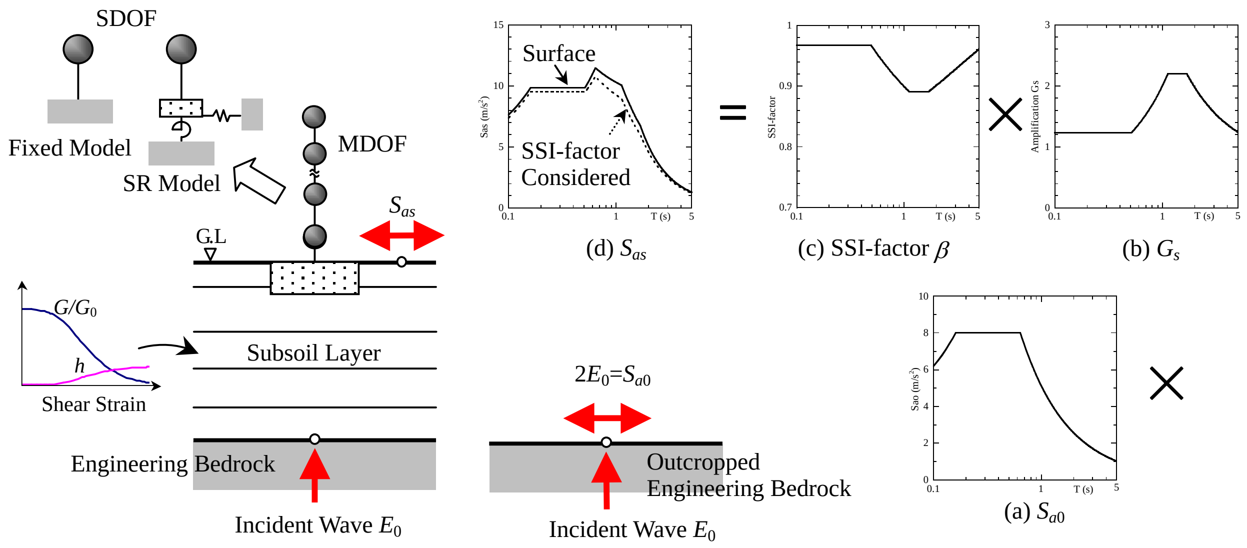
ABSTRACT:

This paper describes a rational evaluation of the foundation input motion in the Response and Limit Strength Calculation (RLSC), which was developed for performance-based design in Japan. In RLSC, the effect of input loss caused by the embedding foundation is calculated using the amplification of the surface strata, G_S, and the soil–structure interaction factor (SSI-factor) β. We previously showed that the evaluation of the embedding effect of the foundation in RLSC is conservative, particularly in a short period range less than the first period of the surface strata. To improve this overestimate of the foundation input motion, a SSI-factor β considering the second vibration mode of the surface strata is incorporated and new formulas are proposed. The response acceleration spectra obtained by the proposed method are in good agreement with those of rigorous analysis.

KEYWORDS: Response and Limit Strength Calculation, Soil-Structure Interaction,
Foundation Input Motion, SSI-Factor, Embedding Foundation

1. INTRODUCTION

In soil–structure interaction (SSI) problems, the dynamic impedance function and the foundation input motion are recognized as fundamental physical properties (AIJ, 1996). In response to the 2000 revision of Japan's Building Standards Law, the "Response and Limit Strength Calculation (RLSC)" was developed toward achieving performance-based design (BRI, 2001). As shown in Figure 1, the main features of RLSC are as follows: (i) Regulation of the design earthquake motion as an acceleration response spectrum at outcropped engineering bedrock; (ii) Incorporation of the nonlinear amplification effect of surface strata; (iii) Incorporation of the effects of soil–structure interaction; and (iv) Modeling of multistory buildings (multi-degrees-of-freedom (MDOF) system) into an equivalent single-degree-of-freedom (SDOF) system. The design acceleration response



(d) S_{as} (c) SSI-factor β (b) G_s (a) S_{a0}

Figure 1 Framework of RLSC

spectrum S_{as} at the ground surface is evaluated by multiplying S_{a0} (see Fig. 1) by the amplification of the surface strata, G_S. Furthermore, if the embedding effect of the foundation needs to be incorporated, the soil–structure interaction factor (SSI-factor) β should be considered.

The response displacement of a structure, called the performance point, is calculated from the acceleration displacement response spectrum (ADRS) format. The demand spectrum of S_{as} versus S_d in the elastic range is converted from the acceleration response spectrum S_{as} at the ground surface, and this spectrum is reduced by hysteretic damping of the structure in the inelastic range. On the other hand, the capacity spectrum of the structure is calculated by push-over analysis, and the performance point is evaluated using the cross-point between the demand spectrum in the inelastic range and the capacity spectrum.

In RLSC, the effect of input loss caused by embedding of the foundation, i.e. an inertial interaction effect, is evaluated using the amplification G_S (see APPENDIX) of the surface strata and the SSI-factor β.

In our previous investigation of the effect of input loss in RLSC (Izumi and Miura, 2006), we pointed out that, in RLSC, the design acceleration response spectrum considering the embedding effect of the foundation is conservative, particularly in a short period range less than the first predominant period of the surface strata. Also, we observed that the acceleration response spectrum at the foundation bed of the free field computed by one-dimensional equivalent linear analysis using SHAKE is similar to the foundation input motion based on an axisymmetric finite element method (AX-FEM) analysis, but the former response is underestimated in specific period ranges. Furthermore, the foundation input motion based on an equivalent two-layer model computed by RLSC is in good agreement with that of AX-FEM.

This overestimate of the foundation input motion in RLSC is because only the first vibration mode of the surface strata is considered in determining the SSI-factor β. In this paper, we describe a rational evaluation of the foundation input motion in RLSC, and we propose new formulas for the SSI-factor.

2. ANALYSIS METHOD

2.1. Analytical Model

2.1.1 Soil and foundation models

In this study, we considered four kinds of subsoil layer (Miura et al., 2001). The initial shear wave velocities of the four different kinds of subsoil are shown in Figure 2, where “C” and “S” denote “clay” and “sand”, respectively. In an Official Notice from the Japanese Ministry of Land, Infrastructure and Transport, the engineering bedrock (EBR) is defined as a layer of bedrock having a shear wave velocity of about 400 m/s or higher. The depths of the EBR below ground level (GL) are GL – 46.6 m for Site 1, GL – 37.0 m for Site 2, GL – 27.5 m for Site 3, and GL – 20.0 m for Site-4. The EBR supports the bottom of piles. In the safety-limit state, the first natural period T_g is 2.23 s for Site 1, 1.56 s for Site 2, 1.40 s for Site 3, and 0.78 s for Site 4.

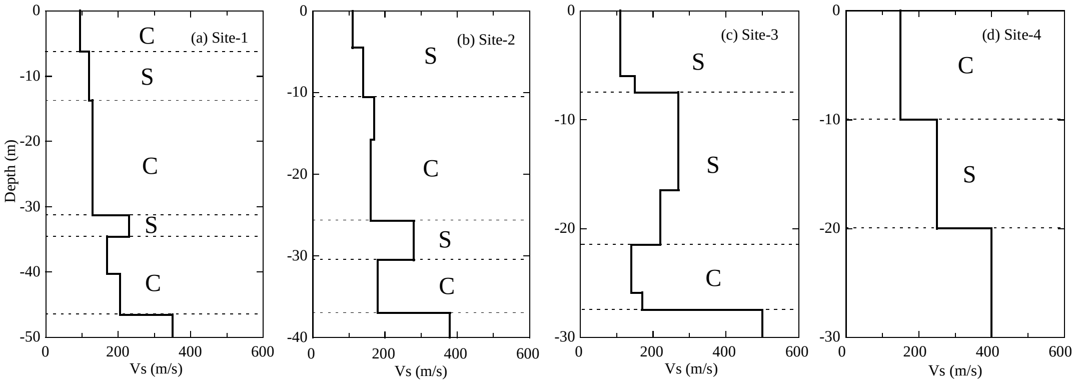


Figure 2 Initial shear velocities of the soil models

The embedding foundation is assumed to be rigid. The embedding depths D_e are set to 6.0 m and 10.0 m. As shown in Figure 3, two foundation types are selected: the raft foundation and the pile foundation. The pile is a cast-in-situ concrete pile. The foundation shape is a 30 m wide by 30 m deep square. This shape replaces an equivalent circular shape having the same area. In the pile foundation, a 6×6 group is assumed, and the diameter of each pile is 1.0 m.

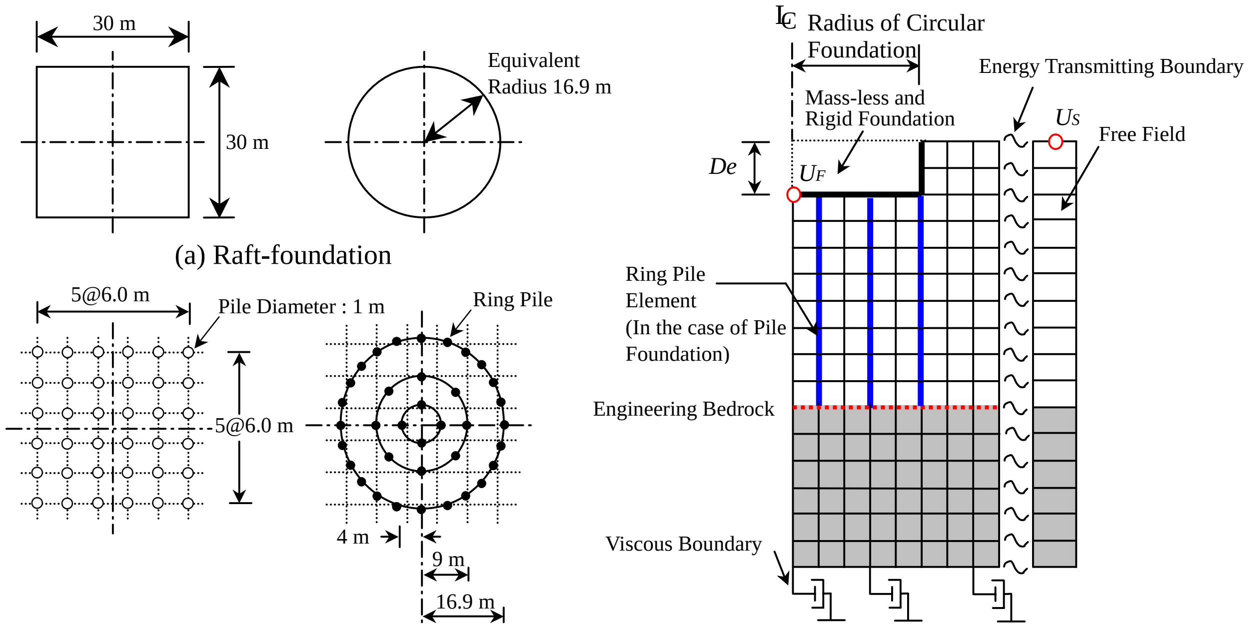
2.1.2 Axisymmetric finite element method analysis

We carried out AX-FEM to estimate the foundation input motion. As shown in Figure 3, the pile group is modeled as ring-pile elements whose moment of inertia is the same as that of the 6×6 square pile arrangement, and the piles are assumed to be elastic. In the AX-FEM analysis, the equivalent shear modulus G_{ei} and the equivalent viscous damping factor h_{ei} in the i-th layer were obtained by RLSC. In the pile foundation, the foundation bed does not contact the ground surface. The vertical incident shear wave is applied at the EBR of each soil model. Furthermore, the transfer functions U_F/U_S, where U_F and U_S are the Fourier amplitudes of the center of gravity of the foundation bed and ground surface of the free field, respectively, were calculated and used to generate the input earthquake motions.

The horizontal component of the foundation input motion time history, $u_F(t)$, is given by the inverse Fourier transform

$$u_F(t) = (1/2\pi)\int_{-\infty}^{\infty} \{U_F(f)/U_S(f)\} \cdot U_S(f) e^{i\omega t}\, d\omega, \tag{2.1}$$

where ω is the circular frequency ($= 2\pi f$). The rotational component of the foundation input motion is neglected in this study.



(a) Raft-foundation

(b) Pile-foundation

(c) AX-FEM Model

Figure 3 Foundation types and AX-FEM model

The design earthquake motion is specified as an acceleration response spectrum S_{a0} with a damping factor of 5% at the outcropped engineering bedrock, as shown in Figure 1(a). The S_{a0} of the damage-limit state is one-fifth of that for the safety-limit state. Ten simulated earthquake motions are generated from the target spectrum S_{a0} for varying phase angles and are used for the one-dimensional equivalent linear analysis SHAKE. The input motion is set up as an outcrop motion ($2E_0$) on the engineering bedrock. The nonlinear characteristics between the shear modulus ratio G/G_0, the damping factor h, and the shear strain are used in Ohsaki-Hara’s model (Ohsaki et al., 1975).

2.1.3 Foundation input motion in RLSC

In RLSC, the effect of input loss caused by embedding of the foundation, i.e., an inertial interaction effect, is evaluated using the amplification G_S of the surface strata and the SSI-factor β. As shown in Figure 4, the SSI-factor β in RLSC is derived from the following assumptions: (1) the amplification G_B on the engineering bedrock is unity, (2) the distribution shape of the amplification between the ground surface and the engineering bedrock is linear, and (3) only the first vibration mode of the surface strata is considered.

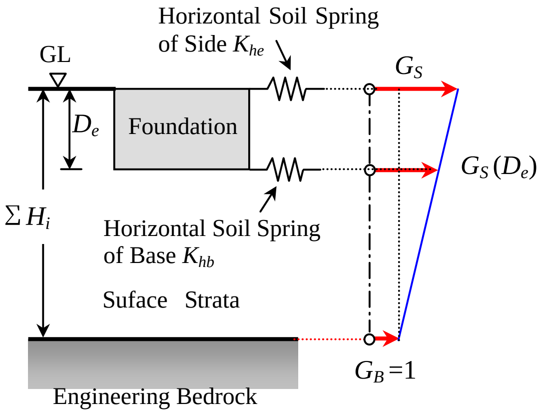


Figure 4 Assumptions of SSI-factor β in RLSC

The foundation input motion corresponds to a weighted average of the seismic horizontal displacement of the free field with soil springs, as follows:

$$G_F = \frac{K_{hb} \cdot G_S(D_e) + K_{he} \cdot G_S}{K_{he} + K_{hb}}, \tag{2.2}$$

where K_{hb} and K_{he} are the soil springs of the foundation bed and the lateral side, respectively. These soil springs are calculated using a simplified Wolf's cone model and the Pais and Kausel formula (BRI, 2001). As shown in Figure 4, G_S (D_e) at the foundation bed is specified by:

$$G_S(D_e) = 1 + \frac{\sum H_i - D_e}{\sum H_i}(G_S - 1) = G_S - \frac{D_e}{\sum H_i}(G_S - 1). \tag{2.3}$$

Substituting Eqn. (2.2) into Eqn. (2.3) and defining the SSI-factor β in RLSC as the ratio of the amplification G_F at the input motion to the amplification G_S at the ground surface yields

$$\beta = \frac{G_F}{G_S} = \frac{K_{hb}\{1 - (1 - 1/G_S)D_e/\Sigma H\} + K_{he}}{K_{hb} + K_{he}}, \tag{2.4}$$

where D_e is the embedded depth and ΣH is the thickness of the surface stratum. Because the amplification G_S is a function of period T, the calculated SSI-factor β is also a function of period T. The design acceleration response spectrum $S_{as}(T)$ with a damping factor of 5% includes a rotational component and is given by

$$S_{as}(T) = \beta \times Gs \times S_{a0}(T), \tag{2.5}$$

where T is the period of a building in seconds, and $S_{a0}(T)$ is the acceleration response spectrum of the ground motion at the outcropped engineering bedrock.

3. PROPOSED METHOD OF SSI-FACTOR

3.1. Characteristics of SSI-factor in RLSC

To investigate the characteristics of the SSI-factor β in RLSC, we conducted AX-FEM analysis using a two-layer model, as shown in Figure 5. The surface stratum is a uniform medium (soil type is clay) whose shear wave velocity V_s is 200 m/s, and V_s of the engineering bedrock is 400 m/s. The foundation plan is a 30 m wide by 30 m deep square, and the embedding depth is 10 m. The SSI-factor β in RLSC and U_F/U_S in the AX-FEM analysis are compared in Figure 5. The initial predominant period of this model is 0.4 s (= $4H/Vs = 4\times20/200$ s), and first and second predominant periods in the safety limit state in RLSC are evaluated to be 0.62 s and 0.21 s, respectively.

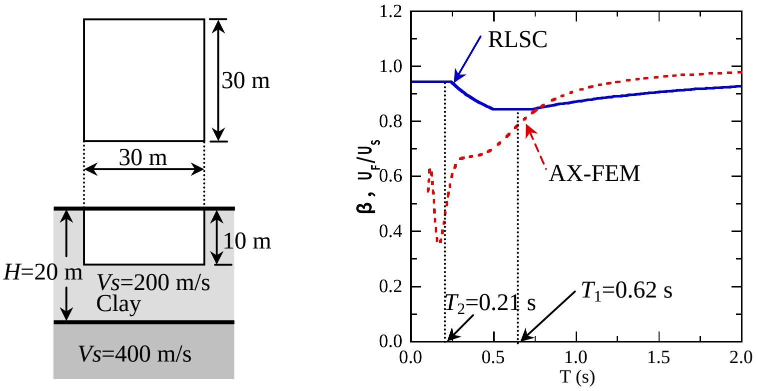


Figure 5 Characteristics of SSI-Factor in RLSC

From Fig. 5, the SSI-factor β in RLSC has the following characteristics: (1) The SSI-factor β shows the minimum value near the first predominant period T_1; (2) U_F/U_S in the AX-FEM analysis shows the minimum value near the second predominant period T_2; (3) The input loss effect in AX-FEM is large at the second predominant period T_2 rather than first predominant period T_1; and (4) RLSC cannot evaluate the input loss effect near the second predominant period T_2. Therefore, from these observations, it can be said that the reduction effect of input loss in RLSC is conservative, particularly in a short period range less than the first predominant period of the surface stratum, and the agreement between RLSC and AX-FEM in the short period range is not good.

3.2. Proposed Method

To overcome issues due to points (1) to (3) mentioned above, we propose new formulas for calculating the SSI-factor β. The following assumptions are used: (i) the amplification G_B at the engineering bedrock is evaluated from Eqn. (3.1) in the first and second modes; (ii) the amplification G_{S1} for the first mode at the ground surface is evaluated from Eqn. (3.2), and G_{S2} for the second mode is evaluated from Eqn. (3.3); and (iii) the distribution shape of amplification is made to correspond to the mode shape calculated based on eigen-value analysis, as shown in Figure 6. Thus

$$G_B = \frac{1.57h}{1.57h+\alpha}, \tag{3.1}$$

$$G_{S1} = \frac{1}{1.57h+\alpha}, \tag{3.2}$$

$$G_{S2} = \frac{1}{4.71h+\alpha}, \tag{3.3}$$

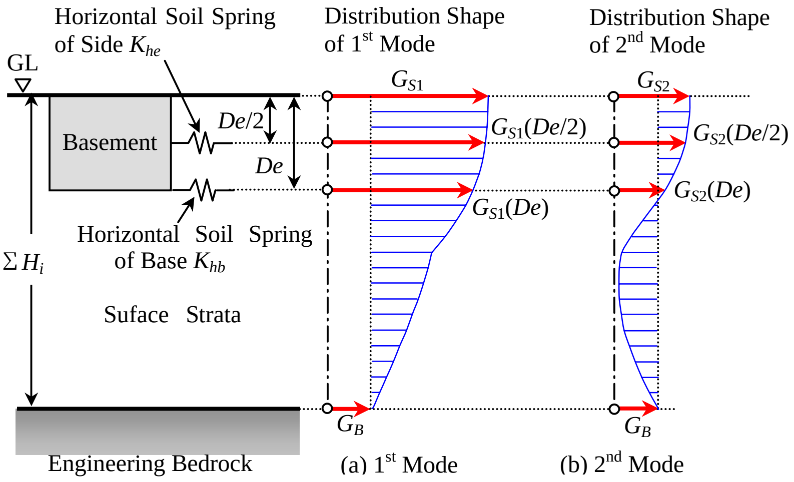


Figure 6 Outline of proposed method

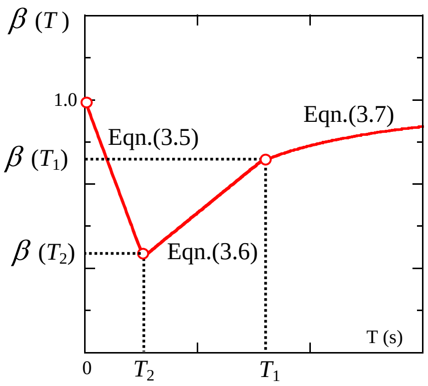


Figure 7 SSI-factor β in the entire period range

where α is the impedance ratio and h is the equivalent damping factor. The SSI-factors β of the first and second modes are given by

$$\beta(T_i) = \frac{K_{hb} \cdot G_{S\,i}(De) + K_{he} \cdot G_{S\,i}(De/2)}{K_{hb} + K_{he}} \cdot \frac{1}{G_{S\,i}}\ , \tag{3.4}$$

where $i = 1$ is the first mode and $i = 2$ is the second mode.

The proposed formulas in the entire period range are presented in Eqn. (3.5) to (3.7), and a graphical illustration of the formulas is shown in Figure 7:

$$\beta(T) = \begin{cases} \dfrac{\beta(T_2) - 1}{T_2} \cdot T + 1 & ;\ T \le T_2 \quad (3.5) \\[2ex] \dfrac{\beta(T_1) - \beta(T_2)}{T_1 - T_2} \cdot T + \dfrac{\beta(T_2) \cdot T_1 - \beta(T_1) \cdot T_2}{T_1 - T_2} & ;\ T_2 < T \le T_1 \quad (3.6) \\[2ex] \dfrac{\beta(T_1) - 1}{1/T_1 - 0.1} \cdot \left(\dfrac{1}{T} - \dfrac{1}{T_1} \right) + \beta(T_1) & ;\ T_1 < T \quad (3.7) \end{cases}$$

where T_1 and T_2 are the first and second natural periods of the subsoil layer, respectively. In RLSC, the horizontal soil spring of the pile-foundation is set to the same value as that of the raft-foundation; therefore, the SSI-factor β is the same for both foundation types.

4. ANALYTICAL RESULTS AND DISCUSSION

To verify the accuracy of the foundation input motion in our proposed method, we carried out an axisymmetric finite element method (AX-FEM) analysis.

A comparison of the SSI-factors β between RLSC and the proposed method is shown in Figure 8. The spectral ratio in Figure 8 is defined as the ratio of the acceleration response spectrum at the foundation bed by AX-FEM to that at the ground surface by SHAKE. Each acceleration response spectrum is the average of ten simulated motions. The pile-foundation shows a large spectral ratio in the short period range, because earthquake motion propagates directly and the pile stiffness becomes relatively high in comparison with the subsoil, whose stiffness degrades due to nonlinearity. The SSI-factor β calculated by the proposed method is similar to that of the AX-FEM result, indicating that the evaluation of the embedding effect in RLSC is conservative.

Next, a comparison of the acceleration response spectra is shown in Figure 9. Acceleration response spectra with a damping factor of 5% were computed for the foundation bed in RLSC, the proposed method, and AX-FEM. The acceleration response spectrum obtained by RLSC almost envelops those obtained by AX-FEM in the entire range of periods, but the response acceleration spectra obtained by the proposed method are in good agreement with those obtained by AX-FEM. We previously confirmed that the embedding effect cannot be expected for the case of foundation embedding depth 2.0 m (Izumi and Miura, 2007). When the subsoil layer thickness is small and the embedding depth of the foundation is large such as Site-4, the SSI-factor β (T_2) for the 2nd mode, will have a tendency to be overestimated, but if a lower limit value is set, this method can be applied to seismic design practice.

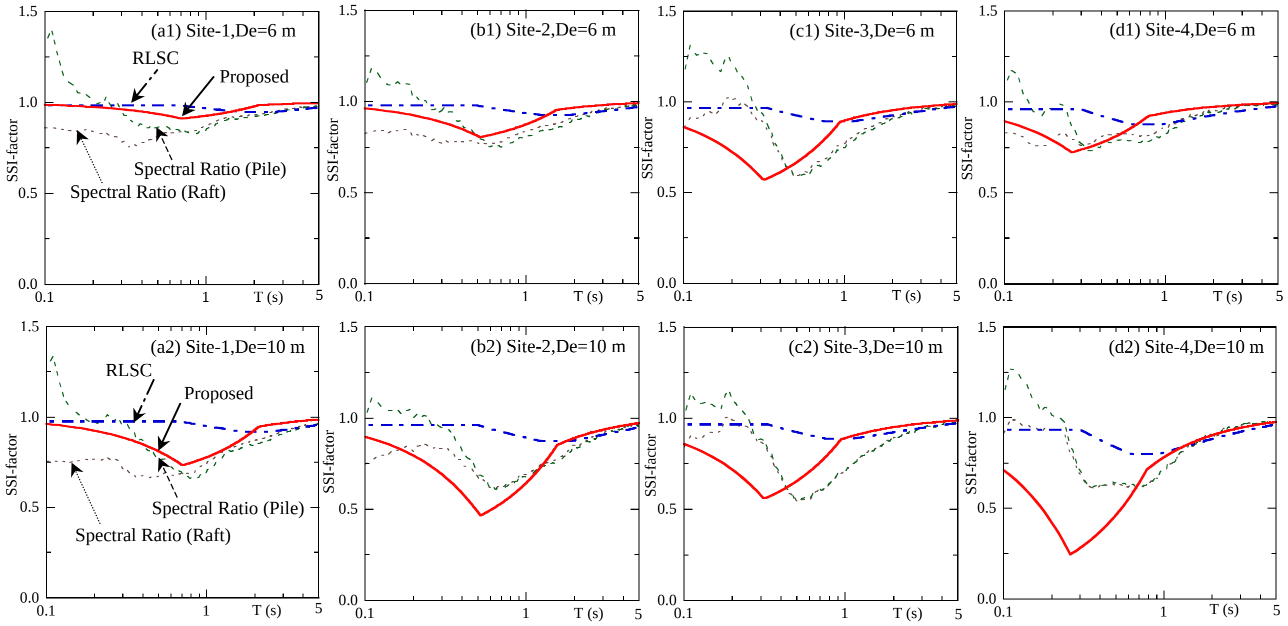


Figure 8 Comparison of SSI-factor β

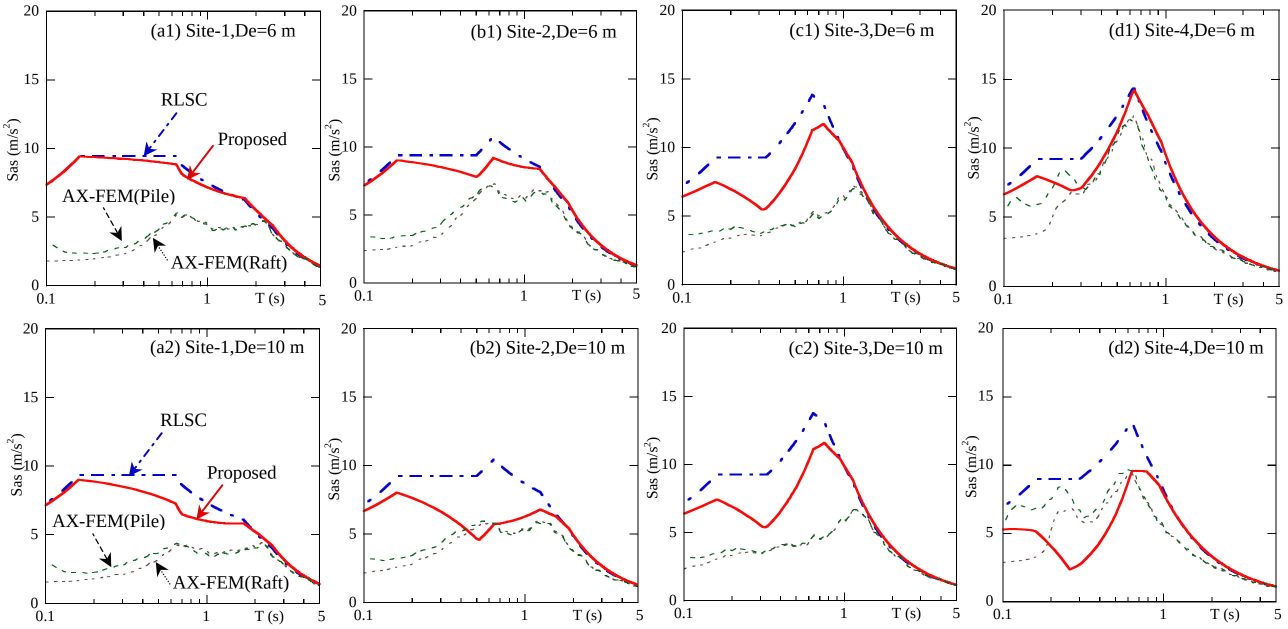


Figure 9 Comparison of response acceleration spectrum

5. CONCLUSIONS

In this paper, we describe a rational evaluation of the foundation input motion in RLSC, and we propose new formulas for the SSI-factor β. We conclude the following:

1. The input loss effect based on RLSC is conservative in the short period range, because of simple assumptions in the formulation of the SSI-factor β.
2. The proposed method incorporates the following assumptions: (1) the amplification G_B on the engineering bedrock is not unity, (2) the first and second vibration modes of the surface strata are considered, and (3) the distribution shape of amplification between the ground surface and the engineering bedrock is based on results of an eigen-value analysis.
3. The SSI-factor β and the foundation input motion obtained by the proposed method are in good agreement with those of an axisymmetric finite element method analysis, and it is thus possible to evaluate the input-loss phenomenon in soil–structure interaction problems.
4. The proposed method is based on the present RLSC framework; therefore, the computation is simple and additional computations are not necessary.
5. When the subsoil layer thickness is small and the embedding depth of the foundation is large, the SSI-factor for the 2nd mode, $\beta(T_2)$, will have a tendency to be overestimated, but if a lower limit value is set, this method can be applied to seismic design practice.

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APPENDIX

Amplification of the ground surface, G_s, is specified as Eqn. (A.1) in an Official Notice from Japan's Ministry of Land, Infrastructure and Transport. The lower limit of G_s is set to 1.23 in the entire period range.

$$G_S = \begin{cases} G_{S2} \cdot \dfrac{T}{0.8T_2} & ;\ T \le 0.8T_2 \\ G_{S2} + \dfrac{G_{S1} - G_{S2}}{0.8(T_1 - T_2)} \cdot (T - 0.8T_2) & ;\ 0.8T_2 < T \le 0.8T_1 \\ G_{S1} & ;\ 0.8T_1 < T \le 1.2T_1 \\ G_{S1} - \dfrac{G_{S1} - 1}{1/(1.2T_1) - 0.1} \cdot \left(\dfrac{1}{1.2T_1} - \dfrac{1}{T} \right) & ;\ 1.2T_1 < T \end{cases} \qquad \text{(A.1)}$$

where T_1 and T_2 are the first and second natural periods of the surface strata, respectively.