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THE DESIGN SEISMIC COEFFICIENT OF THE EMBEDDING FOUNDATION OF BUILDING STRUCTURES

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SUMMARY

This paper describes the design seismic coefficient (DSC) of the embedding foundation of building structures, which is required for the design of foundations such as basements and pile foundations. In the current Building Standard Law (BSL) of Japan, DSC is empirically specified as one-half of the base shear coefficient of a superstructure. However, the seismic design requirements in the BSL were revised in June 2000 to a performance-based design framework. A new seismic design method called the "response and limit strength calculation" (RLSC), which incorporates the effect of the soil-structure interaction, was developed. In the BSL revision, however, DSC is not referred to and must be evaluated by the conventional method mentioned above. Applying the numerical procedures employed in the development of RLSC, a practical evaluation method of DSC is investigated. A regressive formula is derived from the DSC and the ratio of the embedded depth to the foundation width.

INTRODUCTION

As shown in Fig. 1, the design seismic coefficient (DSC) k of the buried part of building structures in Japan's current Building Standard Law (BSL) is specified as

$$k = \begin{cases} 0.1Z(1 - D/40) & D \le 20\,\mathrm{m} \\ 0.05Z & D > 20\,\mathrm{m} \end{cases} \qquad (1)$$

where Z is the seismic zone factor ranging from 0.7 to 1.0, and D is the depth from the ground surface (unit: meter). This DSC is empirically specified and its theoretical basis is not shown. Furthermore, a design seismic load for piles Q_F [1] is recommended

$$Q_F = (Q_B + \Sigma k \cdot W_F) \times (1 - 0.2\sqrt{H} / \sqrt[4]{D_f}) \qquad (2)$$

where Q_B is the base shear force of a superstructure, W_F is the weight of the foundation and H is the total

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height of a superstructure. At the present time, a second design of a foundation such as a basement and pile has not been specified for a large earthquake.
On the other hand, the seismic design requirements in BSL were revised in June 2000 to a performance-based design framework. A new seismic design method called the "response and limit strength calculation" (RLSC) was developed. The following summarize the features of RLSC: (1) the guideline of the design earthquake motion as an acceleration response spectrum at the outcropped engineering bedrock (EBR), (2) incorporation of the nonlinear amplification effect of surface strata, (3) incorporation of the effects of the soil-structure interaction (SSI), and (4) modeling of a multi-story building into an equivalent single-degree-of-freedom (ESDOF) system. In this revision, however, DSC is not referred to and must be evaluated by the conventional method. It can be said that a consistent design from superstructure to foundation has not been attained.

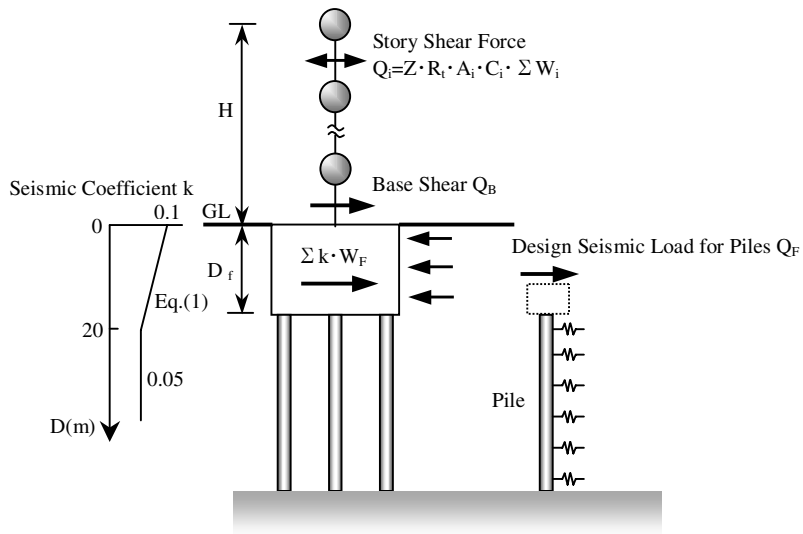

Fig. 1 Current design seismic load in Japan

This paper describes the design seismic coefficient of the embedding foundation, which is required for the design of foundations such as basements and pile foundations.

ANALYSIS METHOD

There are two approaches for the analysis of the dynamic SSI problem: the direct method and the substructure method. This study adopted the substructure method. Soil springs and foundation input motion are fundamental physical properties in SSI. These physical properties are obtained from numerical procedures employed in the development of RLSC. Numerical analyses are performed to set the analytical parameters for (1) soil conditions, (2) number of stories, (3) foundation types and (4) embedding depths of a foundation.

Analytical Model

A superstructure is modeled as reinforced concrete structures that are 5, 10, 15 and 20 stories. The height of each story is 3 m and the mass of each story is 980 ton. The horizontal stiffness of each story is determined such that the horizontal stiffness distribution along the height varies from 1.0 (first story) to 0.5 (top story), and the first natural period of the structure under a fixed base condition is T=0.02H (H is the total height of the structure). As shown in Fig. 2, the multi-degrees-of-freedom system is reduced to an ESDOF system, and the foundation mass, sway spring and rocking spring are added in this system.
The embedding foundation is assumed to be rigid. The embedding depths De are selected as 2, 6, 10 m. Two foundation types are selected: the spread foundation and the pile foundation (hereafter called the R-foundation and P-foundation, respectively). The foundation shape is set as a 30 m wide (2B) by 30 m

depth (2D) square shape, and the weight is assumed to be 1960 ton for De=2 m, 3920 ton for De=6 m and 5880 ton for De=10 m. This shape replaces an equivalent circular shape having the same area. In the P-foundation, a 6×6 square pile group is assumed and each pile diameter is 1 m. The damping factor of the superstructure is assumed to be 3%.

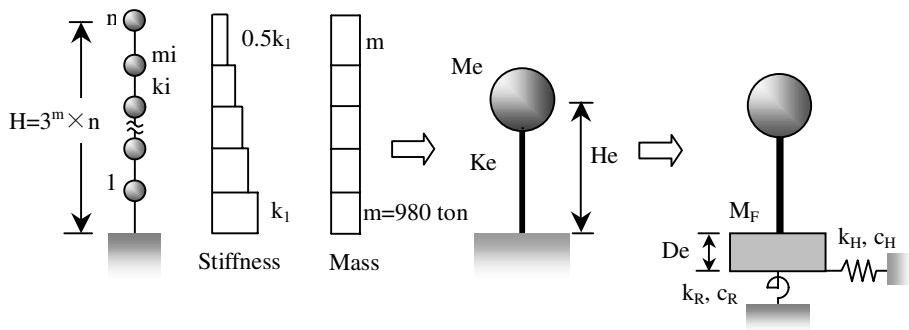

Fig. 2 Analytical model

Soil Model

The initial shear wave velocities of four different kinds of subsoil are shown in Fig. 3. "C" and "S" in Fig. 3 denote "clay" and "sand," respectively. In the Notification of Ministry of Construction, EBR is defined as a layer of bedrock having a shear wave velocity of about 400 m/sec or higher. The depths of 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, GL-20.0 m for Site-4. EBR supports the pile bottom.

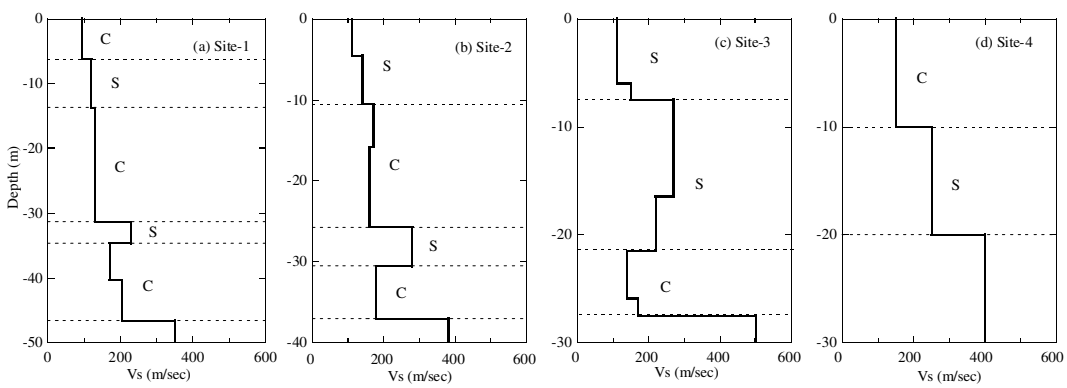

Fig. 3 Initial shear velocities of the soil models

Nonlinear Amplification of the Surface Strata

Nonlinear amplification Gs of the surface strata is computed by the response spectrum method (RSM) proposed by Miura et al [2]. In RLSC, a design acceleration response spectrum Sas(T) with a damping factor of 5% is specified as

$$Sas(T) = Gs \times Sao(T) \qquad (3)$$

where T is the period of a building in sec, Sao(T) is the acceleration response spectrum of ground motion at cotcropped engineering bedrock. In the damage-limit state, the first natural period Tg of the four sites is 1.603 sec for Site-1, 1.117 sec for Site-2, 0.714 sec for Site-3 and 0.519 sec for Site-4.

Input Acceleration on EBR

The design earthquake motion is specified as an acceleration response spectrum Sao at the outcropped EBR is shown in Fig. 4. The Sao 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 Sao for varying phase angles and used for the one dimensional equivalent linear analysis "SHAKE". The input motion is set up as an outcrop motion (2Eo) on EBR. The nonlinear characteristics between the shear modulus ratio G/Go, damping factor h and shear strain are used by the Notification of Ministry of Construction. The acceleration response spectrum with a damping factor of 5% is shown in Fig. 4.

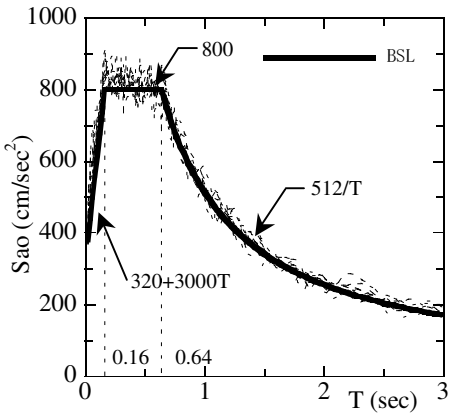

Fig.4 Acceleration response spectrum on the outcropped EBR (safety-limit state)

Axisymmetric Finite Element Method Analysis

We carried out an axisymmetric finite element method (AX-FEM) analysis to verify the soil springs and damping factor and to estimate the foundation input motion. As shown in Fig. 5, 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 pile is assumed to be elastic. In the AX-FEM analysis, the equivalent shear modulus Gei and equivalent viscous damping factor hei in the i-th layer were obtained by RSM. In the P-foundation, the foundation bed does not contact the ground surface. The vertical incident S-wave is applied at the EBR of each soil model. Furthermore, the transfer functions U_F/U_S and $U_F/2E_o$, 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 for the ESDOF sway-rocking (SR) system shown in Fig. 2,

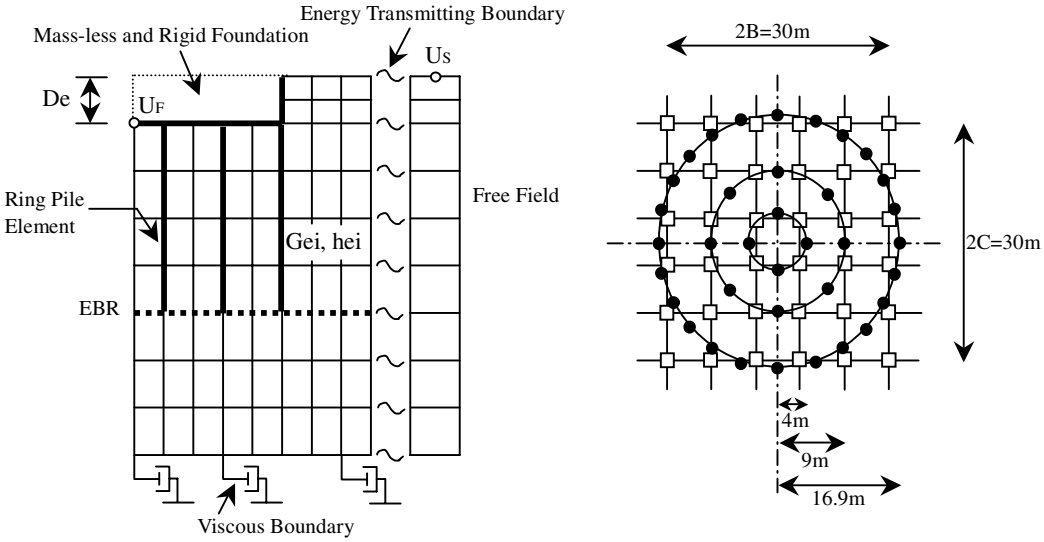

Fig. 5 AX-FEM model and ring-pile arrangement

SOIL SPRINGS AND EQUIVALENT DAMPING FACTOR

In the practical application of RLSC, soil springs are evaluated as static values, neglecting their frequency dependence. Sway and rocking soil springs at the foundation bed are calculated using a simplified Wolf's cone model [3], and the rocking springs of the pile foundation are calculated using Randolph's formula [6], and the horizontal springs of the embedding lateral side are calculated using the Pais and Kausel formula [7]. Also, the sway spring of the P-foundation is supposed to use that of the R-foundation. The results of RLSC and AX-FEM for the static soil springs are compared in Fig. 6. The horizontal spring of the embedding lateral side is compared with Novak's spring [8]. There is no significant difference in the sway springs between the R-foundation and P-foundation.

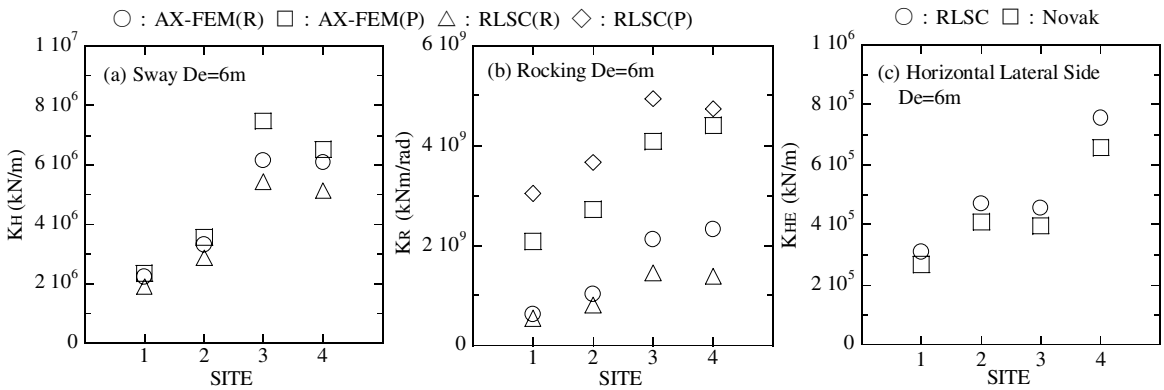

Fig. 6 Comparison of soil springs: De=6 m

On the other hand, the equivalent damping factor is calculated from an imaginary part of the impedance which is considered frequency-dependent. In RLSC, the rocking equivalent damping factor for R-foundation is evaluated as 0.75 times the sway equivalent damping factor, and the rocking equivalent damping factor for the P-foundation is evaluated as two-thirds of that of the rocking equivalent damping factor for the R-foundation. The results of AX-FEM and RLSC for the equivalent damping factor are compared in Fig. 7. From these results, it can be said that proposed procedure in RLSC is appropriate.

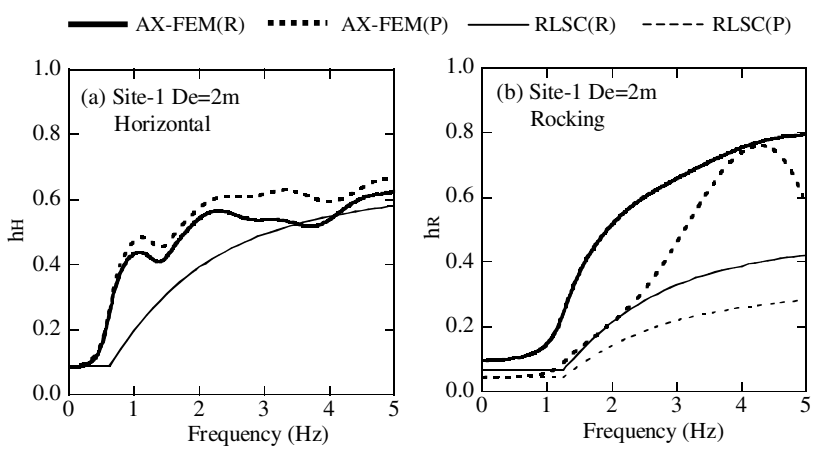

Fig. 7 Comparison of equivalent damping factor: Site-1, De=2 m

FOUNDATION INPUT MOTION

The horizontal component of the foundation input motion (FIM) time history is given by the inverse Fourier transform in Eq. (4).

$$u_F(t) = (1/2\pi)\int_{-\infty}^{\infty}\{U_F(f)/U_S(f)\}\cdot U_S(f)\,e^{i\omega t}\,d\omega \qquad (4)$$

where ω is the circular frequency ($=2\pi f$). The rotational component of FIM is neglected in this study. On the other hand, the embedding effect of the foundation in RLSC is specified as

$$\beta' = \frac{K_H\{1-(1-1/Gs)De/\Sigma H\}+K_{HE}}{K_H+K_{HE}} \qquad (5)$$

$$Sas(T) = \beta'\cdot Gs\cdot Sao(T) \qquad (6)$$

where De is the embedded depth, ΣH is the thickness of the surface stratum, Gs is the amplification factor of the ground surface, and K_H and K_{HE} are the soil springs of the foundation bed and lateral side, respectively. The design acceleration response spectrum obtained by Eq.(6) includes a rotational component.

As an example, the transfer function of Site-2 is shown in Figs. 8 and 9. From this result, increasing the embedded depth decreases the response amplitude, but the P-foundation shows a large response amplitude in the high-frequency range, because earthquake motion propagates directly and the pile stiffness becomes relatively high comparison with the subsoil, whose stiffness degrades due to nonlinearity.

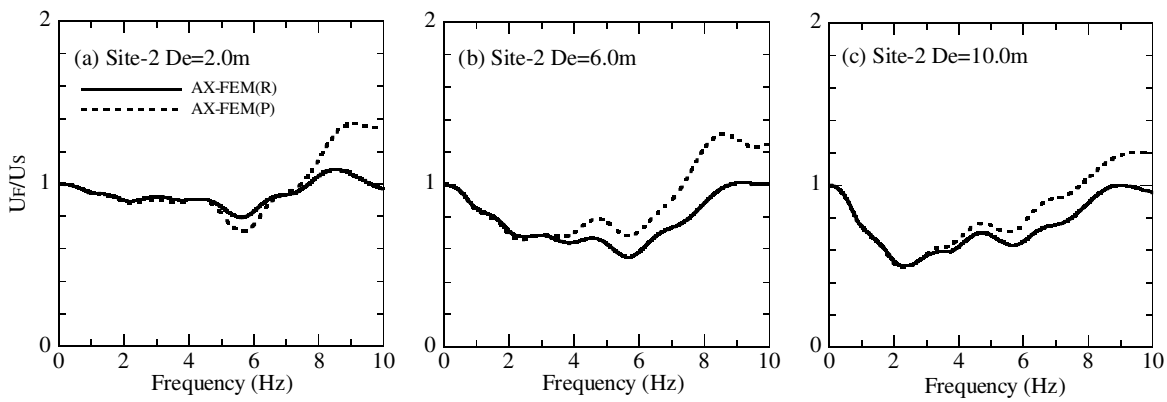

Fig. 8 Transfer function UF/US: Site-2

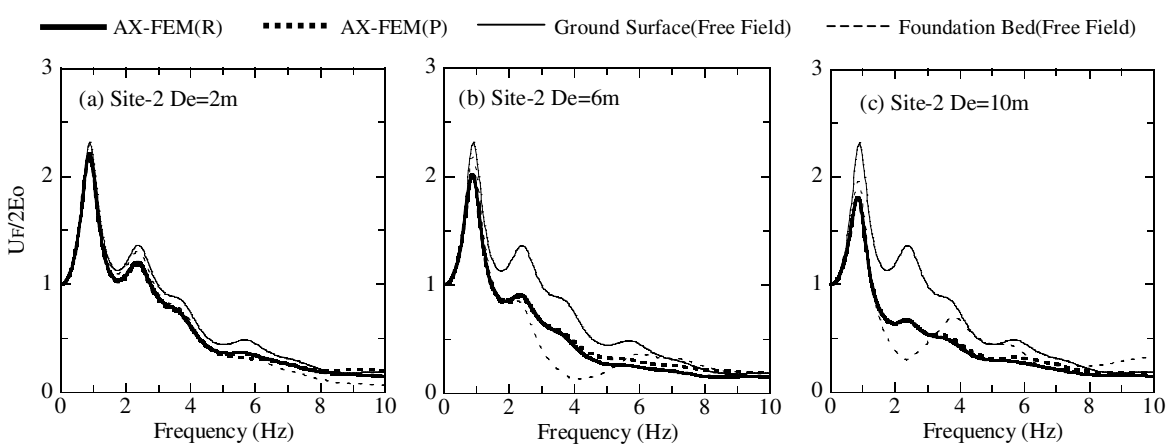

Fig. 9 Transfer function UF/2Eo: Site-2

Acceleration response spectra with a damping factor of 5% were computed for four different procedures: AX-FEM, the ground surface of SHAKE, the foundation bed of SHAKE, and RLSC, as shown in Fig. 10. Each acceleration response spectrum is the mean of ten simulated motions. The embedding effect cannot

be expected for 2 m. It is observed that the spectrum at the foundation bed of the free field computed by SHAKE is similar to FIM, but the former response is underestimated in specific period ranges. The acceleration response spectrum obtained by RLSC almost envelops those obtained by AX-FIM and SHAKE in the range of the whole periods. Therefore, it can be said that the evaluation of the embedding effect in RLSC is conservative.

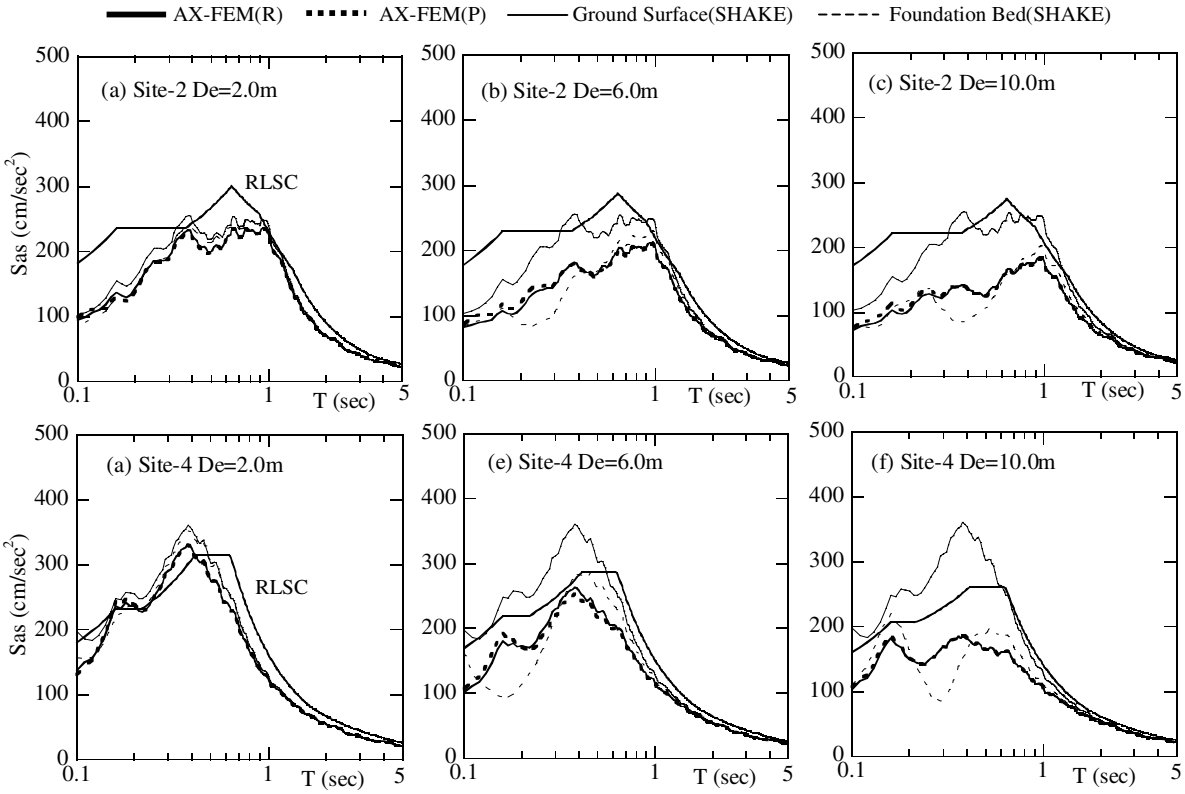

Fig. 10 Comparison of acceleration response spectra of input motion (h=0.05): Site2 and Site-4

ANALYTICAL RESULTS AND DISCUSSION

Dynamic elastic response analyses are carried out on ESDOF sway-rocking models using an excitation FIM. From the eigenvalue analysis, the natural period of coupled system Te and the ratio of Te to To under the fixed base condition in the case of De=10 m are shown in Fig. 11. It is observed that Te is longer so that the soil is soft, and Te is shorter in the pile foundation under the same soil condition.

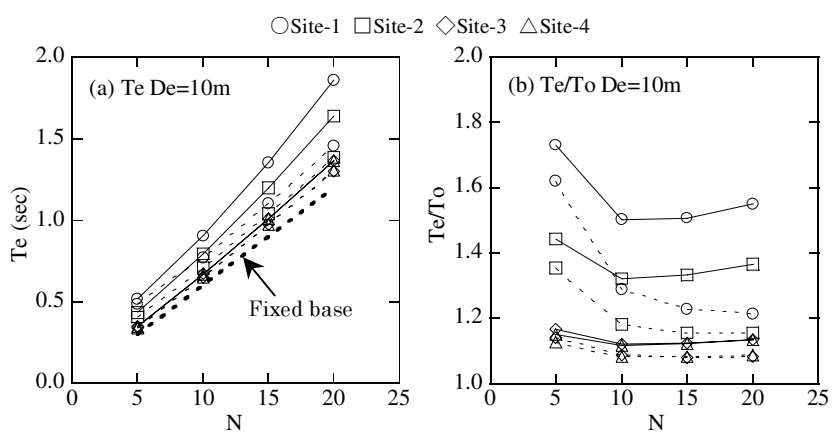

Fig. 11 Natural period of coupled system: De=10 m

DSC is calculated by the difference of the base shear force $Q_B(t)$ and sway spring shear force $Q_S(t)$ on the time history divided by the foundation weight in Eq. (7).

$$k = \frac{Q_B(t) - Q_S(t)}{W_F} \qquad (7)$$

Analytical results are arranged as the mean value for ten waveforms. Figure 12 shows the DSC distributions for each embedding depth. The mean values of DSC are 0.123 for De=2 m, 0.097 for De=6 m and 0.086 for De=10 m. Increasing the embedded depth causes a decreasing DSC and the distribution of DSC toward the depth is almost uniform regardless of soil conditions and the number of stories. Also, it is observed that there is no significant difference in DSC between the R-foundation and P-foundation. Therefore, DSC can be formulated using the embedding depth as a parameter.

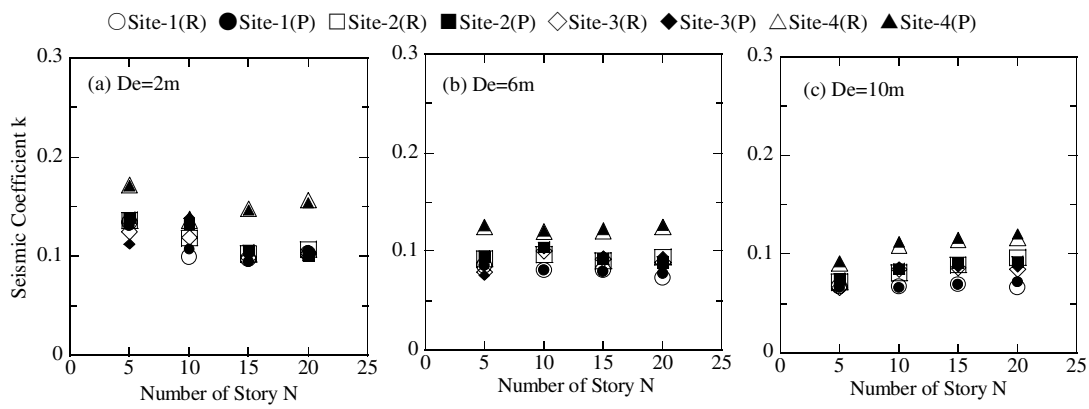

Fig. 12 DSC distributions

Figure 13 shows the relationship of DSC versus the embedding ratio that defines the ratio of the embedding depth De to the foundation width 2B. We propose a regressive formula, Eq.(8), derived from DSC and the embedding ratio by the least squares method.

$$k = -0.140(D_e / 2B) + 0.130 \qquad (8)$$

This formula is a simple expression and useful for the seismic design of a building foundation.

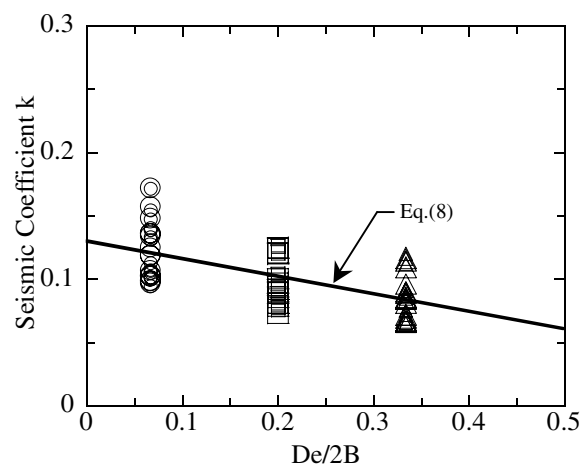

Fig. 13 Relationship of DSC versus the embedding ratio

CONCLUSIONS

This paper describes the design seismic coefficient of the embedding foundation, which is required for the design of a foundation such as a basement and pile foundation. The concluding remarks of this paper are as follows.

1. The practical evaluation procedures of static soil springs and equivalent damping factors in RLSC are appropriate in comparison with rigorous analysis.
2. Design input earthquake motions for the SR model can be approximated as response acceleration waveforms at the foundation bed of a free field, but this waveform can be underestimated in specific period ranges. The evaluation of the embedding effect in RLSC is conservative, particularly in a short period range.
3. Increasing the embedded depth decreases the DSC. The distribution of DSC toward the depth is almost uniform regardless of the soil conditions, number of stories and foundation types.
4. A regressive formula is derived from DSC and the ratio of embedded depth to foundation width. This formula is a simple expression and useful for the practical seismic design of a building foundation.

In this paper, the intensity of input excitations is that of the damage-limit state, not the safety-limit state. Further research is needed.

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