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SOIL-STRUCTURE INTERACTION AND ITS IMPLICATION FOR SEISMIC DESIGN OF STRUCTURES

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SUMMARY

This paper presents a modified response spectrum method using the response spectra of the motions of rigid and massless embedded foundation (the result of kinematic interaction) for the seismic design of structures with huge foundations, such as suspension bridges and nuclear containments. The design procedure developed in this paper takes into consideration not only the effect of soil flexibility but also the effect of spatial variability of free-field ground motions. An illustrative pilot application example may aid in understanding the procedure, and also the soil structure interaction effect on the design requirements.

INTRODUCTION

Over the years, the conventional assumption of the rigidly founded structures has gradually been abandoned while the flexibility of soil supporting the structures has usually been taken into consideration in the seismic design procedure. However, in addition to the soil flexibility, it has been recognized from the linear soil structure interaction studies, that the spatial variability of ground motion over distances comparable to the scale of foundations is an additional important factor in determining the input of seismic motions to the foundations. This mechanism is known as a kinematic interaction named by the researchers of MIT (Ref.1) or represented by a effective seismic input motion (Refs.2,3).

This paper presents a seismic design procedure for the structures with embedded foundations that can take into account not only the effect of soil flexibility but also the effect of the spatial variability of ground motions in the framework of the conventional seismic design method using the response spectrum.

METHOD

Interpretation of Soil-Structure Interaction Soil-structure interaction generally may be defined as the difference of motion {UB} at any point on the soil-structure interface (point B) from that {UA} which would occur at this point in the free-field if the structure were not present (point A) as shown in Fig.1. It is now useful to consider the soil-structure interaction by separating the inertial effect from it. To do this, consider the motion {UC} at point C on the soil-structure interface where the structure's mass [m] is ignored but its stiffness [KF] is included. Even in this massless structure, there is soil-structure interaction because the motion at point C differs, in general, from the motion at point A in the free-field. However, in the case of massless structures the soil-structure interaction does not include the inertial effect on it. This interaction is called kinematic interaction (Ref.1), and the resulting motion of massless structure is termed as effective seismic input motion (Refs.2,3).

Denoting the motion due to inertial effect (inertial interaction) by {UD}, then, the motion {UB} due to total soil-structure interaction is expressed as

$$\{UB\} = \{UC\} + \{UD\} \tag{1}$$

Introducing the impedance [K], which is defined as the dynamic soil reaction against unit structural displacement at structure-soil interface, the equation of motion of the structure can be written in frequency ω domain such that

$$\underbrace{-\omega^2[m]\{UB\}}_{\text{Inertial Force}} + \underbrace{[KF]\{UD\}}_{\text{Structural Reaction}} + \underbrace{[K]\{UD\}}_{\text{Soil Reaction}} = 0 \tag{2}$$

Substituting Eq.1 into Eq.2 yields

$$[-\omega^2[m] + [KF + K]]\{UD\} = \omega^2[m]\{UC\} \tag{3}$$

If the kinematic interaction is negligible, the effective input motion {UC} can be replaced by the motion {UA} in the free-field following its definition. Equation 3 then is reduced to the equation of motion which is usually used in the seismic response analysis of structures using the free-field ground motion {UA} and can be expressed as

$$[-\omega^2[m] + [KF + K]]\{UD\} = \omega^2[m]\{UA\} \tag{4}$$

In general, the relative importance of inertial versus kinematic interaction effects on structural responses depends on the structural and soil properties as well as the frequency characteristics of earthquake ground motions. As shown schematically in Fig.2, inertial interaction may predominate for above-ground structures supported by surface or shallow foundations, while the kinematic interaction may be relatively more significant for under-ground structures such as buried pipelines and tunnels. For the structures with deeply embedded huge foundations, the inertial interaction as well as the kinematic interaction may be important.

In the conventional seismic design methods, the two extreme cases have been taken into consideration by the well known response spectrum method for the above-ground structures, and the response-displacement method for the under-ground structures. However, for the intermediate structures, where the inertial effect as well as the kinematic effect predominates, the conventional design methods have to be improved, at least, from a soil-structure interaction point of view. The main problem at hand is to develop a design method based on Eq.3 instead of Eq.4.

<u>Modified Response Spectrum Method</u> The above interpretation on soil-structure interaction makes it possible to develop a modified response spectrum method on the basis of Eq.3, because the essential difference between Eqs.3 and 4 is

the input motion to the structures-the effective seismic input motion {UC} in Eq.3, while the free-field motion {UA} in Eq.4. It should be noted here, in developing a modified response spectrum method, that the impedance [K] has to be reduced to a frequency independent stiffness and damping coefficient by an appropriate approximation because the response spectrum method is based on the classical modal analysis.

As shown schematically in Fig.3, in a modified response spectrum method, the response spectrum of the effective seismic input motion {UC} can be expressed by multiplying the response spectrum of the free-field ground motion {UA} by a conversion factor; for the horizontal and rocking components of the effective input motions (motions of massless-rigid foundation), for example,

$$SA(T,h)=CH.SA0(T,h), \quad SR(T,h)=CR.SA0(T,h) \tag{5}$$

where SA(T,h) and SR(T,h) are the horizontal and rocking components of the response spectra for the effective input motions, and SA0(T,h)is the horizontal component of the response spectrum of the free-field motion at any point. T and h are the natural period and damping ratio of one-degree-of-freedom system, respectively. If CH=1 and CR=0 in Eq.5, the response spectra of the effective seismic input motions coincide with that of the free-field ground motion which is usually used in the conventional seismic design method based on Eq.4.

NUMERICAL EXAMPLE

The seismic responses of the two soil-caisson (cylindrical rigid foundation) models with different embedments in each model as shown in Table 1 and Fig.4 are examined. In this numerical example, a finite element method has been successively utilized to evaluate the effective seismic input motions defined as the seismic responses of massless foundation, while the approximations for the impedances have been adopted to evaluate the mode shape, the natural period, and damping ratio of the caisson foundations (Refs.4,5)

Figure 5 shows the response spectra (horizontal and rotational compoments) of 5 % damping ratio for the effective seismic input motion (ESM) at foundation base in the shallowest embedment (case 1) in each caisson model. This figure also shows the response spectra of the free-field ground surface motion. It is interesting to observe from Fig.5 that the response spectrum of the effective seismic input motion for A caisson foundation is larger than that of the free-field ground surface motion in the period of 0.1-1.0 sec, while for P caisson foundation it is smaller than the response spectrum of free-field ground surface motion. In general, the response spectra of the effective seismic input motions take smaller values than those of the free-field ground surface motion. However, there are exceptions as shown in the A caisson foundation (Refs.4,5).

Figure 6 shows the conversion factors CHE and CRE for various embedment depths which can be defined as follows:

$$SA(T,h)=CHE.SAcase1(T,h), \quad SR(T,h)=CRE.SRcase1(T,h) \tag{6}$$

where, SAcase1(T,h), SRcase1(T,h), (CH.SA0(T,h) and CR.SA0(T,h)) are the response spectra of the effective input motions in the shallowest case 1 in each caisson foundation model. Although the rotational conversion factor CRE in P caisson model increases as the depth of the embedment increases, the other embedment conversion factors decreases. Moreover, it is confirmed later as shown in Table 2 that the effect of rotational component on the responses is negligible in the shallow foundations as used in this example.

Table 2 indicates the final results: the maximum seismic response accelerations of the two caisson foundations at their mass center which are calculated by the response spectrum method. This table indicates the shallowest and deepest cases in each caisson model for three different seismic input motions: the response spectrum of free-field ground surface motion (F.F.(1) in Table 2); the response spectrum of horizontal component of effective seismic input motion (E.S.M.(2)); and the response spectra of horizontal and rotational components of effective seismic input motion (E.S.M.(H+R)(3)). In the calculation of responses, modification of response spectra with respect to the damping ratio h is expressed by the equation (Ref.4),

$$SAO(T,h) = [1.5/(40h + 1) + 0.5\ ]\ SAO(T,0.05) \tag{7}$$

The superposition of the modes (1st and 2nd in this example), and the horizontal and rotational components of effective seismic input motions have been based on the rule of square-root-of-sum-of-squares (SRSS) of maximum values in each component. It can be observed from Table 2 that the use of the effective seismic input motions (consideration of kinematic interaction) predicts the larger responses than those calculated by the free-field ground surface motion in the A caisson foundation, while the responses in the P caisson foundation by the use of the effective seismic input motion are smaller than those by the free-field ground surface motion. It is also observed from Table 2 that the effect of the rotational component of the effective seismic input motions on the maximum response accelerations of foundation may be negligible in the A and P caisson foundations.

RESULTS AND CONCLUSIONS

Based from the above numerical examples and from the additional computations (Ref.4), the following conclusions have been derived:
(1) The modified response spectrum method using the response spectra of the effective seismic ground motions usually gives small values of responses, compared with the conventional response sepectrum method based on the response spectrum of free-field ground motions.
(2) For a special foundations, the conventional response spectrum method, where the effective seismic input motions have not been taken into consideration, does not always predict the conservative responses. Hence, it is recommended for the seismic designs of structures with huge embedded foundations to take into consideration the response spectra of the effective seismic input motions as described in this paper.

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REFERENCES

1. Ad Hoc Group, Analyses for Soil-Structure Interaction Effects for Nuclear Power Plants, ASCE, pp.122-127, (1980)
2. Harada, T., Kubo, K., and Katayama, T., "Dynamic Soil-Structure Interaction Analysis by Continuum Formulation Method," Report of the Institute of Industrial Science, The University of Tokyo, Vol.29,No.5, (1981)
3. Luco, J.E., and Wong, H.L., "Seismic response of Foundations Embedded in a Layered Half-Space," Earthquake Engineering and Structual Dynamics, Vol.15, pp.233-247, (1987)
4. Japan Society of Civil Engineers, Study and Research Report on Earthquake Resistant Design for Honshu-Shikoku Bridge, (1986)
5. Kashima, N., Harada, T., and Isoyama, R., "Response Spectra Including Dynamic Soil-Structure Interaction effects for seismic Design, "Proc. of the 7th Japan Earthquake Engineering Symposium, pp. 1756-1770, (1986)

Fig. 1 Definition of Soil Structure Interaction (Kinematic and Inertial Interaction)

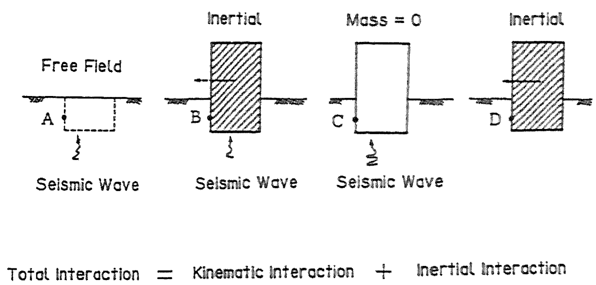


Fig. 2 Implication of Kinematic and Inertial Interaction for Seismic Design Methods

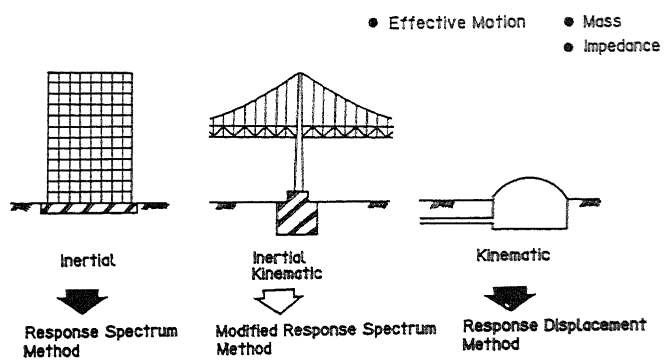
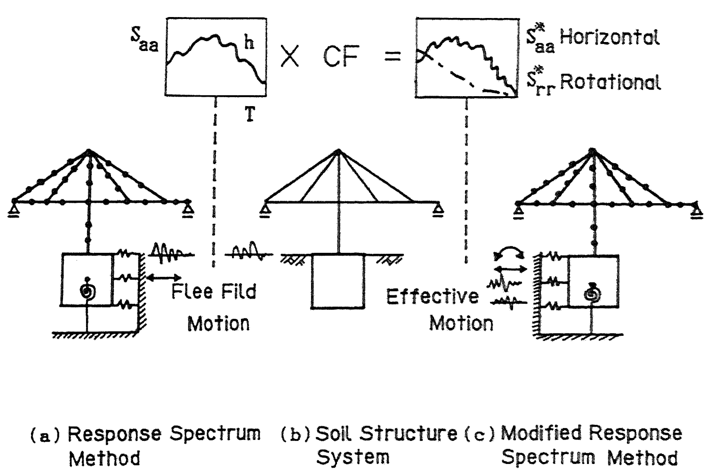
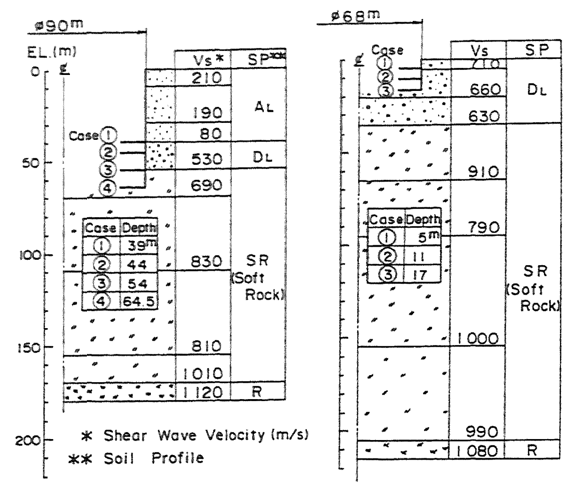


Fig. 3 Schematic Relationship between Response Spectrum Method and Modified Response Spectrum Method





(a) A Caisson (b) P Caisson

Fig.4 Two Soil-Caisson Models

Table 1 Example Caisson Models

Caisson / Case	A ①	A ④	P ①	P ③
Diameter (m)	90		68	
Height (m)	93		70.5	
M*(t·s²/m x10⁵)	1.045		7.566	
J*(t·s² m x10⁷)	14.33		5.32	
Natural ** Period (sec)	0.65	0.40	0.47	0.40
Damping ** Const (%)	27.9	41.1	6.8	14.3

* M : Mass, J : Moment of Inertia of Mass
** Value of 1st Mode

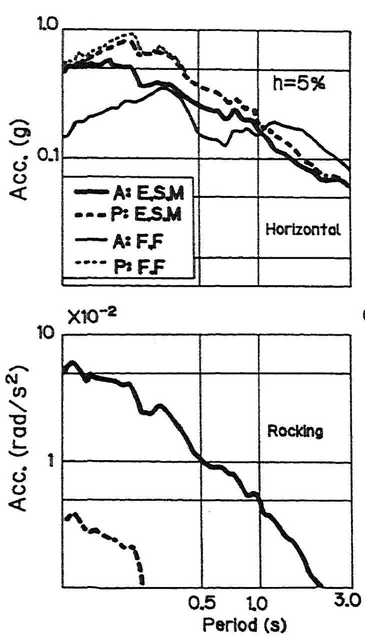


Fig. 5 Response Spectra of Free-Field Motion and Effective Seismic Input Motion for Case 1

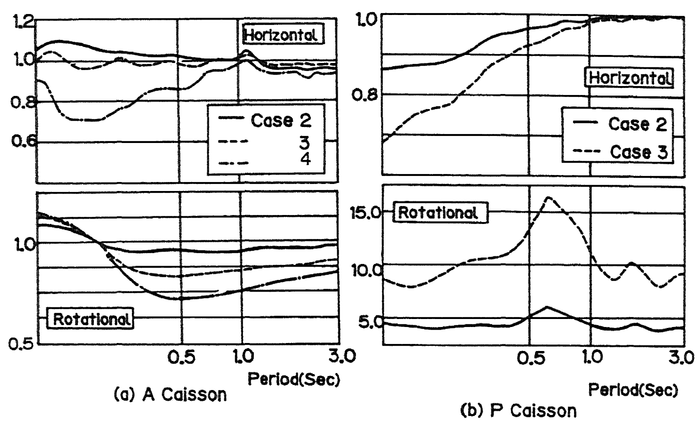


Fig.6 Response Spectrum Ratio when Case 1 = 1.0 (Embedment Conversion Factors)

Table 2 Effect of Effective Seismic Input Motion on Caisson Responses

Caisson	Input	F.F. (1)	E.S.M (H) (2)	E.S.M.(H+R) (3)
A Case①/④	Horizontal Acc. (g)	0.14 / 0.07	0.18 / 0.08	0.19 / 0.08
A Case①/④	Rotation (rad x10⁻⁴)	1.28 / 0.90	1.92 / 0.96	1.98 / 1.03
P Case①/③	Horizontal Acc. (g)	0.30 / 0.33	0.29 / 0.28	0.29 / 0.28
P Case①/③	Rotation (rad x 10⁻⁴)	2.92 / 2.38	2.84 / 2.04	2.84 / 2.04

(1) Free Field Motion at Ground Surface
(2) Effective Seismic Motion - Horizontal Motion Only
(3) Effective Seismic Motion - Horizontal + Rotational Motion