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STUDY ON EFFECTIVE SEISMIC MOTION AND ITS APPLICATION TO SEISMIC DESIGN

M SAITOH[1] And A NISHIMURA[2]

SUMMARY

An effective seismic motion is a rigorous input motion to analyze dynamic behaviors of soil-foundation-structure system. The author has already investigated the behaviors of effective seismic motion through a theoretical approach, in which a theory was derived based on the three-dimensional wave propagation theory [Saitoh and Murono], and also through an analytical approach with the three-dimensional finite element method [Saitoh and Kaneda]. As a result, the effective seismic motion is much affected by the shape of the foundation, and the stiffness and damping ratio of the surface layer. In this paper, the modelling of the effective seismic coefficient, which expresses the characteristics of the effective seismic motion, is performed to apply to seismic design. In addition to the modelling, an application method is developed to rectify the demanded strength spectrum for taking the effects of input loss. The characteristics of the rectification index, which is applied to rectifying the yielding strength of structure, are investigated. It is concluded that the index is much affected by the progression of non-linear response of structure.

INTRODUCTION

A dynamic analysis has mainly been applied to seismic design against considerably strong earthquakes since the 1995 Hyogo-ken Nanbu earthquake. As for the application of the conventional soil-foundation-structure interaction analysis to seismic excitation, one needs to evaluate the motions at the head of the foundation, which is called the effective seismic motion. The effective seismic motion is generally defined as the motions of the massless foundation, and treated as a valid seismic excitation to the inertial systems. The author has already investigated these behaviors through a theoretical approach, in which a theory was derived based on the three-dimensional wave propagation theory [Saitoh and Murono]. This theory assumes that the surface layer is an elastic single-layered stratum resting on the bedrock. However, the actual surface layer is composed of a multi-layered stratum. Therefore, the different analyses applying for the three-dimensional finite element method are performed for estimating the behaviors of effective seismic motion in the condition [Saitoh and Kaneda]. According to these results, an approximate solution is derived from the theoretical solution for the purpose of applying the effective seismic motion easily to the actual seismic design. In addition to that, an effective seismic coefficient, which is an important index to understand the effects of input loss (details in **2. BEHAVIORS OF EFFECTIVE SEISMIC MOTION**), is modeled for the same purpose as the previous one.

[1] *Structure Technological Development Division, Railway Technical Research Institute, Japan Email: saity@rtri.or.jp*
[2] *Structure Technological Development Division, Railway Technical Research Institute, Japan Email: saity@rtri.or.jp*

Table 1: Properties of Models

Properties	Unit	Values
Soil properties		
mass density (ƒ Ï)	t/m^3	1.8
Poisson’s ratio (ƒ Ë)	|	0.49
Standard shear velocity of surface (Vs)	m/s	100.0
Standard shear velocity of bedrock (Vd)	m/s	400.0
Foundation properties		
Young modulus (E)	KN/m^2	2.5×10^7
Thickness of side-wall (t)	m	0.8
Standard diameter (D)	m	6.8
Length of foundation (L)	m	17.0

Table 2: Properties of Layered Surface Ground

Case1		Case2		Case3		Case4		Case5	
Thick.	Vs	Thick.	Vs	Thick.	Vs	Thick.	Vs	Thick.	Vs
m	m/s	m	m/s	m	m/s	m	m/s	m	m/s
17	100	8.05	50	15.725	200	2.3	50	4.25	59
						6.2	200	4.25	118
		8.95	50			2.3	50	4.25	177
				1.275	50	6.2	200	4.25	236

The dynamic analysis, in general, is very difficult and complicated for designers. Therefore, a reasonable method to use demanded strength spectrum is often applied to estimating the dynamic response of structure. This study also investigates an application method to the demanded strength spectrum taking the effects of input loss into consideration. Therefore, the rectification index is defined as an index that rectifies the yielding strength of structure and evaluates its response with the effects of effective seismic motion taken into consideration. The characteristics of rectification index are estimated and modeled to easily apply to seismic design.

BEHAVIORS OF EFFECTIVE SEISMIC MOTION

The objective of this section is to present the numerical results of the effective seismic motion to investigate the following four effects.

1) Shape of foundation
2) Stiffness of the surface layer
3) Damping ratio of the surface layer
4) Multi-layered surface ground

Concerning 1), 2),3), the effective seismic motions are calculated by an theoretical approach, in which the surface layer is treated as a single-layered stratum resting on an rigid bedrock. Fig.1 shows the theoretical model of soil-foundation system. The properties of models are presented in details in Table.1. Concerning 4), they are calculated by an analytical approach to use the three dimensional finite element method. Table.2 shows the analyzed cases of multi-layered stratum The behaviors of effective seismic motion are generally expressed by an index, called the effective seismic coefficient (η). The effective seismic coefficient is defined as the absolute value of the amplitude that is normalized by the corresponding amplitudes of the free surface motion as follows.

$$\eta = \left| \frac{\ddot{u}_f(\omega)}{u_g(\omega)} \right| \quad (1)$$

where

$\ddot{u}_{eff}(\omega)$: Effective seismic motion

$\ddot{u}_g(\omega)$: Free surface ground motion

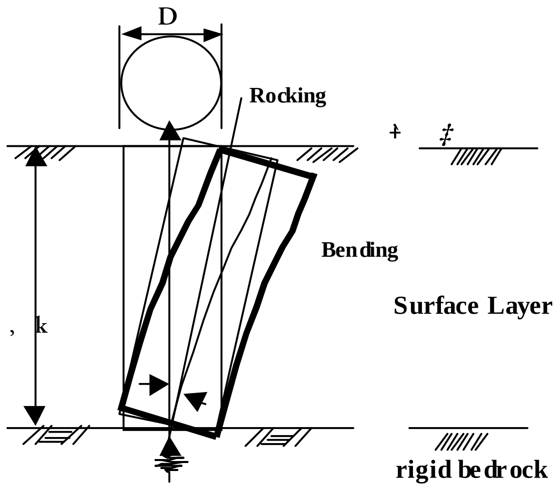

Figure 1: Theoretical model of soil-foundation system

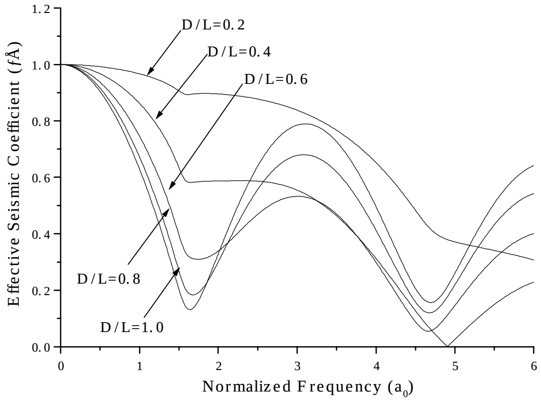

Figure 2: Theoretical results of effective seismic coefficient comparison between differences of D/L

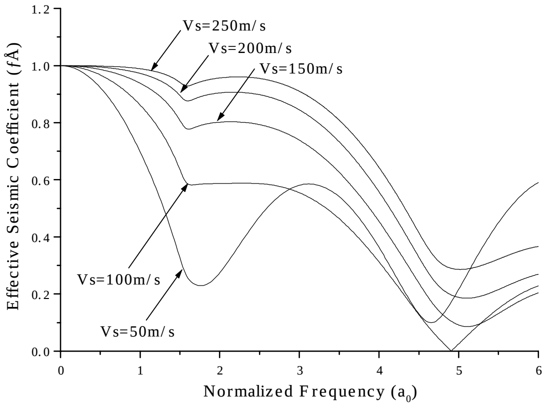

Figure 3: Theoretical results of effective seismic coefficient comparison between differences of Vs

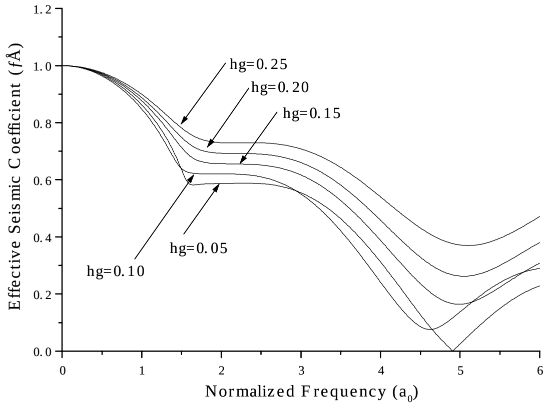

Figure 4: Theoretical results of effective seismic coefficient comparison between differences of h_g

The effective seismic coefficient is treated hereafter as an index of estimating the dynamic behaviors of the effective seismic motion. The effective seismic motion is much affected by the frequency of an input motion put into rigid bedrock. Therefore, the abscissa of the graph for the effective seismic coefficient is a non-dimensional frequency defined by $\omega H/V_s\ (= a_0)$. This means the ratio of the length of the foundation to the wavelength through the surface layer. If the excitation frequency is equal to the predominant frequency of surface ground, the value of a_0 will be 0.5π . If the value of the effective seismic coefficient approaches unity, this means that the amplitude of acceleration at the head of foundation is the same as that of the ground motion. If the value is smaller than unity, on the other hand, this implies that the amplitude at the head of the foundation is smaller than that of the ground motion.Fig.2 presents the theoretical results of effective seismic coefficient with different ratios of the diameter (D) to the length (L) of the foundation. In this analysis, the length of the foundation is a constant value that is the same as that of the standard model. Fig.2 implies that the larger the diameter becomes, the larger the effect of input loss becomes. This means that, as the width of the foundation increases, the rocking motion occupies the larger portion than the flexural one. Therefore, the motion of foundation gradually becomes difficult to follow the motion of the ground. Fig.3 shows the theoretical results of effective seismic coefficient with the different values of stiffness of the surface layer. In this analysis, the shape of the foundation is the same as those of the standard model, and the depth, the damping ratio of the surface layer are also same as the standard model.According to these conditions, the differences in the stiffness correspond to the differences in the longitudinal

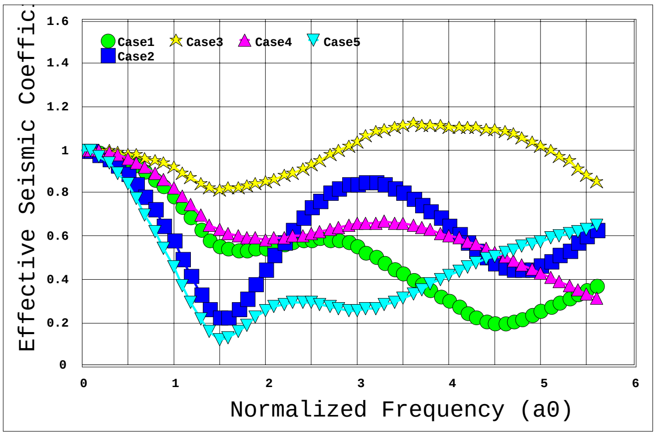

Figure 5: Analytical results of effective seismic coefficient resting on multi-layered stratum

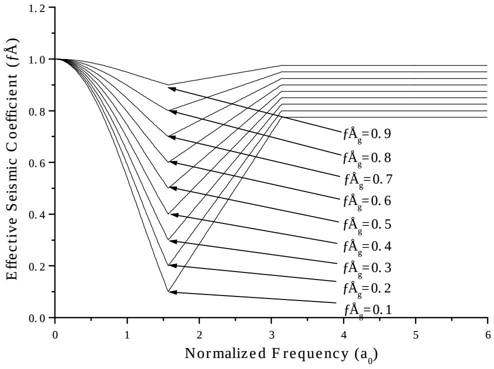

Figure 6: Approximate solution of effective seismic coefficient

velocity (V_s). Inthis analysis, the parameter on the longitudinal velocity (V_s) is changed from 50m/s to 250m/s at intervals of 50m/s. Fig.3 displays that the more the longitudinal velocity decreases, the more the effect of input loss increases. This indicates the relations between the length of the foundation and the wave transmitted to the surface layer. When the length of the transmitted wave is shorter than that of the foundation, the force that has a phase difference acts on the side-wall of the foundation. Thus the foundation doesn't react much. In contrast, when the length of the transmitted wave is longer than that of the foundation, the force that has the same phase acts on the foundation. Therefore, the foundation reacts to a large extent. For these reasons, when the longitudinal velocity is small, the length of the transmitted wave is short. Therefore, the effects of input loss become large. Fig.4 presents the theoretical results with the different damping ratios of the surface layer. When the damping ratio becomes small, the effective seismic coefficient becomes small. The ground motion is much affected by the damping ratio rather than the foundation motion is. The effective seismic coefficient is the ratio of the amplitude of the effective seismic motion to the corresponding surface ground motion (following the previous definition). Therefore, the larger the damping ratio is, the more the ground motion decreases. In contrast, there are no significant changes in the effective seismic motion. Thus, the effective seismic coefficient becomes relatively smaller.Fig.5 shows the results of the effective seismic coefficient when the condition that the foundation rests on a multi-layered soil medium calculated by the three-dimensional finite element method. Every model has the same 1st predominant frequency, but, the compositions of the layers are different. Fig.5 implies that every case has similar characteristics that the effective seismic coefficient has one of the smallest points at the 1st predominant frequency of the surface layer of the ground. In the high frequency region, there are no significant common characteristics. Except for Case3, the effective seismic coefficient resting on the single-layered stratum in Case1 is similar to or larger than those in other cases in the low frequency region.

MODELING OF EFFECTIVE SEISMIC COEFFICIENT FOR SEISMIC DESIGN

From the viewpoint of seismic design, structures of the ordinary type are affected by the characteristics in low frequency region. Therefore, when a designer takes the previous characteristics of input loss into a seismic design, it is appropriate to apply the result of Case1 to represent the cases of having a common 1st predominant frequency. With the result of theoretical approach and analytical approach concerning the standard model are compared, the effective seismic coefficients are close to each other, especially in the low frequency range. From these results, an approximate solution of the effective seismic coefficient is derived. The shape of the function is decided as shown in Fig.6 and Eq.2. This function is composed of the following parameters; a)1st predominant frequency, b) The value of one of the smallest points at the 1st predominant frequency called the estimation coefficient (η_g). The estimation coefficient is derived from the previous theoretical solution. The theoretical solution is expressed by a complex function. Therefore, essential functions are selected and recomposed among the components of complex function. The function of estimation coefficient is expressed as Eq.3.

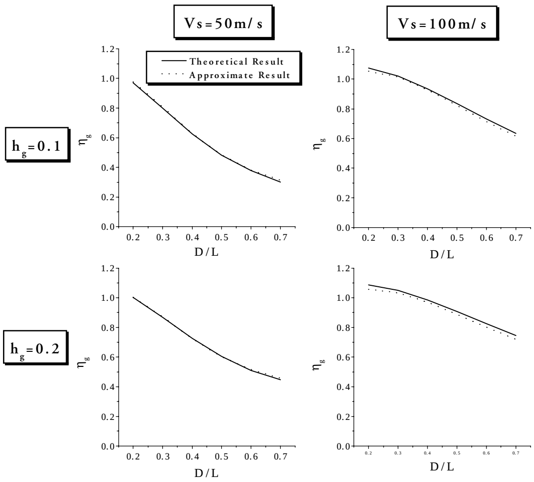

Figure 7: Comparison of estimation coefficient between theoretical solution and approximate solution

$$\eta_{eff}(\omega) = \frac{2}{3}\left(1-\eta_g\right)\left[\cos\left(\frac{2}{3}\pi\cdot\frac{\omega}{\omega_g}\right)-1\right]+1 \qquad \left(\omega \le \omega_g\right)$$

$$= \frac{3}{4}\left(1-\eta_g\right)\left[\left(\frac{\omega}{\omega_g}\right)-1\right]+\eta_g \qquad \left(\omega_g \le \omega \le 2\omega_g\right)$$

$$= \frac{1}{4}\left(3+\eta_g\right) \qquad \left(2\omega_g \le \omega\right)$$

(2)

$$\eta_g = \frac{3}{2}\left[\frac{\Phi_R + \left(4/\pi - 2\right)\beta_{eff} + \left(16/\pi\right)\gamma}{\Phi_I + 2\left(1 - 4/\pi\right)\beta_{eff} + \left(8/\pi\right)^2\gamma}\right] + \eta_r \ \ldots\ 1.0$$

(3)

$$\beta_{eff} = \left(G_e A/EI\right)\left(2L/\pi\right)^2,\ \gamma = \left(L/D\right)\left(G_e/G_r\right)\left(1-\nu_r\right)$$

$$\Phi_R = \left[0.22 + \left(1/6\right)\sqrt{\left(1-2\nu_d\right)/2\left(1-\nu_d\right)}\right]\left[\left(\pi D/4L\right)^2 h_{ge}\right]^{0.9}$$

$$\Phi_I = \left[0.23 + \left(1/3\right)\sqrt{\left(1-2\nu_d\right)/2\left(1-\nu_d\right)}\right]\left[\left(\pi D/4L\right)^2 h_{ge}^{-0.43}\right]^{0.7}$$

$$\eta_r = \left(3-0.02v_{sde}\right)\left[0.01+0.4\left(D/L-0.2\right)\left(h_{ge}-0.15\right)\right]$$

where G_e is the equivalent shear modulus of surface layer; A is the cross sectional area of foundation; EI is the bending stiffness of foundation; G_r is the shear modulus of rigid bedrock; ν_d is the Poisson ratio of surface layer; ν_r is the Poisson ratio of rigid bedrock; h_{ge} is the equivalent damping ratio of surface layer, and v_{sde} is the equivalent longitudinal velocity of surface layer.

Fig.7 compares the estimation coefficient between the theoretical and approximate solution. Fig.7 represents very limited cases. However, other various cases have already been calculated to give the fitness of approximate solution.

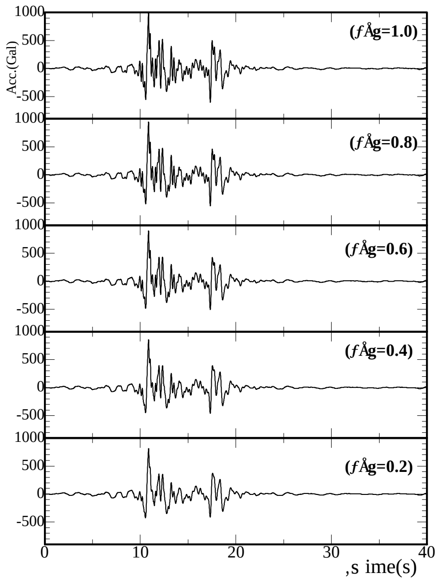

Figure 8: Effective seismic motions corresponding to the estimation coefficient (η_g)

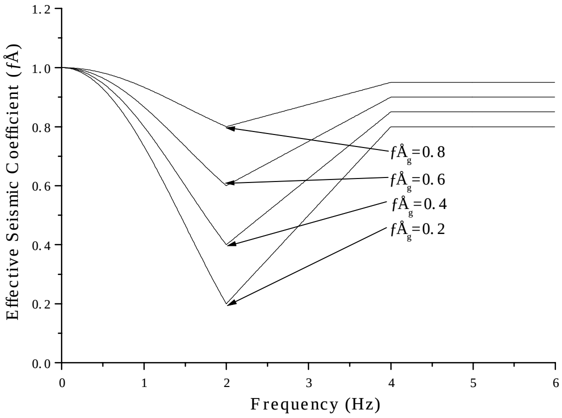

Figure 9: Effective seismic coefficient corresponding to the estimation coefficient (η_g)

EFFECTS OF EFFECTIVE SEISMIC MOTION TO STRUCTURE

This section investigates the effects of effective seismic motion on the 1DoF system that has non-linear characteristics. The demanded strength spectrum displays the behaviors of structural response corresponding to the 1st predominant frequency and the yielding strength of structure. In this section, this demanded strength spectrum is applied to investigate the effects of the effective seismic motion. Fig.8 shows the time history of the effective seismic motion corresponding to the value of estimation coefficient (η_g). These waves are evaluated after transformed by the Fourier transform by using the original wave and previous effective seismic coefficients.

The original wave ($\eta_g = 1.0$) is a response acceleration of surface layer which is prescribed as one of the seismic designed waves in railway structural design in Japan. Therefore, this is not the actual response of the surface layer. The applicable condition of this wave indicates that the range of predominant frequency of the surface ground is from 2.0 (Hz) to 4.0 (Hz). According to this applicable condition, the predominant frequency that decides the shape of the function (Eq.2) is assumed to be 4.0 (Hz) in this case. In addition, considering the non-linearity of the surface layer, it is assumed that the predominant frequency 4.0 (Hz) is changed into a half value of the frequency 2.0(Hz). Therefore, the effective seismic coefficients by using these transforms are expressed as shown in Fig.9. Fig.8 implies that the smaller the value of the estimation coefficient is (the larger the effect of input loss is), the smaller the amplitude of the effective seismic motion is. Moreover, the high frequency components of the wave seem to be filtered. Fig.10 shows the results of demanded strength spectrum. The abscissa of the graph corresponds to the equivalent period of structure (T_{eq}). The ordinate of the graph corresponds to the yielding strength (K_y). The graphs are separated by the response ductility (μ). These graphs indicate that the smaller the estimation coefficient is, the smaller the yielding strength is in spite of the differences with response ductility. Fig.11 displays the ratio of the yielding strength of the estimation coefficient ($\eta_g = 1.0$) to that of the other estimation coefficients ($\eta_g = 0.8, 0.6, 0.4$). This graph implies that the values of the ratio of the yielding strength at the smallest point in the linear case ($\mu = 1.0$) are smaller than those in other nonlinear cases ($\mu = 2.0, 6.0, 8.0$), and moreover, the values become larger, when the non-linearity of the structural response make progress more. It seems to be trivial, but the equivalent period of structure at the

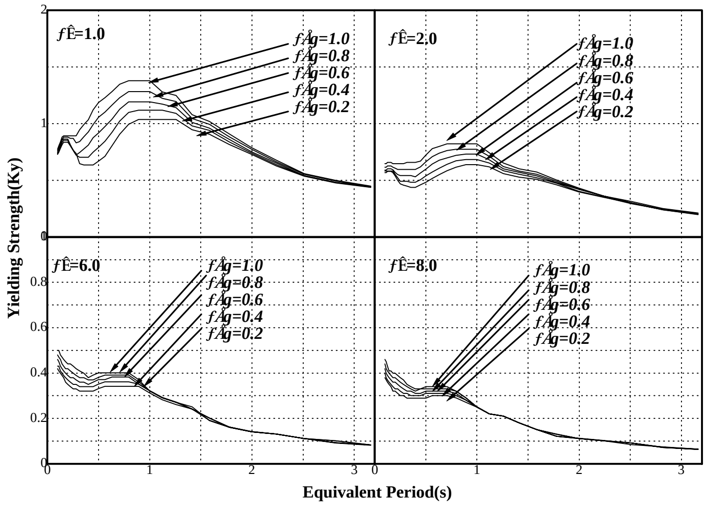

Figure 10: Results of demanded strength spectrum

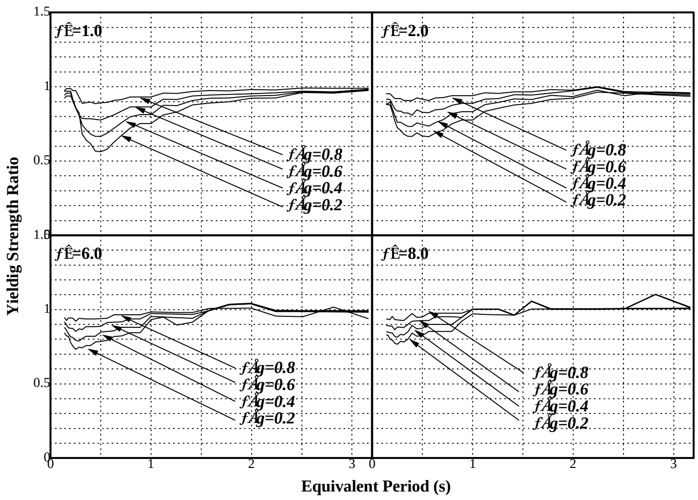

Figure 11: Ratio of yielding strength

smallest point is the same as the predominant period of the surface layer (0.5s). Nevertheless, the more the non-linearity of the structural response advances, the shorter the period becomes. This tendency is caused by the progression of inelastic response of the structure. From the view point of seismic design, the ratio of the yielding strength becomes the rectification index. When a designer estimates the response of structure with the effects of effective seismic motion taken into consideration, the response can be evaluated by applying the yielding strength divided by the rectification index to the demanded strength spectrum. Various layers that have the different 1st predominant frequencies are investigated in the previous study. As the result of these investigations, the approximate rectification index is derived as Eq.4. The results are shown in Fig.12.

$$
\begin{aligned}
f\grave{I}_{eff}(T_{eq}) &= \frac{1}{2}(1+f\grave{I}_f) && \left(,0 \le T_{eq} \le \frac{T_g}{2} \right) \\
&= \frac{1}{2}(1-f\grave{I}_f)\left[\left(\frac{T_g}{T_{eq}}\right)-1\right]+f\grave{I}_f && \left(\frac{T_g}{2} \le T_{eq} \le T_g\right) \qquad (4) \\
&= \frac{T_g}{T_{eq}}(f\grave{I}_f - 1)+1 && (T_g \le T_{eq})
\end{aligned}
$$

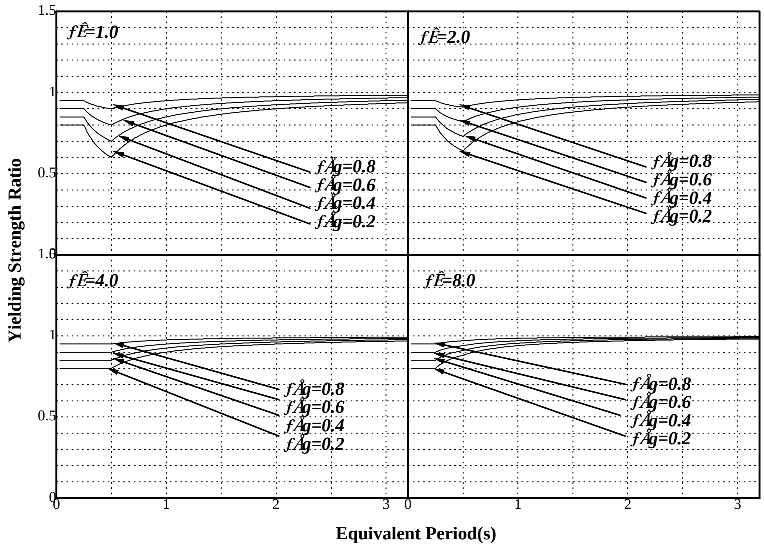

Figure 12: Approximate rectification index for demanded strength spectrum

$$f\grave{I}_f = 0.1\left(1 - f\grave{I}_g\right)\left(f\hat{E} - 1\right) + f\grave{I}_g$$

$$f\grave{I}_g = 0.5 f\mathring{A}_g + 0.5 \qquad \left(T_g \le 1.0s\right)$$

$$= 0.7 f\mathring{A}_g + 0.3 \qquad \left(1.0s \le T_g\right)$$

CONCLUSION

This paper investigates the behaviors of effective seismic motion and the characteristics of effective seismic coefficient by using a theoretical approach and analytical approach. It is concluded that the effective seismic motion is much affected by the shape of the foundation, and the stiffness and damping ratio of the surface layer. As the results of these analyses, the effective seismic coefficient is modeled for the seismic design, and the rectification index is derived by using this model, which is applied to the demanded strength spectrum for taking the effects of input loss.

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