MODIFIED SEISMIC COEFFICIENT METHOD OF EMBANKMENT DAMS REVIEWED BY RECENT SEISMIC RECORDS

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ABSTRACT

In 1991, The “Draft of Guidelines for Seismic Design of Embankment Dams” was drawn up in Japan. The Draft of Guidelines was established as both a future design method for new dams and as a simplified seismic performance evaluation method for existing dams. In the Draft of Guidelines, a modified seismic coefficient method was proposed as the seismic performance evaluation method for embankment dams with a height less than 100m, in which the vertical distribution of seismic force was determined while considering the seismic response of the dam body. The seismic force coefficients were formulated based on the examination and analysis of eight seismic motions recorded at dam sites, during relatively large earthquakes at the time. But, since the implementation of the Draft of Guidelines, a number of seismic motions have been recorded at many dam sites in Japan. In our research, we re-examined seismic force coefficients using recent seismic motion records and proposed revised seismic force coefficients for a modified seismic coefficient method, which is applicable to embankment dams greater than 100 m in height.

INTRODUCTION

Recently in Japan, frequent large-scale earthquakes have occurred, so seismic performance evaluation of dams, which store huge amount of water in their reservoirs, has attracted rising attention. Because there are more than 1,500 existing embankment dams in Japan, it is difficult to evaluate the seismic performance by dynamic analysis for all embankment dams in a short period and with a limited budget. In order to determine the priority of detailed seismic performance evaluations for existing embankment dams, it is necessary to develop a simple and practical seismic performance evaluation method.

The “Draft of Guidelines for Seismic Design of Embankment Dams” (hereinafter referred to as the “Draft of Guidelines”) was drawn up in June, 1991, as both a simplified seismic performance evaluation method for existing embankment dams and a future design method for new embankment dams. In the Draft of Guidelines, the application of a modified seismic coefficient method is proposed for embankment dams in Japan with a

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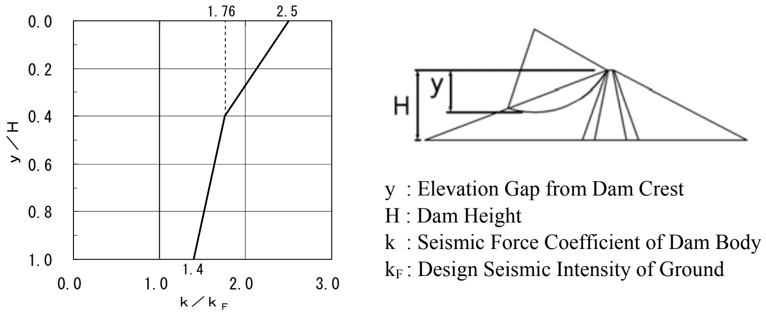
height less than 100m, in which the vertical distribution of seismic force has been determined by taking the seismic response of a dam body into account. The modified seismic coefficient method uses seismic force coefficients that change the seismic force to be applied to the sliding mass depending on the depth from the top to the slip surface's lowest point in the dam body, as in Fig. 1, in order to consider the lack of uniformity of the seismic response of the dam body during earthquakes.



y : Elevation Gap from Dam Crest
H : Dam Height
k : Seismic Force Coefficient of Dam Body
k_F : Design Seismic Intensity of Ground

Figure 1. Seismic force coefficients in the Draft of Guidelines.

The seismic force coefficients in the Draft of Guidelines were formulated based on the examination and analysis of eight seismic motions recorded at dam sites during actual relatively large earthquakes, and the coefficients are the same regardless of dam height and slopes of surfaces. But, after the implementation of the Draft of Guidelines, a number of seismic motions have been recorded at many dam sites in Japan. Based on many recent seismic motions obtained at dam sites from 1966 to 2008, we examine the seismic force coefficients corresponding to the dam height that can also be applied to embankment dams with a height greater than 100m. In addition, we investigate the effects of gradients of upstream and downstream surfaces on the values of the seismic force coefficients. Based on the results, we propose revised seismic force coefficients which will be utilized by design methods for new dams and simple seismic performance evaluation of existing dams.

ANALYSIS METHOD AND ANALYSIS CONDITIONS

Analysis Method

As for the analysis method applied to investigate seismic force coefficients, equivalent linearization analysis based on the complex response method is conducted for rockfill dam models to determine the time history of the response accelerations of the dam body against input seismic motions. Then, the time history of the average response accelerations of the sliding mass for each of 20 upstream slip circles as shown in Fig. 2 and 20 downstream slip circles as shown in Fig. 3 is calculated, and the maximum value in the time history of the average response accelerations is divided by the maximum acceleration of the input seismic motion to determine the seismic force coefficient (k/k_F). The slip circles for upstream side and downstream side are divided into four groups, respectively, shown in Fig. 2 and 3. Here, k represents the seismic force coefficients of the dam body and k_F represents the design seismic intensity of the ground.

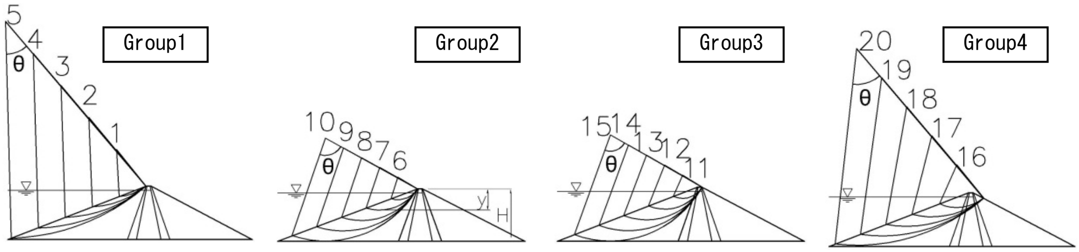


Figure 2. Upstream side slip circles for analysis.

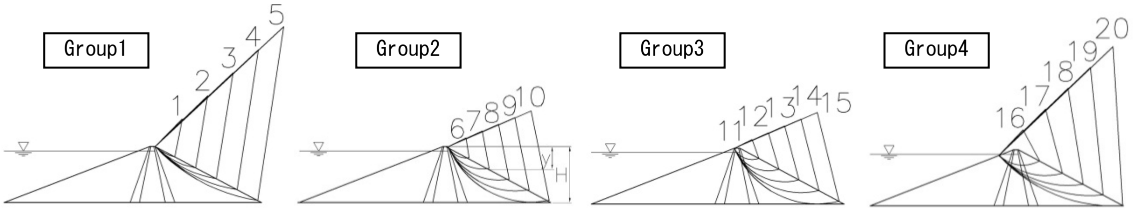


Figure 3. Downstream side slip circles for analysis.

Analysis model and material properties

The analytical models were rockfill dams with a central impervious core, and heights of 50m, 75m, 100m, 125m and 150m, respectively. The upstream and downstream slope gradients were determined by stability analysis based on the seismic coefficient method that is the present design standard in Japan, and the seismic coefficient was set at 0.15. The reservoir water level was set at 92% of the dam height and both the upstream and downstream gradients were calculated so that the minimum safety factor against sliding exceeded 1.2. The 100m-high dam model obtained is illustrated in Fig. 4. The material properties of the dam body used to determine the cross-section are shown in Table 1.

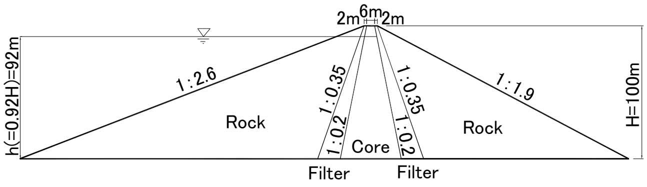


Figure 4. Analytical model for 100m-high dam.

Table 1. Input material properties used to determine upstream and downstream gradients.

Material	Wet Density ρ_t(g/cm^3)	Saturated Density ρ_{sat}(g/cm^3)	Cohesion (kN/m^2)	Internal friction angle (°)
Core	2.22	2.23	0	35
Filter	2.13	2.24	0	36
Rock	1.94	2.15	0	42

The finite element mesh of the model used for equivalent linearization analysis is shown in Fig. 5. The material properties used by the equivalent linearization method for seismic response analysis are summarized in Table 2 and Fig. 6. These material properties were determined based on the design values or on laboratory test values of existing rockfill dam materials considered as standard values in Japan. Energy dissipation from dam body to foundation was taken into consideration by adding an equivalent radiation damping ratio of 15% to the material damping ratio.

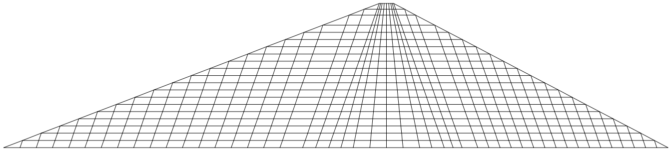


Figure 5. Finite elements of analytical model.

Table 2. Input material properties used for the equivalent linearization analysis.

Material	Wet Density $\rho_t(g/cm^3)$	Saturated Density $\rho_{sat}(g/cm^3)$	Initial Shear Modulus $G_0(MPa)$※
Core	2.22	2.23	$\{60(2.17\text{-}e)^2/(1+e)\}\sigma_m^{0.7}$
Filter	2.13	2.24	
Rock	1.94	2.15	$\{93(2.17\text{-}e)^2/(1+e)\}\sigma_m^{0.6}$

※ e : Void Ratio ,
σ_m' : Mean Effective Principal Stress $\sigma_m' = \frac{1+2K}{3} \cdot \rho \cdot g \cdot D$
k : Principal Stress Ratio (=0.5), ρ : Density(g/cm^3)
g : Gravitational Acceleration (=$9.8m/s^2$)

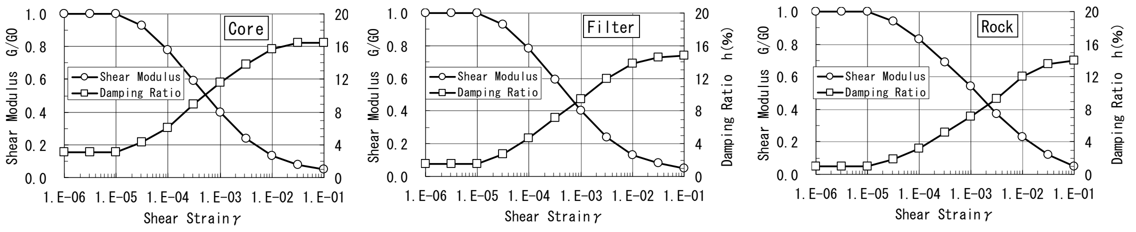


Figure 6. Strain-dependent shear modulus and damping ratio of materials.

Selection of input seismic motions

Among 1,883 seismic motions recorded in bedrock or inspection galleries at dam sites from 1966 to 2008, those with a maximum horizontal acceleration exceeding 100 gal were selected. Thus, 48 seismic motions were selected as the input seismic motions.

Seismic motion records were normalized to make the maximum acceleration of the horizontal seismic motions of the selected 48 seismic motions become 196 gal (0.2 G).Vertical seismic motions were also normalized by multiplying the same ratio for the horizontal seismic motions.

ANALYZED CASES

Three cases were analyzed as in Table 3.

Table 3. Analyzed cases.

Analyzed Case	Slope Gradient		Slip Arc for Analysis	Dam Height
	Upstream	Downstream		
【Case 1】Effects of dam heights	1:2.6	1:1.9	Upstream Side	50,75,100, 125,150
【Case 2】Comparison between upstream side sliding and downstream side slidings	1:2.6	1:1.9	Upstream Side Downstream Side	100
【Case 3】Effects of slope gradients	1:2.4	1:1.8	Upstream Side Downstream Side	100
	1:2.6	1:1.9		
	1:3.0	1:2.2		

In Case 1, effects of the dam height on seismic force coefficients were examined. A dam model with a height of 100 m as shown in Fig.4 as well as four models with dam heights of 50 m, 75 m, 125 m, and 150 m were used. The dam body shape of each model, other than the basic 100-m height model, was determined proportionally based on the basic 100-m height model. For determination of the reservoir water level and mesh size of finite element dimensions of each model, the same principle was applied. Slip circles for analysis were set only on the upstream side.

In Case 2, using the dam model with height of 100-m, the seismic force coefficients of the downstream slip circles were investigated, because in Case 1, slip circles for analysis were set on the upstream side. Differences in seismic force coefficients between upstream and downstream surfaces were examined.

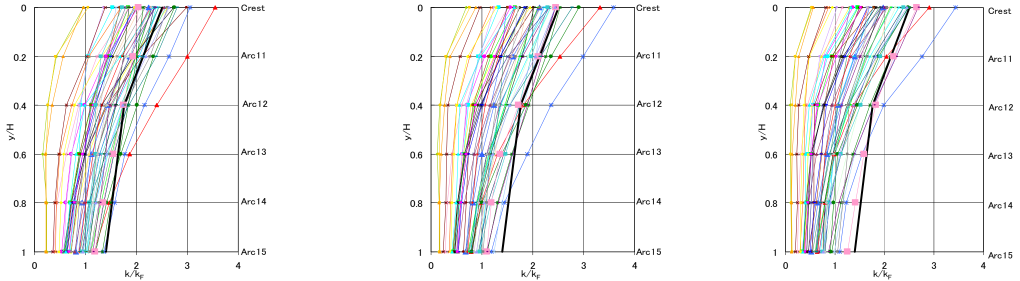
In Case 3, we examined effects of slope gradients on seismic force coefficients in the dam models with different slope gradients. The dam models for analysis were set by changing the slope gradients of a dam with height of 100 m and upstream and downstream surface gradients of 1:2.6 and 1:1.9, respectively, as shown in Fig. 4. The cross-sectional gradients for analysis were determined based on the results of the survey of the upstream and downstream slope gradients of existing rockfill dams in Japan. The range of gradients for analysis contains the majority of the cross-sectional gradients of existing rockfill dams. As a result, a model of a steep slope dam with gradients of 1:2.4 and 1:1.8 for the upstream and downstream slopes and a model of a gentle slope dam with 1:3.0 and 1:2.2 respectively were investigated.

RESULTS OF ANALYSIS

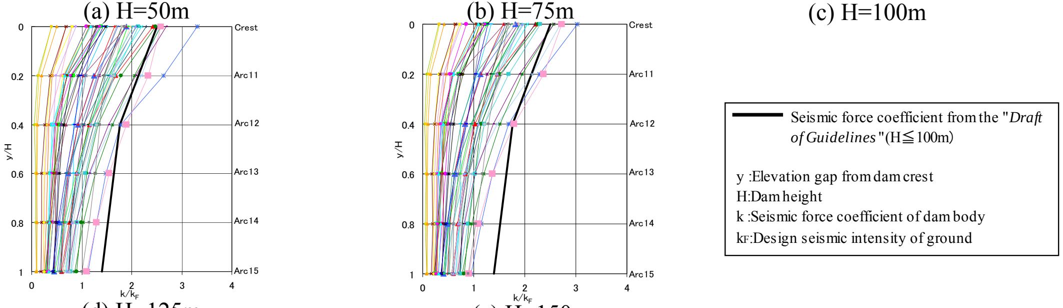
Effects of dam heights (Case 1)

The results of the analysis of the model dams with heights of 50m, 75m, 100m, 125m and 150m are shown in Fig. 7. The height of a slip circle (y) is defined as the vertical distance from the dam crest to the lowest point of the slip circle. The height of slip circle (y) is nondimensionalized by the dam height (H). Fig. 7 indicates the relationship between y/H and seismic force coefficients (k/k_F). We examined 20 slip circles in Fig. 2, but no significant difference was detected in the four groups, so the results from the analysis of

Group 3, which mostly exhibited the largest seismic force coefficients in four groups, are taken as examples for this paper.



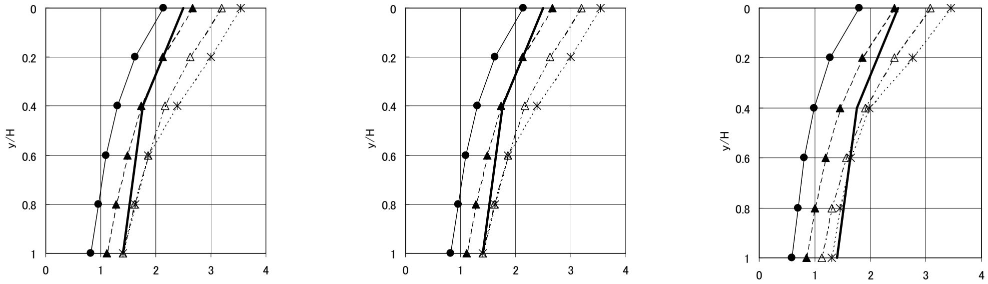
(a) H=50m (b) H=75m (c) H=100m



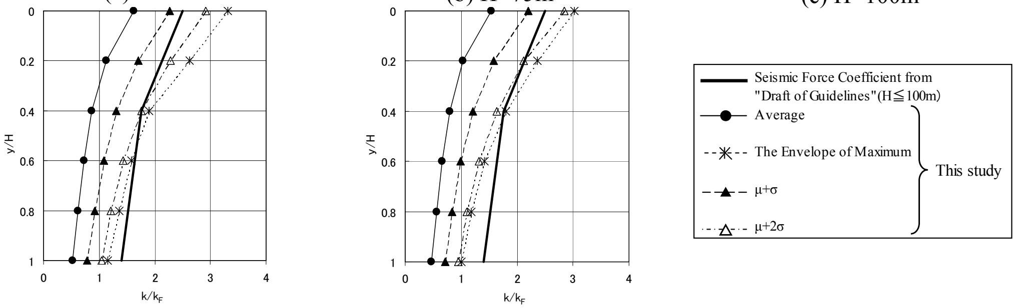
(d) H=125m (e) H=150m

Figure 7. The relationship between y/H and seismic force coefficients (k/k$_F$) (Results of Group 3).

The results of the analysis of all dam height cases were compared with the seismic force coefficients in the Draft of Guidelines. It was found that seismic force coefficients at higher elevations exceeded those in the Draft of Guidelines. This tendency is more clearly found in the model dams with relatively low heights of 50m and 75m. With the exception of these cases, most of the seismic force coefficients were lower than those in the Draft of Guidelines.



(a) H=50m (b) H=75m (c) H=100m



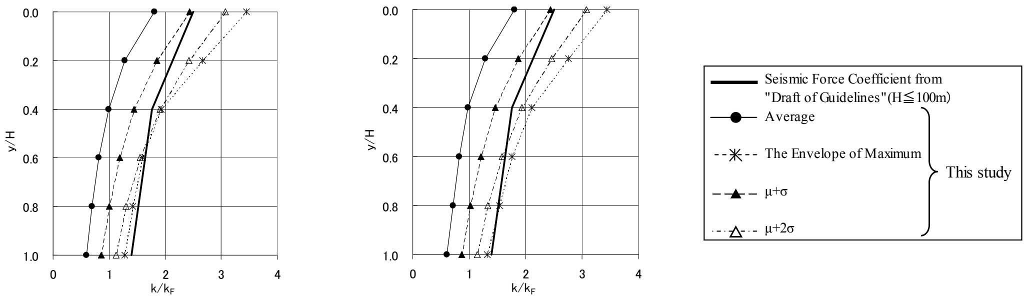
(d) H=125m (e) H=150m

Figure 8. Statistical values of seismic force coefficients.

As shown in Fig. 8, the seismic force coefficients obtained in Fig. 7 were reorganized from the viewpoint of the statistical values of the mean (μ) and the standard deviation (σ). In the 50-m high model dam case, the value μ + σ of the seismic force coefficients at the crest (y/H = 0) was slightly larger than that in the Draft of Guidelines. But in the other dam model cases, the values of μ and μ + σ of the seismic force coefficients are smaller than those in the Draft of Guidelines over the whole range of y/H. The values μ + 2σ of the seismic force coefficients are situated close to the envelope lines of maximum values, and they exceed those in the Draft of Guidelines in the high elevation area where y/H is smaller than approximately 0.4.

Comparison between upstream and downstream side slidings (Case 2)

Analysis of upstream and downstream side sliding was conducted for a total of 48 input earthquake motions, and the statistically processed results are shown in Fig. 9. The graphs show the seismic force coefficients of the upstream and downstream side sliding obtained as the average (μ), showing almost no difference between the average plus standard deviations (μ + σ).

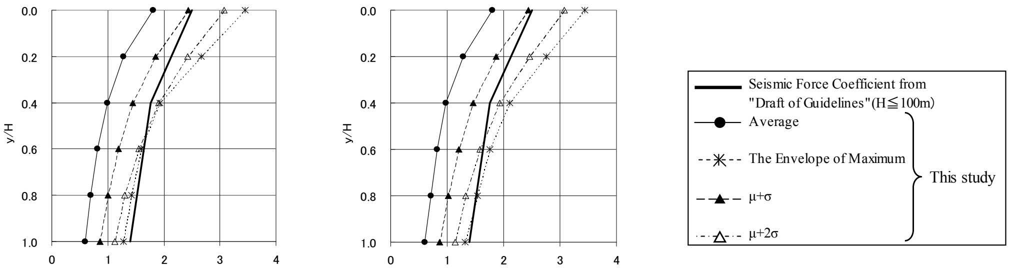


(Upstream side sliding) (Downstream side sliding)

Figure 9. Statistical values of seismic force coefficients in Case 2.

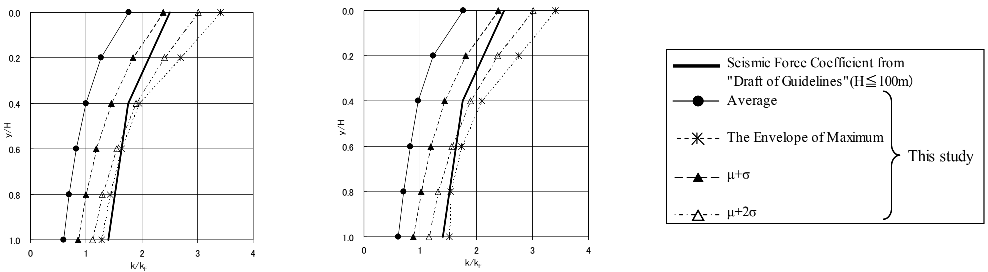
Effects of slope gradients (Case 3)

Figs. 10 and 11 graphically present the statistically processed results of analysis of upstream and downstream side sliding for 48 seismic motions based on the steeper model with gradients of 1:2.4 and 1:1.8 for upstream and downstream respectively and the gentler model with 1:3.0 and 1:2.2 for upstream and downstream, respectively.
These figures show that very similar results were obtained for both the average (μ) and the average plus standard deviation (μ + σ) by different gradients on upstream side sliding. When we focus on the effects of different gradients on downstream side sliding, the figures also show results similar to those found for upstream side sliding.



(Upstream side sliding) (Downstream side sliding)

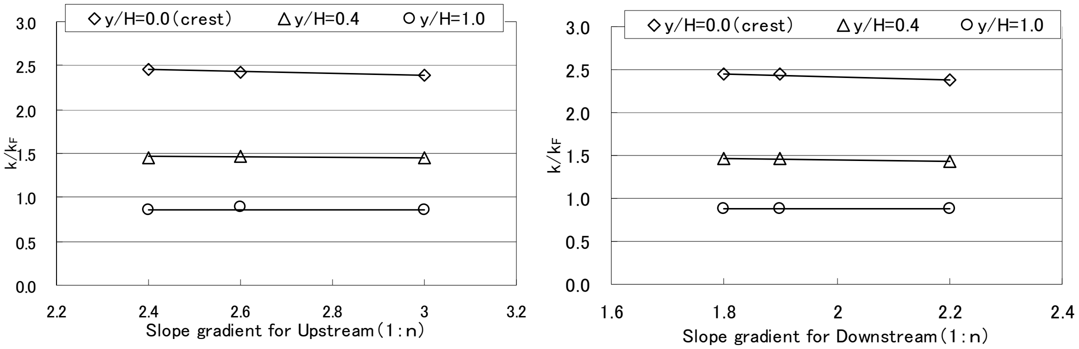
Figure 10. Statistical values of seismic force coefficients in the steeper dam model (upstream and downstream gradients of 1:2.4 and 1:1.8).



(Upstream side sliding) (Downstream side sliding)

Figure 11. Statistical values of seismic force coefficients in the gentler dam model (upstream and downstream gradients of 1:3.0 and 1:2.2).

For the relationship between the gradient and the average + standard value ($\mu + \sigma$) of seismic force coefficients (k/k_F), Fig. 12 shows the relationships for upstream and downstream side sliding with the results of Figs. 9, 10 and 11. The distribution of seismic force coefficients (k/k_F) in the Draft of Guidelines is shown with broken lines at y/H = 0.0, 0.4 and 1.0 as in Fig. 1. Therefore, the focus with respect to the results of our research is also put on y/H = 0.0, 0.4 and 1.0. It is shown that the seismic force coefficients, k/k_F, almost have the same values at any y/H for both upstream and downstream side sliding in the range of upstream and downstream gradients of ordinary rockfill dams in Japan.



(Left figure : Upstream sliding, Right figure : Downstream sliding).

Figure 12. Relationships between gradient and k/k_F ($\mu + \sigma$)

PROPOSAL OF REVISED SEISMIC FORCE COEFFICIENTS

Now we propose revised seismic force coefficients applicable to rockfill dams greater than 100 m in dam height using recent seismic motion records.
Based on the analysis results with Case 1 models with dam heights of 50 m, 75 m, 100 m, 125 m and 150 m, the relationship with dam height H for each of y/H 0.0, 0.4 and 1.0, with respect to the average + standard deviation (μ+σ) of seismic force coefficients (k/k_F) is shown in Fig. 13. A high correlation can be seen for all y/H, indicating that the seismic force coefficients (k/k_F) linearly decrease as the dam height increases.

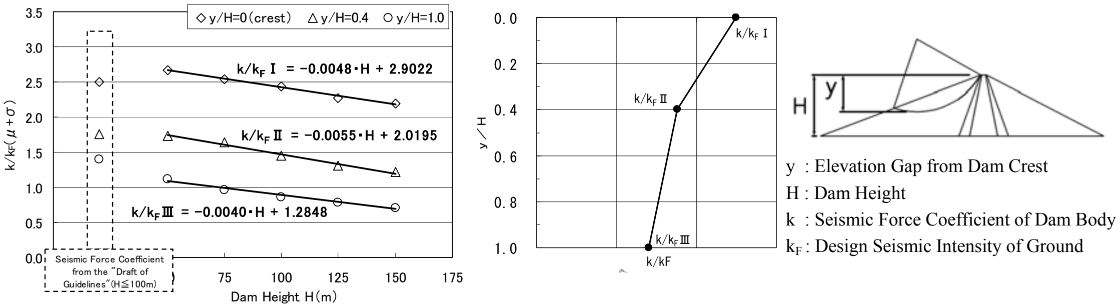


Figure 13. The relationship between dam height (H) and "μ+σ" of seismic force coefficients (k/k_F).

Reviews of Case 2 and Case 3 also clarified that the differences between upstream and downstream side sliding in rockfill dam models or the differences in slope gradients in the ordinary range in Japan of upstream and downstream side gradients have almost no effect on seismic force coefficients (k/k_F). Therefore, considering the fact that seismic force coefficients (k/k_F) have particularly a high correlation with dam height, it is reasonable to think that the seismic force coefficients in the modified seismic coefficient method can be expressed with approximation equations using dam height H as a parameter as in Table 4.

Table 4. Proposal of revised seismic force coefficients with dam height.

y/H	Approximation of the seismic force coefficient
0.0（Crest）	k/k_F Ⅰ *＝-0.0048・H＋2.9022
0.4	k/k_F Ⅱ *＝-0.0055・H＋2.0195
1.0	k/k_F Ⅲ *＝-0.0040・H＋1.2848

k:Seismic force coefficient of dam body
kF:Design seismic intensity of ground
k/kF:Seismic force coefficient
H:Dam height (m)
*Round up to the second decimal place

CONCLUSIONS

We used recent seismic motion records and re-examined seismic force coefficients for embankment dams. In this re-examination, the research also focused on the effects of the differences in upstream and downstream side slip surfaces and slope gradients on seismic force coefficients in addition to dam heights. The following are the conclusions of this research.

(1) Analysis upstream side sliding of dam models featuring dam heights of 50 m, 75 m, 100 m, 125 m, and 150 m was done, and the results indicate that a high correlation exists between the seismic force coefficients and dam height in the range of height from 50 m to 150 m and that seismic force coefficients (k/k_F) linearly decrease as the dam height increases for every y/H of 0.0, 0.4 or 1.0.

(2) Analysis of upstream and downstream side slidings indicates that the differences between upstream and downstream side slidings have almost no effect on seismic force coefficients (k/k_F). It is also shown that the differences in slope gradients have almost no effect on seismic force coefficients (k/k_F) in the ordinary range in Japan of upstream and downstream side slope gradients of rockfill dams.

(3) As summarized in (1), revised equations with dam heights are proposed with respect to seismic force coefficients in the modified seismic coefficient method.

In order to reflect to the "Draft of Guidelines", we proposed a simple and practical seismic performance evaluation method for embankment dams in accordance with the modified seismic coefficient method and we will make a further study of the seismic force coefficients.

REFERENCES

N.Matsumoto, N.Yasuda, M.Okubo, N.Sakano, Dynamic analysis of the dam Shichikashuku , Technical Memorandum of Public Works Research Institute, No.2460, Mar. 1987(in Japanese)

River Development Division, River Bureau, Ministry of Construction: Draft of Guidelines for Seismic Design of Embankment Dams, pp.5-10, pp.43-48, Jun. 1991(in Japanese)

Y.Yamaguchi, N.Tomida and M.Mizuhara, Sliding Arc to Give the Maximum Sliding Deformation of Rockfill Dams due to Large Earthquakes, Dam Engineering, No.229, pp.13-22, Oct. 2005 (in Japanese)

Y.Yamaguchi, H.Satoh, H.Sawada, Investigation of design seismic coefficients and slope gradients of existing embankment dams, The 37th Japan National Conference on Geotechnical Engineering, No1281-1282, Jul. 2002

Y.Yamaguchi, H.Satoh and H.Sakamoto, High-Precision Strength Evaluation of Rock Materials and Stability Analysis for Rockfill Dams, Second International Symposium on Rockfill Dams, Oct. 2011