Study of Seismic Force Coefficient for Rockfill Dams Based on Recent Seismic Motion Records

by

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ABSTRACT

In 1991, a modified seismic coefficient method was proposed for the seismic performance evaluation of rockfill dams in Japan with a height less than 100m, in which the vertical distribution of seismic force is established with taking dam body's seismic response into account.

We studied the design rationalization of rockfill dams on the basis of the modified seismic coefficient method. This method can be used for a simple evaluation method for the seismic performance of rockfill dams as well. Drawing on many recent records of seismic motion occurring at dam sites, this paper examines the seismic force coefficient that represents seismic force in the modified seismic coefficient method and proposes a revised seismic force coefficient that can also be applied to rockfill dams with a height greater than 100m.

KEYWORDS: Earthquake, Modified seismic coefficient method, Rockfill dams, Seismic response.

1. INTRODUCTION

The seismic coefficient method, which is the current design standard used in rockfill dams in Japan, defines seismic force as a constant inertial force in the vertical direction [1]. This assumption, however, does not reflect actual rockfill dam behavior during earthquakes, thus making it difficult to achieve efficient design rationalization. The "*Draft of Guidelines for Seismic Design of Embankment Dams*" [2] (hereinafter referred to as the "*Draft of Guidelines*") was drawn up in June, 1991, as a seismic performance evaluation method for rockfill dams in preparation for a prospective design method with a more realistic seismic load and material strength. In the *Draft of Guidelines*, a modified seismic coefficient method is proposed as a seismic performance evaluation method for rockfill dams under 100m in height, in which the vertical distribution of seismic force is established with taking dam body's seismic response into account. In fact, the seismic force coefficient had been formulated prior to the implementation of the *Draft of Guidelines* through the examination of various data including eight events of relatively large seismic motion recorded at dam sites. But, since the implementation of the *Draft of Guidelines*, a number of seismic motion with large peak acceleration have been recorded at many dam sites. With the aim of realizing the design rationalization of rockfill dams using the modified seismic coefficient method, it became necessary to review the seismic force coefficient by referring to recent seismic motion records and examine the implementation to rockfill dams with a height greater than 100m.

2. OUTLINE OF THE STUDY

The seismic force coefficient in the *Draft of Guidelines* [2] was formulated through an examination of seismic motion recorded at dam sites in the 1980s and earlier in Japan. Following the implementation of the *Draft of Guidelines*, however, a number of large-scale earthquakes such as the South Hyogo prefecture Earthquake in 1995 have occurred and many seismic motion data with large peak accelerations have been recorded at some dam sites.

Furthermore, the seismic force coefficient in the *Draft of Guidelines* can be applied only to embankment dams with a height less than 100m.

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As for embankment dams with a height greater than 100m, the following explanation is noted in the *Draft of Guidelines*: embankment dams with a height greater than 100m tend to have a longer natural period that may be a significant factor in reducing the seismic force specified in the *Draft of Guidelines,* provided that the frequency characteristics of seismic motion in bedrock are taken into account [2].

In the light of these situations, the seismic force coefficient in the modified seismic coefficient method needs to be reviewed with reference to seismic motion records from dam sites in recent years. We gathered seismic motion records, including the latest data and analyzed these to select input seismic motions in order to examine the seismic force coefficient. The chosen seismic motions were used to investigate the seismic force coefficients for model rockfill dams with heights of 50m, 75m, 100m, 125m and 150m, respectively. Based on the results, we discuss the relationship between the dam height and the seismic force coefficient of rockfill dams including those with a height greater than 100m.

3. SELECTION OF INPUT EARTHQUAKE MOTIONS

Among 1,883 data of seismic motion 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. These are listed in Table 1. The histogram of maximum horizontal acceleration values of selected seismic motions is illustrated in Fig. 1, where most data are distributed in the range between 100 and 200 gal.

The relationship between maximum horizontal acceleration and maximum vertical acceleration for the selected 48 seismic motions is shown in Fig. 2. Although the ratios of maximum horizontal acceleration to maximum vertical acceleration are mostly plotted around 1:0.5, some data lie close to or beyond the 1:1 line. In view of the maximum vertical acceleration in Table 1, some relatively recent seismic motions recorded after 1997 are found to be in the ratio of approximately 1:1 and a tendency for the maximum horizontal acceleration to increase can also be observed after 1997.

The acceleration response spectra of horizontal seismic motions with a damping factor of h=5% and of vertical seismic motions are shown in Fig. 3 and in Fig. 4, respectively. The peak acceleration response spectra of the 48 seismic motions are in the range of between 0.1 and 0.3 seconds.

4. METHOD OF ANALYSIS

4.1 Outline

Equivalent linearization analyses [3] was conducted for the rockfill dam models using the complex response method to obtain the dam body's seismic response. We examined 20 circles on the upstream side [4] shown in Fig. 5 to calculate the seismic force coefficient (k/k_F) for each circle by dividing the average response acceleration by the maximum acceleration of input seismic motion. Here, k is the seismic force coefficient of a dam body and k_F is the design seismic intensity of the ground [2].

4.2 Analytical Models and Input 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 with a stability analysis based on the seismic coefficient method [1] 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 narrowly exceeded 1.2 [3]. The 100m-high dam model obtained is illustrated in Fig. 6. Other model dam shapes were decided in proportion to the 100m-high model dam. The specifications and reservoir water level of the model dams are listed in Table 2 and their finite element mesh is shown in Fig. 7.

Table 1. List of 48 Selected Seismic Motions

No.	Date	Name of Dam	Location of Seismometer	α_{xmax}(gal) ※1	α_{ymax}(gal) ※2	$\lvert\alpha_{ymax}\rvert / \lvert\alpha_{xmax}\rvert$	Name of Earthquake
No.1	1976.06.16	Miho	Observation Room of Water Leakage	−125.57	43.17	0.344	The Eastern Yamanashi prefecture Earthquake
No.2	1978.06.12	Tarumizu	Inspection Gallery Located at bottom Part	178.43	83.88	0.470	Earthquake Off Coast of Miyagi prefecture
No.4	1983.08.08	Miho	Observation Room of Water Leakage	−149.37	−54.60	0.366	Boundary in Mid-Kanto Earthquake
No.5	1986.06.27	Ishibuchi	Ground on the Right Bank	−180.30	※)No Records	−	The Southen Iwate prefecture Earthquake
No.6	1987.01.09	Tase	Inspection Gallery	103.40	30.97	0.300	The Northern Iwate prefecture Earthquake
No.7	1987.12.17	Nagara	Dam Foundation	−262.00	−86.00	0.328	Earthquake off the East Coast of Chiba prefecture
No.11	1987.12.17	Nagara	Ground on the Left Bank	−281.00	111.00	0.395	Earthquake off the East Coast of Chiba prefecture
No.13	1989.10.27	Sugesawa	Ground on the Right Bank	−101.36	−26.28	0.259	The Western Tottori prefecture Earthquake
No.14	1993.07.12	Pirika	Inspection Gallery	116.69	72.53	0.622	Earthquake off the Southwest Coast of Hokkaido
No.17	1994.12.28	Wada	Ground on the Right Bank	108.75	50.63	0.466	Earthquake far off the Coast of Sanriku
No.19	1995.01.17	Gongen	Foundation	103.67	−65.71	0.634	The South Hyogo prefecture Earthquake
No.20	1995.01.17	Hitokura	Lower Inspection Gallery	−182.13	62.86	0.345	The South Hyogo prefecture Earthquake
No.21	1995.01.17	Minoogawa	Inspection Gallery Located at bottom Part	−134.99	80.21	0.594	The South Hyogo prefecture Earthquake
No.22	1996.03.06	Miho	Observation Room of Water Leakage	−140.06	−73.63	0.526	The Eastern Yamanashi prefecture Earthquake
No.23	1997.03.16	Ameyama	Inspection Gallery	172.75	63.69	0.369	The Northeastern Aichi prefecture Earthquake
No.25	1997.03.26	Turuda	Inspection Gallery	−154.94	−71.44	0.461	The Northwestern Kagoshima prefecture Earthquakes
No.28	1997.04.03	Turuda	Inspection Gallery	−110.69	29.00	0.262	The Northwestern Kagoshima prefecture Earthquakes
No.31	1997.05.13	Turuda	Inspection Gallery	−109.00	62.13	0.570	The Northwestern Kagoshima prefecture Earthquakes
No.33	1997.08.23	Kasho	Inspection Gallery Located at bottom Part	117.61	117.46	0.999	The Western Tottori prefecture Earthquake
No.34	1997.09.02	Kasho	Inspection Gallery Located at bottom Part	−113.37	−48.18	0.425	The Western Tottori prefecture Earthquake
No.35	1997.09.04	Kasho	Inspection Gallery Located at bottom Part	344.02	−152.49	0.443	The Western Tottori prefecture Earthquake
No.36	1997.09.04	Kasho	Inspection Gallery Located at bottom Part	−244.24	−152.49	0.624	The Western Tottori prefecture Earthquake
No.37	2000.10.06	Kasho	Inspection Gallery Located at bottom Part	−528.49	485.21	0.918	The Western Tottori prefecture Earthquake
No.38	2000.10.06	Kasho	Inspection Gallery Located at bottom Part	−531.12	485.21	0.914	The Western Tottori prefecture Earthquake
No.39	2000.10.06	Sugesawa	Lower Inspection Gallery	−157.60	−108.74	0.690	The Western Tottori prefecture Earthquake
No.41	2000.10.06	Sugesawa	Ground on the Right Bank	−307.01	249.20	0.812	The Western Tottori prefecture Earthquake
No.42	2000.10.06	Takasegawa	Inspection Gallery Located at bottom Part	−106.20	70.93	0.668	The Western Tottori prefecture Earthquake
No.43	2000.10.07	Kasho	Inspection Gallery Located at bottom Part	133.82	−63.58	0.475	The Western Tottori prefecture Earthquake
No.44	2000.10.07	Kasho	Inspection Gallery Located at bottom Part	−113.25	−63.58	0.561	The Western Tottori prefecture Earthquake
No.46	2003.05.26	Tase	Dam Foundation	−232.09	117.72	0.507	Earthquake off the Coast of Miyagi Prefecture
No.47	2003.05.26	Hanayama	Ground on the Right Bank	237.20	−122.68	0.517	Earthquake off the Coast of Miyagi Prefecture
No.49	2004.10.23	Gejogawa	Inspection Gallery of the Central Lower	215.11	66.06	0.307	Mid Niigata Prefecture Earthquake
No.50	2004.10.23	Sabaishigawa	Lower Inspection Gallery	130.56	−81.35	0.623	Mid Niigata Prefecture Earthquake
No.51	2004.10.23	Shirokawa	Inspection Gallery Located at bottom Part	−161.55	−48.29	0.299	Mid Niigata Prefecture Earthquake
No.52	2004.10.23	Sabaishigawa	Lower Inspection Gallery	−231.20	224.39	0.971	Mid Niigata Prefecture Earthquake
No.53	2004.10.23	Shirokawa	Inspection Gallery Located at bottom Part	−191.73	78.80	0.411	Mid Niigata Prefecture Earthquake
No.54	2004.10.24	Shinyamamoto	Bedrocks in the Traverse Line B	609.15	182.47	0.300	Mid Niigata Prefecture Earthquake
No.55	2004.10.24	Shinyamamoto	Bedrocks in the Traverse Line B	−751.21	182.47	0.243	Mid Niigata Prefecture Earthquake
No.56	2004.10.27	Shinyamamoto	Bedrocks in the Traverse Line B	−371.82	−174.93	0.470	Mid Niigata Prefecture Earthquake
No.57	2004.10.27	Shinyamamoto	Bedrocks in the Traverse Line B	−682.55	−174.93	0.256	Mid Niigata Prefecture Earthquake
No.58	2005.08.16	Kejonuma	Dam Foundation	100.44	−39.31	0.391	Earthquake off the Coast of Miyagi Prefecture
No.59	2007.03.25	Hakkagawa	Foundation	166.78	166.78	1.000	Noto Hanto Earthquake
No.61	2007.07.16	Kakizakigawa	Foundation	−143.34	75.62	0.528	The Niigataken Chuetsu-oki Earthquake
No.62	2007.07.16	Sabaishigawa	Foundation	−129.46	84.44	0.652	The Niigataken Chuetsu-oki Earthquake
No.63	2007.07.16	Kochi	Foundation	291.50	−152.63	0.524	The Niigataken Chuetsu-oki Earthquake
No.64	2007.07.16	Tan-ne	Foundation	−157.25	86.88	0.552	The Niigataken Chuetsu-oki Earthquake
No.98	2008.6.14	Minase	Foundation	158.44	182.19	1.150	The Iwate-Miyagi Nairiku Earthquake
No.99	2008.6.14	Ishibuchi	Foundation(estimated)	−465.34	−621.39	1.335	The Iwate-Miyagi Nairiku Earthquake

※1 Maximum Horizontal Acceleration : Downstream Direction ＋, Upstream Direction －.
※2 Maximum Vertical Acceleration : Upward Direction ＋, Downward Direction －.

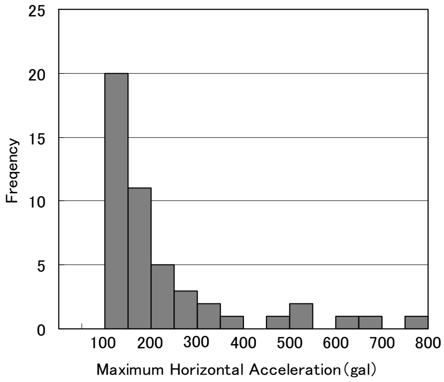


Fig.1 Distribution of Maximum Horizontal Acceleration

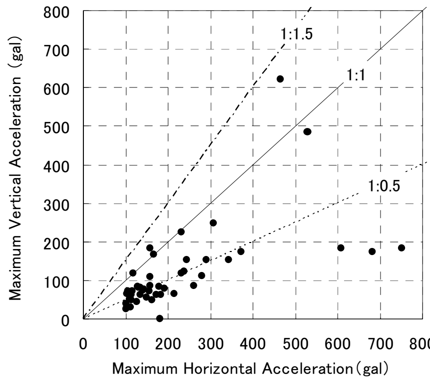
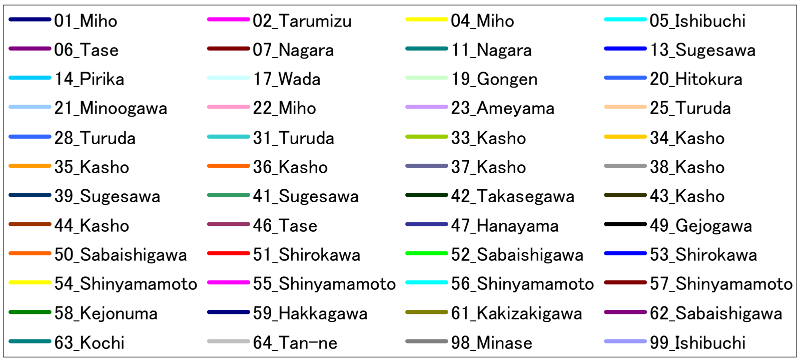


Fig.2 Ratio of Maximum Horizontal Acceleration to Maximum Vertical Acceleration



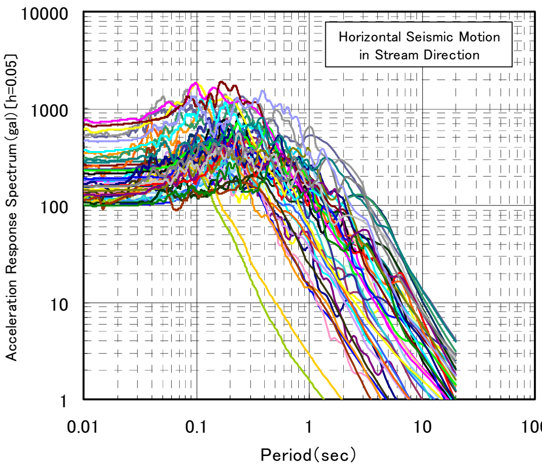


Fig.3 Acceleration Response Spectra in Horizontal Seismic Motion

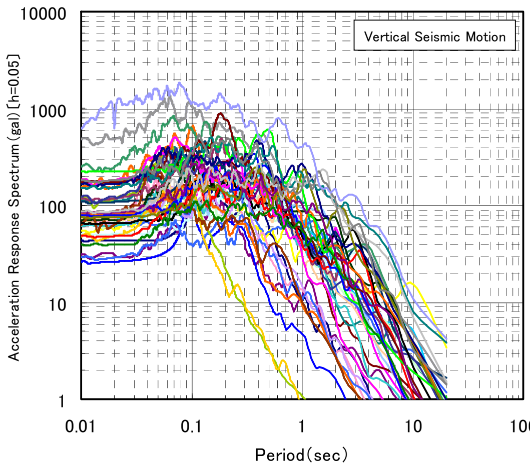


Fig.4 Acceleration Response Spectra in Vertical Seismic Motion

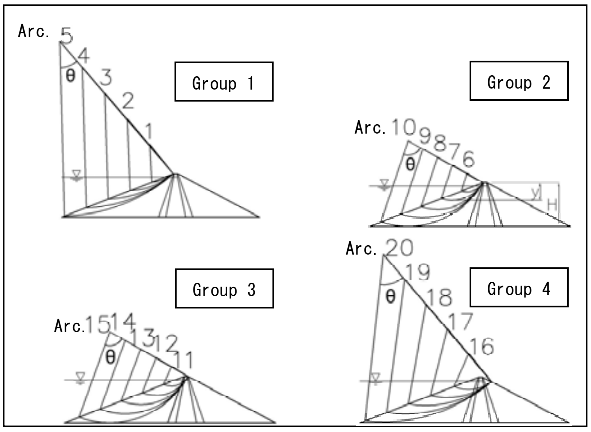


Fig.5 20 Sliding Circles for Analysis

Table 2. Analytical Models

Dam Height (m)	Crest Width			Slope Gradient		Zone Boundary Gradient		Reservoir Water Level (m)
	Total Width (m)	Core Width (m)	Filter Width (m)	Upstream	Downstream	Core	Filter	
50	5.0	3.0	1.0	1 : 2.6	1 : 1.9	1 : 0.2	1 : 0.35	46
75	7.5	4.5	1.5					69
100	10.0	6.0	2.0					92
125	12.5	7.5	2.5					115
150	15.0	9.0	3.0					138

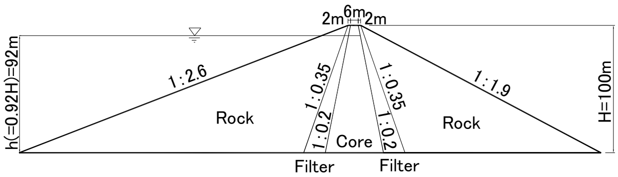


Fig.6 Analytical Model for 100m-High Dam Model

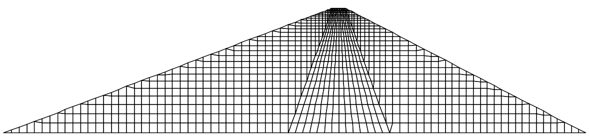


Fig.7 Finite Elements of Analytical Model

The input material properties used in the equivalent linearization method for seismic response analysis are summarized in Table 3 and Fig. 8. These material properties were set, based on the design values or test values of existing rockfill dam materials [3]. 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.

Table 3. The Input Material Properties used for the Equivalent Linearization Analysis

Material	Wet Density ρ_t(g/cm^3)	Saturated Density ρ_{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:Voio Ratio, σ_m:Mean Effective Principal Stress $\sigma_m=\{(1+2k)v\}/3$
k:Principal Stress Ratio (=0.5), v:Poisson's Ratio(=0.35)

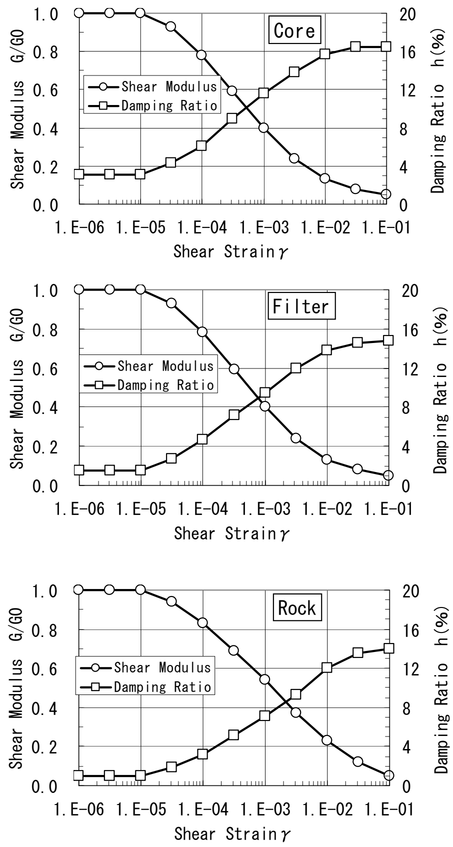


Fig.8 Dynamic Deformation Characteristics of Materials

5. RESULTS OF ANALYSIS

The results of the analysis of the model dams with heights of 50m, 75m, 100m, 125m and 150m are shown in Fig. 9. The height of circle (y) is defined as the vertical distance from the dam crest to the lowest point of a sliding circle. The height of circle (y) is nondimensionalized with the dam height (H). Fig. 9 indicates the relationship between the y/H value and the seismic force coefficient (k/k_F). We examined 20 sliding circles in Fig. 5, but no significant difference was detected in the four groups, and so the results from the analysis of Group 3, which mostly exhibited the largest seismic force coefficients in all groups, is taken as an example shown in this paper.

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

As shown in Fig. 10, the seismic force coefficients obtained in Fig. 9 were reorganized from the viewpoint of the statistical values of the mean (μ) and the standard deviation (σ). In the 50m-high model dam case, the value μ + σ of the seismic force coefficient at the crest (y/H = 0) was slightly larger than that given in the *Draft of Guidelines*. But in the other dam models, the values of μ + σ of the seismic force coefficients are smaller than those given 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 given in the *Draft of Guidelines* in the high elevation area where y/H is smaller than approximately 0.4.

On the basis of these results, the relationship between height (H) and the values μ + σ of seismic force coefficient (k/k_F) according to y/H (= 0, 0.4 and 1.0) are illustrated in Fig. 11. To illustrate the k/kF distribution, we followed the *Draft of Guidelines*, in which values of y/H (= 0, 0.4 and 1.0) are drawn in a line graph. The values of μ + σ of k/k_F correlate well at the same y/H and the values of μ + σ of k/k_F decline linearly with the increase in the height of the dam models. Therefore, the seismic force coefficient can be calculated with a function of a dam height according to y/H and suggests the possibility of the seismic force coefficient being reduced by an increase in dam height. On the basis of the correction between dam heights and seismic force coefficients obtained in this paper, the approximations of the seismic force coefficients with dam heights as parameters were formulated. These are shown in Table 4.

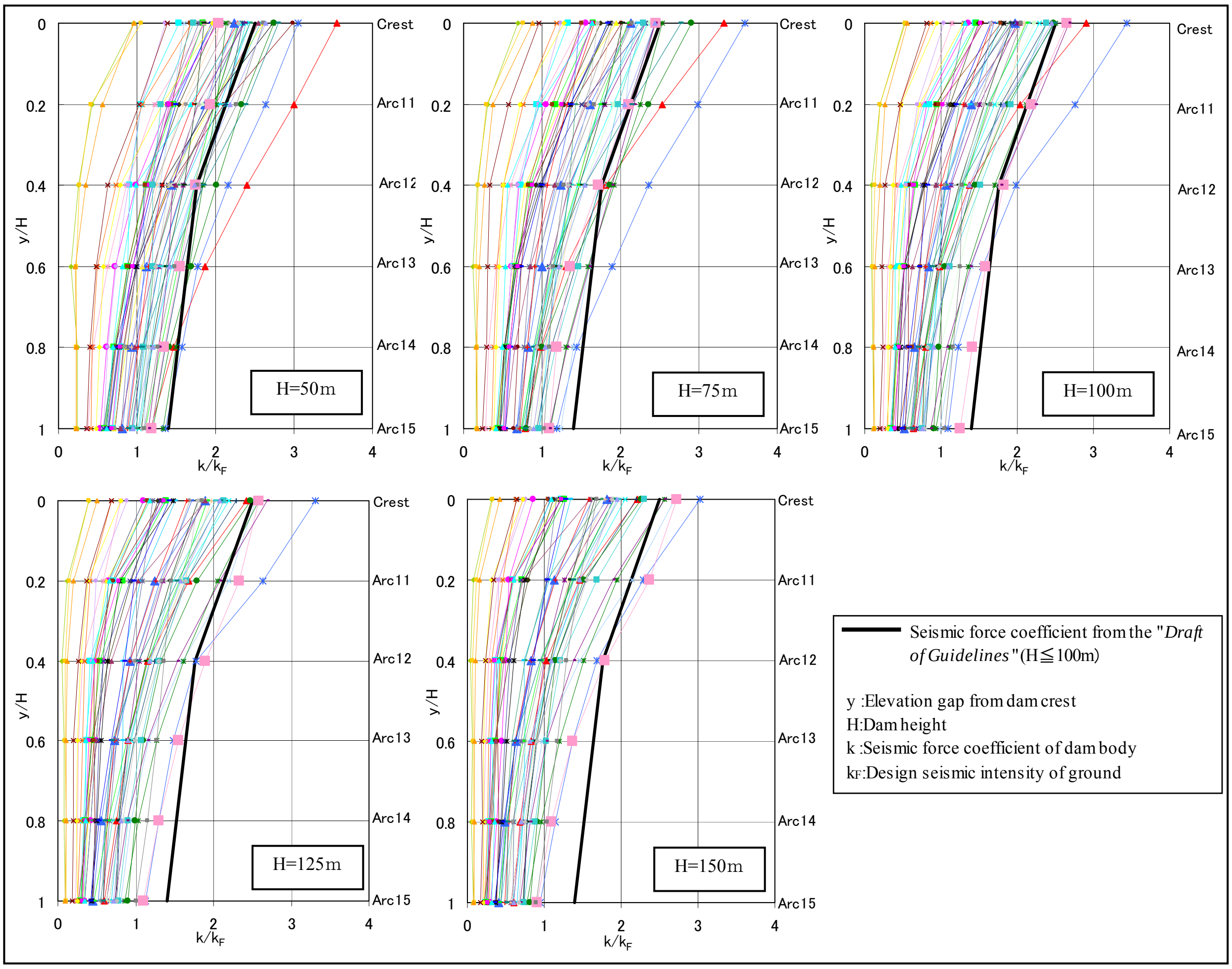


Fig.9 The Relationship between the y/H and the Seismic Force Coefficient (k/k_F)
(Results of Group 3)

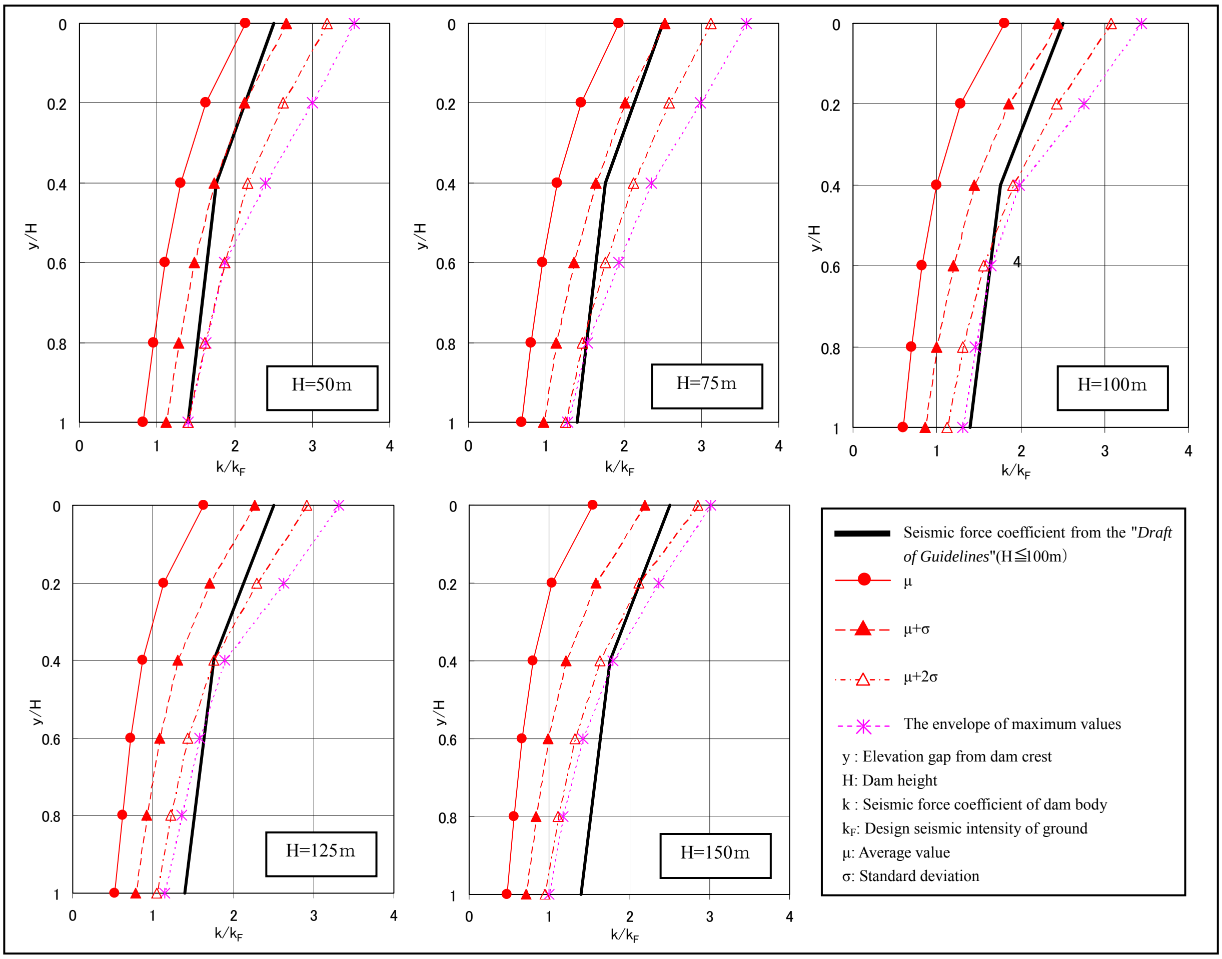


Fig.10 Statistical Analysis of Seismic Force Coefficient

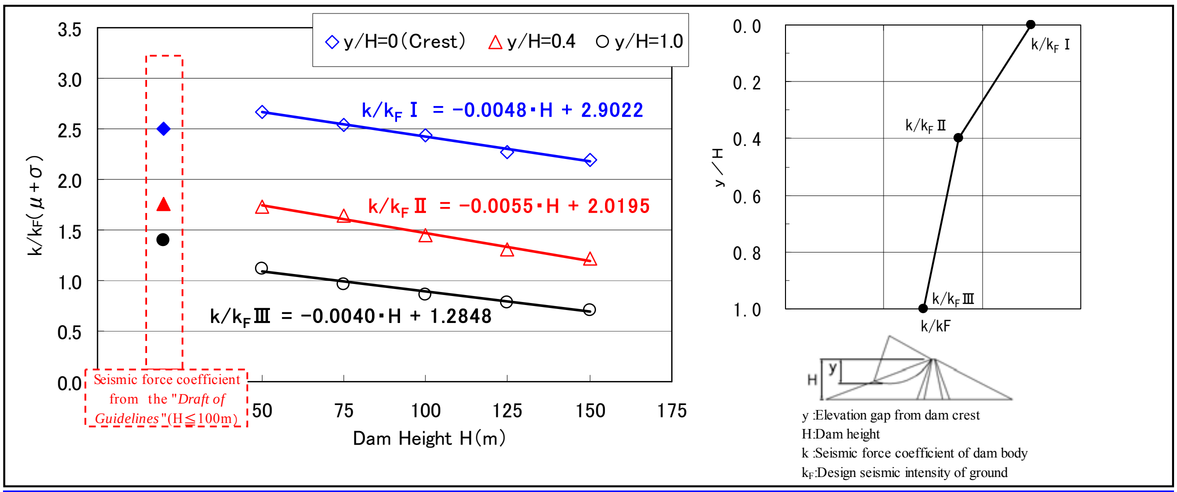


Fig.11 The Relationship between Height (H) and "μ + σ" of Seismic Force Coefficient (k/k_F)

Table 4. Approximation of Seismic Force Coefficient 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
k_F:Design seismic intensity of ground
k/k_F:Seismic force coefficient
H :Dam height (m)

6. CONCLUSIONS

In this paper, on the basis of seismic motion data recently recorded at dam sites in Japan, we examined the seismic force coefficient using the modified seismic coefficient method that has been promoted as a rational design method and a simple seicmic performance evaluation method for rockfill dams. As a result, we obtained the following findings.

(1) Recent seismic motion records were used to calculate seismic force coefficients for rockfill dam models with heights of 50m, 75m, 100m, 125m and 150m. The results of calculations were treated statistically and the values of $\mu + \sigma$ of the seismic force coefficients were found to be almost equal to or lower than that given in the *Draft of Guidelines*.
(2) High correlations appeared between the seismic force coefficients and the dam height in the range of dam height between 50m and 150m. It was also observed that the seismic force coefficient declines linearly with an increase in dam height. Based on these results, we formulated an approximation formula for the seismic force coefficient as a function of dam height. The proposed formula can be applied to those dams taller than 100m up to 150m described in this paper.

In order to establish and propose rational design methods for rockfill dams in accordance with the modified seismic coefficient method, the authors will make a further study on the seismic force coefficient by taking the design strength of rockfill dam materials into consideration [5].

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