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EFFECTS OF NEW MODIFIED SEISMIC FORCE COEFFICIENTS ON MINIMUM SLIDING SAFETY FACTORS OF EXISTING ROCKFILL DAMS (*)

Hiroyuki SATO
Senior Researcher, Dam and Appurtenant Structures Research Team, Hydraulic Engineering Research Group, Public Works Research Institute (PWRI)

Katsushi AOI
West Japan Engineering Consultants Inc.

Hiroki SAKAMOTO
Japan Water Agency

Takashi SASAKI
Dr. Eng., National Institute for Land and Infrastructure Management (NILIM)

Yoshikazu YAMAGUCHI
Dr. Eng., Japan Dam Engineering Center

JAPAN

1. INTRODUCTION

Recently in Japan, large-scale earthquakes have frequently occurred, so seismic performance evaluation of dams, which store huge amount of water in their reservoirs, has become more important. Because there are more than 1,500 existing embankment dams in Japan, conducting of seismic performance evaluations by the dynamic analysis is difficult for all embankment dams in a short period and with the limited budget. In order to determine the priority of detailed

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(*) *Effets de coefficients de force sismique modifiés sur les facteurs de sécurité de glissement minimaux des barrages existants en enrochement.*

seismic performance evaluations for existing embankment dams, it is necessary to study 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 [1], as both a seismic performance evaluation method for existing embankment dams and a future design method for new embankment dams. In the Draft of Guidelines, a modified seismic coefficient method was proposed as the seismic performance evaluation method for embankment dams in Japan with the height less than 100 m, in which the vertical distribution of seismic force was determined with taking the seismic response of a dam body into account. The modified seismic coefficient method in the Draft of Guidelines uses seismic force coefficients that changes 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 that the seismic response of the dam body is not uniform in the vertical direction during earthquakes.

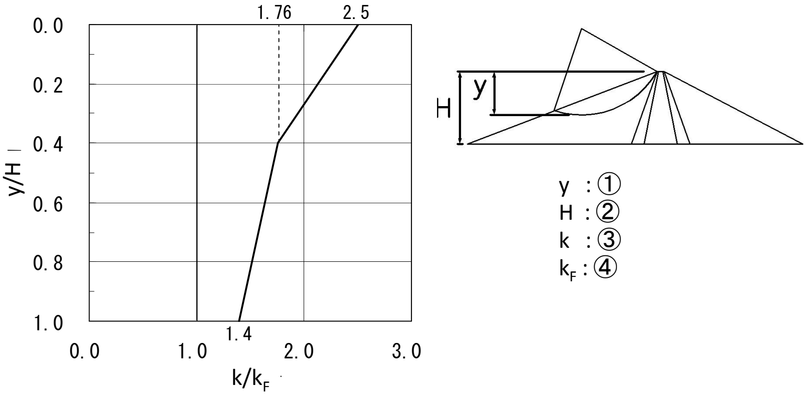

Fig.1

Seismic force coefficient in the Draft of Guidelines in 1991 [1]

Coefficients de force sismiques dans le projet de lignes directrices en 1991 [1]

1	Elevation gap from dam crest	*1*	*Écart d’élévation à la crête du barrage*
2	Dam height	*2*	*Hauteur du barrage*
3	Seismic force coefficient	*3*	*Coefficient de force sismique*
4	Ground seismic coefficient	*4*	*Coefficient sismique au sol*

The seismic force coefficients in the Draft of Guidelines are formulated based on the examination and analysis using eight seismic motions recorded at dam sites during actual relatively large earthquakes, and it is same regardless of dam height and slope gradients. 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 2011, we examine the seismic force coefficients corresponding to the dam height that can also be applied to embankment dams with the height greater than 100 m. Based on the results, we propose a revised seismic force coefficient which can be utilized in design method of new dams and simple seismic performance evaluation of existing dams as shown in Fig. 2 [2].

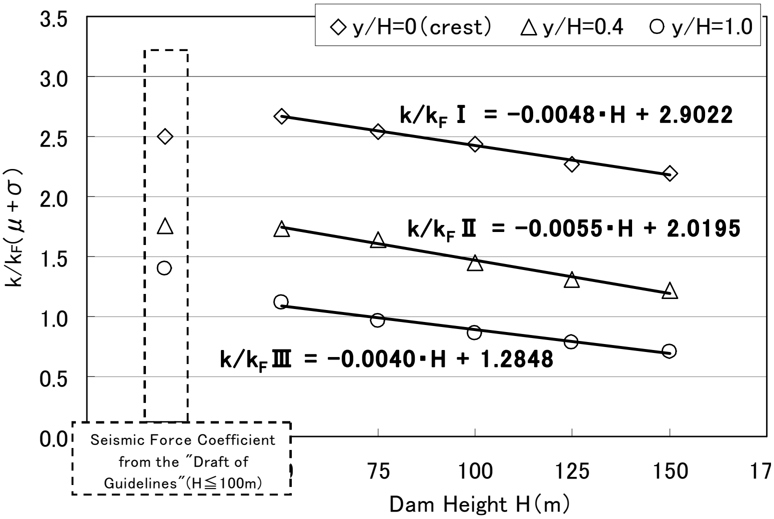

Fig.2

The relationship between dam height and revised seismic force coefficients [2]

Relation entre la hauteur du barrage et les nouveaux coefficients de force sismique [2]

This paper reports the results of stability analysis based on the modified seismic coefficient method which uses both the revised seismic force coefficients and the seismic force coefficients in the Draft of the Guidelines in 1991. First, we introduce the summary of the method how to decide the revised seismic force coefficients. Next, we describe the conditions and the results of stability analysis and investigate the effects of the differences of the seismic force coefficients on minimum safety factors against sliding of existing rockfill dams.

2. SUMMARY OF CONDITIONS AND RESULTS OF REVISED SEISMIC FORCE COEFFICIENTS

We have already reported the detail of the revised seismic force coefficients in ICOLD annual meeting in 2013 [2]. We briefly introduce how we decided the revised seismic force coefficients.

As for the analysis method to investigate seismic force coefficients, seismic response analysis based on the complex response method by the equivalent linearization is conducted for a rockfill dam model shown in Fig. 3 to determine the time history of the response accelerations of the dam body against input seismic motions. Then, the time histories of the average response accelerations of the sliding mass for each of 20 upstream slip circles and 20 downstream slip circles as shown in Fig. 4 are calculated, and the maximum value out of the time history of the average response accelerations is divided by the maximum acceleration of the input seismic motion to determine seismic force coefficient (k/k_F). Here, k is seismic force coefficients of dam body and k_F is ground seismic coefficient. More information is in the paper [2].

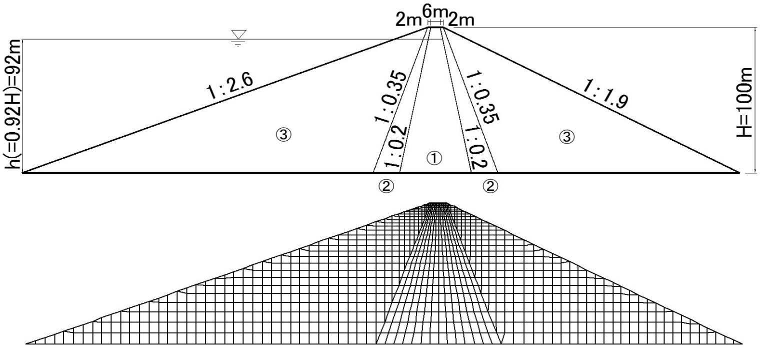

Fig. 3

Analytical model and finite elements for seismic response analysis [2]

Modèle analytique et éléments finis pour l'analyse de la réponse sismique [2]

1	Core zone	*1*	*Zone centrale*
2	Filter zone	*2*	*Zone de filtre*
3	Rock zone	*3*	*Zone d'enrochement*

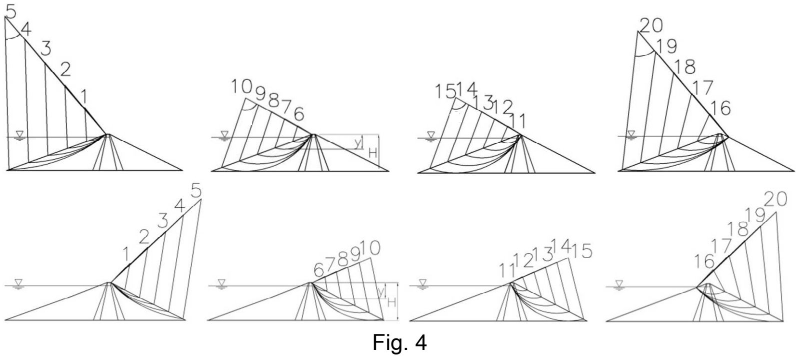

Fig. 4

Circles to calculate seismic force coefficient [2]

Cercles pour calculer le coefficient de force sismique [2]

Among 1,883 seismic motions recorded in bedrock or inspection galleries at dam sites from 1966 to 2008, 48 seismic motions are selected as the input seismic motions with a maximum horizontal acceleration exceeding 0.1 m/s^2. 7 seismic motions recorded during the 2011 Tohoku Earthquake are added to the input motions. Thus, a total of 55 seismic motions are used for input motions as shown in Table 1. For the seismic response analysis, seismic motion records are normalized to make the maximum acceleration of the horizontal seismic motions of the selected 55 seismic motions become 0.2 m/s^2. Vertical seismic motions are also normalized by multiplying the same ratio for the horizontal seismic motions. From the results of seismic force coefficients, k/k_F, obtained by the seismic response analysis, the statistical values of the average (μ) plus standard deviation (μ + σ) of k/k_F are selected as the revised seismic force coefficients for each slip circle. As a result, we proposed the revised seismic force coefficients for the modified seismic coefficient method as shown in Fig. 2.

3. STABILITY ANALYSIS USING REVISED SEISMIC FORCE COEFFICIENTS

3.1. Outline of Analytical Procedure and Studied Dams

Stability analysis is conducted according to the Draft of Guidelines. Table 2 shows fundamental information of studied dams. 12 existing rockfill dams are selected to investigate the influences of the revised seismic force coefficients on minimum safety factors by stability analysis. Dam type of all 12 studied dams is a rockfill dam with a center core. Water level of upstream reservoir is set to the normal water level of each existing dam for stability analysis.

As shown in Table 2, ground seismic coefficients, k_F, are 0.18, 0.16 or 0.13 for strong earthquake zone, moderate earthquake zone and minor earthquake zone, respectively. Determination of the ground seismic intensity zone is shown in Fig. 5 in the Draft of Guidelines.

Physical properties for stability analysis are also shown in Table 3. Shear strength of core materials is evaluated using Eq. [1] and shear strengths of filter and rock materials using Eq. [2], basically.

$$\tau = c + \sigma \tan\phi \qquad [1]$$

$$\tau = A{\sigma_n}^b \qquad [2]$$

In Eq. [1], τ is shear strength, c is cohesion, σ is confining pressure, ϕ is internal friction angle and σ_n is normal stress. In Eq. [2], A and b are parameters determined by triaxial strength tests.

5 dams, from Dam H to Dam L, have been calculated the minimum safety factors by the modified seismic coefficient method according to the Draft of Guidelines in the design stage and physical properties in this paper used the same values.

Table 1
Summary of input seismic motions

No.	Date	Name of dam	Type	Height (m)	Horizontal maximum acceleration (gal) *1	Vertical maximum acceleration (gal) *2	Name of earthquake
No.1	1976.06.16	Miho	R	95.0	-125.57	43.17	1976 Yamanashi
No.2	1978.06.12	Tarumizu	R	43.0	178.43	83.88	1978 Miyagi-oki
No.3	1983.08.08	Miho	R	95.0	-149.37	-54.60	1983 Kanto-chubu
No.4	1986.06.27	Ishibuchi	R	53.0	-180.30	No record	1986 Iwate
No.5	1987.01.09	Tasa	G	81.5	103.40	30.97	1987 Iwate
No.6	1987.12.17	Nagara	E	52.0	-262.00	-86.00	1987 Chiba Toho-oki
No.7	1987.12.17	Nagara	E	52.0	-281.00	111.00	1987 Chiba Toho-oki
No.8	1989.10.27	Sugesawa	G	73.5	-101.36	-26.28	1989 Tottori
No.9	1993.07.12	Pirika	GF	40.0	116.69	72.53	1993 Hokkaido Nansei
No.10	1994.12.28	Wada	F	44.0	108.75	50.63	1994 Sanriku Haruka-oki
No.11	1995.01.17	Gongen	R	32.6	103.67	-65.71	1995 Kobe
No.12	1995.01.17	Hitokura	G	75.0	-182.13	62.86	1995 Kobe
No.13	1995.01.17	Minoo	R	47.0	-134.99	80.21	1995 Kobe
No.14	1996.03.06	Miho	R	95.0	-140.06	-73.63	1996 Yamanashi
No.15	1997.03.16	Ameyama	G	21.5	172.75	63.69	1997 Aichi
No.16	1997.03.26	Tsuruda	G	117.5	-154.94	-71.44	1997 Kagoshima
No.17	1997.04.03	Tsuruda	G	117.5	-110.69	29.00	1997 Kagoshima
No.18	1997.05.13	Tsuruda	G	117.5	-109.00	62.13	1997 Kagoshima
No.19	1997.08.23	Kasho	G	46.4	117.61	117.46	2000 Tottori
No.20	1997.09.02	Kasho	G	46.4	-113.37	-48.18	2000 Tottori
No.21	1997.09.04	Kasho	G	46.4	344.02	-152.49	2000 Tottori
No.22	1997.09.04	Kasho	G	46.4	-244.24	-152.49	2000 Tottori
No.23	2000.10.06	Kasho	G	46.4	-528.49	485.21	2000 Tottori
No.24	2000.10.06	Kasho	G	46.4	-531.12	485.21	2000 Tottori
No.25	2000.10.06	Sugesawa	G	73.5	-157.60	-108.74	2000 Tottori
No.26	2000.10.06	Sugesawa	G	73.5	-307.01	249.20	2000 Tottori
No.27	2000.10.06	Takasegawa	G	67.0	-106.20	70.93	2000 Tottori
No.28	2000.10.07	Kasho	G	46.4	133.82	-63.58	2000 Tottori
No.29	2000.10.07	Kasho	G	46.4	-113.25	-63.58	2000 Tottori
No.30	2003.05.26	Tase	G	81.5	-232.09	117.72	2003 Miyagi-oki
No.31	2003.05.26	Hanayama	G	48.5	237.20	-122.68	2003 Miyagi-oki
No.32	2004.10.23	Gejyogawa	G	31.0	215.11	66.06	2004 Mid Niigata
No.33	2004.10.23	Sabaishigawa	G	37.0	130.56	-81.35	2004 Mid Niigata
No.34	2004.10.23	Shirokawa	G	21.7	-161.55	-48.29	2004 Mid Niigata
No.35	2004.10.23	Sabaishigawa	G	37.0	-231.20	224.39	2004 Mid Niigata
No.36	2004.10.23	Shirokawa	G	21.7	-191.73	78.80	2004 Mid Niigata
No.37	2004.10.24	Shinyamamoto	R	42.4	609.15	182.47	2004 Mid Niigata
No.38	2004.10.24	Shinyamamoto	R	42.4	-751.21	182.47	2004 Mid Niigata
No.39	2004.10.27	Shinyamamoto	R	42.4	-371.82	-174.93	2004 Mid Niigata
No.40	2004.10.27	Shinyamamoto	R	42.4	-682.55	-174.93	2004 Mid Niigata
No.41	2005.08.16	Kejyonuma	E	24.0	100.44	-39.31	2005 Miyagi-oki
No.42	2007.03.25	Hakkagawa	G	52.0	166.78	166.78	2007 Noto
No.43	2007.07.16	Kakizakigawa	R	54.0	-143.34	75.62	2007 Niigata Chuetsu-oki
No.44	2007.07.16	Sabaishigawa	G	37.0	-129.46	84.44	2007 Niigata Chuetsu-oki
No.45	2007.07.16	Kouchi	G	55.0	291.50	-152.63	2007 Niigata Chuetsu-oki
No.46	2007.07.16	Tanne	G	54.0	-157.25	86.88	2007 Niigata Chuetsu-oki
No.47	2008.6.14	Minase	R	66.5	158.44	182.19	2008 Iwate-Miyagi
No.48	2008.6.14	Ishibuchi	R	53.0	-465.34	-621.39	2008 Iwate-Miyagi
No.49	2011.03.11	Kamafusa	G	45.5	125.42	91.99	2011 Tohoku
No.50	2011.03.11	Miharu	G	65.0	194.80	146.90	2011 Tohoku
No.51	2011.03.11	Sounoseki	GF	23.5	290.73	145.62	2011 Tohoku
No.52	2011.03.11	Minamikawa	G	46.0	270.85	145.40	2011 Tohoku
No.53	2011.03.11	Takashiba	G	59.5	151.03	107.44	2011 Tohoku
No.54	2011.03.11	Shitoki	R	83.5	109.81	100.94	2011 Tohoku
No.55	2011.03.11	Aratozawa	R	74.4	102.25	65.34	2011 Tohoku

**1 Positive values mean to the downstream direction.*

**2 Positive values mean to the upper direction*

Table 2
Fundamental information of 12 existing dams

Name of dam	Height (m)	Completion year	Upstream slope gradient	Downstream slope gradient	Zone of seismic intensity	Ground seismic coefficient in the Draft of Guidelines
A	91.7	1974	2.25	2.0	Minor	0.13
B	85	1975	2.65	1.9	Moderate	0.16
C	153	1979	2.6	1.85	Moderate	0.16
D	69	1981	2.5	2.3	Moderate	0.16
E	112	1990	2.9	2.1	Moderate	0.16
F	90	1991	2.6	2.0	Strong	0.18
G	119.5	1993	2.4	1.9	Moderate	0.16
H	66.5	2004	2.7	2.2	Minor	0.13
I	105	2006	2.65	2.0	Strong	0.18
J	41.2	2009	2.4	1.8	Moderate	0.16
K	84.9	2012	2.8	2.1	Moderate	0.16
L	132	2013	2.7	2.0	Strong	0.18

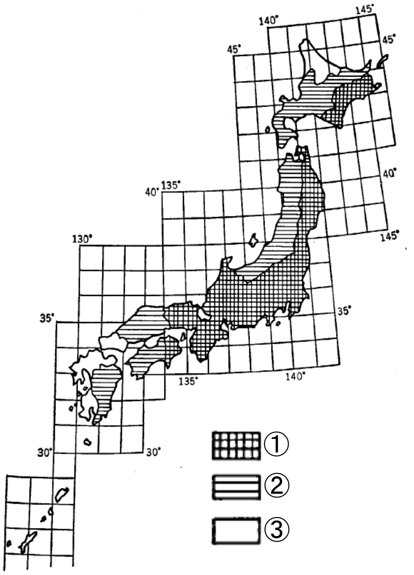

Fig. 5
Area classification for ground seismic coefficient [1]
Classification de zone pour sol coefficient sismiques [1]

1	Strong seismic zone	*1*	*Zone sismique forte*
2	Moderate seismic zone	*2*	*Zone sismique modérée*
3	Minor seismic zone	*3*	*Zone sismique mineure*

Because the completion year is older than the implementation of the Draft of Guidelines in 1991, 7 dams, from Dam A to Dam G, have not been investigated stability according to the Draft of Guidelines. We set physical properties of 7dams from the reports which evaluate seismic performances during large earthquakes according to the "Guidelines for Seismic Performance Evaluation of Dams against Large Earthquake (Draft)" [3], especially coefficients of A and b in Eq. [2].

Standard cross sections of 12 existing dams are used for the stability analysis. Standard cross sections are shown from Figs. 6 to 17. Only dam body is considered for stability analysis.

As shown in Fig. 2, the seismic force coefficients in the Draft of Guidelines have nothing to do with the dam height. However, our proposed revised seismic force coefficients have relationships with the dam height to consider the nonlinear behavior of higher rockfill dams during earthquakes. Seismic force coefficients of 12 studied dams are shown in Figs 18 and 19. If dam height is relatively small, for example Dam J, our proposed revised seismic force coefficient is similar to that of the Draft of Guidelines. If dam height is relatively large, for example Dam C with a height of 153 m, our proposed revised seismic force coefficient tends to be smaller than that of the Draft of Guidelines.

3.2. ANALYTICAL RESULTS

Table 4 shows minimum safety factors by stability analysis according to the conditions in Chapter 3.1. From Table 4, minimum safety factors of the 12 dams using the revised seismic force coefficients show relatively larger than those according to the Draft of Guidelines. This tendency is thought to come from the differences of the distributions of two seismic force coefficients in Figs. 18 and 19.

Fig. 20 shows the relationship with the dam height and the minimum safety factors of the 12 dams in Table 4. Fig. 20 shows the minimum safety factors using the revised seismic force coefficient tend to be larger. All analytical results show the minimum safety factors are larger than 1.0, and most results also show those are larger than 1.2, the design required minimum safety factor against sliding in Japan.

Fig. 21 shows the relationship with the dam height and the differences of minimum safety factors of the 12 dams in Table 4. Fig. 21 shows the differences of minimum safety factors tend to be larger when dam heights become larger.

As described above, the Draft of Guidelines shows the seismic force coefficient which is basically applicable to embankment dams with heights of less than 100 m and indicates that seismic force may be able to reduce from the value of the Draft of Guidelines if dam height is greater than 100 m because of the nonlinear behavior of higher embankment dams during earthquakes. Our proposed seismic force coefficient meets the indication in the Draft of Guidelines. We think we proposed the better seismic force coefficient which included the nonlinear behavior of higher embankment dams during earthquakes.

Table 3
Physical properties of 12 existing dams

Name of dam	Material	Saturated unit weight (kN/m^3)	Wet unit weight (kN/m^3)	c, Cohesion (kPa)	ϕ, Internal friction angle	A, in Eq [2] (kPa)	b, in Eq [2]
A	core	19.53	18.89	5.88	33.9	–	–
	filter	22.60	20.80	–	–	2.146	0.870
	transition	23.58	21.87	–	–	6.855	0.738
	rock	21.47	18.47	–	–	7.768	0.689
B	core	22.95	22.95	–	–	3.112	0.801
	filter	23.44	22.06	0.00	33.0	–	–
	riverbed gravel a	21.57	18.63	1.57	38.0	–	–
	riverbed gravel b	21.57	18.63	1.57	40.0	–	–
	rock	23.14	21.48	–	–	3.112	0.801
C	core	22.50	22.50	12.50	36.5	–	–
	filter	22.90	21.80	–	–	3.844	0.817
	transition	22.70	21.10	–	–	4.353	0.805
	inner rock	22.80	21.20	–	–	5.049	0.777
	outer rock	22.30	20.80	–	–	4.711	0.792
D	core	22.41	22.27	70.00	36.0	–	–
	filter	22.43	21.36	–	–	4.999	0.791
	rock	21.09	19.04	–	–	4.071	0.779
E	core	20.01	19.72	0.00	25.0	–	–
	coarse filter	23.74	22.56	–	–	1.745	0.918
	fine filter	23.15	22.66	–	–	1.745	0.918
	rock	23.35	21.68	–	–	4.245	0.788
F	core	21.88	21.78	0.00	35.0	–	–
	filter	21.97	20.90	–	–	1.650	0.893
	rock I	21.09	19.03	–	–	4.554	0.794
	rock II	20.90	19.33	–	–	4.554	0.794
G	core	22.56	22.46	0.00	28.0	–	–
	filter	23.25	21.68	–	–	2.878	0.831
	rock I, rock II	23.25	20.31	–	–	3.252	0.836
H	core	23.45	20.90	0.00	30.0	–	–
	filter	21.09	20.31	–	–	2.401	0.848
	inner rock	23.45	20.90	–	–	2.401	0.848
	outer rock	23.45	20.90	–	–	2.401	0.848
I	core	20.80	20.11	0.00	33.0	–	–
	fine filter	22.07	20.40	–	–	3.686	0.860
	coarse filter	21.97	20.31	–	–	2.394	0.860
	rock II-1	21.68	19.62	–	–	2.573	0.830
	rock II(inner)	21.58	19.42	–	–	3.118	0.830
	rock I(outer)	21.68	19.42	–	–	3.955	0.790
J	core	21.09	20.80	0.00	37.4	–	–
	filter	23.35	22.96	–	–	3.137	0.825
	transition	21.78	20.99	–	–	1.068	0.925
	rock	22.17	20.40	–	–	3.137	0.825
K	core	20.11	19.62	0.00	33.0	–	–
	filter	20.60	18.15	–	–	1.976	0.880
	outer rock(upstream)	21.58	19.62	–	–	3.264	0.826
	inner rock(upstream)	19.62	19.13	–	–	2.161	0.868
	outer rock(downstream)	21.58	19.62	–	–	3.264	0.826
	inner rock(downstream)	19.13	18.15	–	–	1.637	0.901
	inner rock II(downstream)	19.13	18.15	–	–	1.637	0.901
L	core	20.60	20.31	0.00	36.0	–	–
	filter	21.09	20.40	–	–	2.602	0.902
	inner rock	20.21	19.13	–	–	2.029	0.889
	outer rock	20.70	19.72	–	–	3.227	0.827

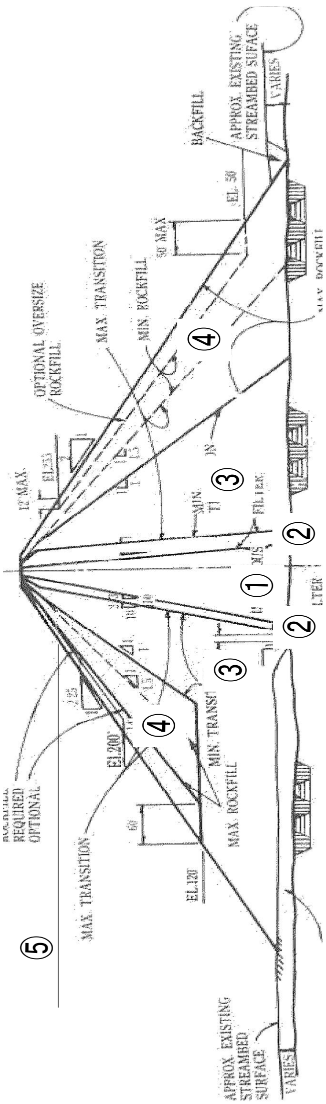

Fig. 6
Standard cross section of dam A
Coupe standard du barrage A

1 Core zone
2 Filter zone
3 Inner rock zone
4 Inner rock zone II
5 Outer rock zone
6 Normal water level

1 Zone centrale
2 Zone de filtre
3 Zone d’enrochement intérieure
4 Zone d’enrochement intérieure II
5 Zone d’enrochement externe
6 Niveau d'eau normal

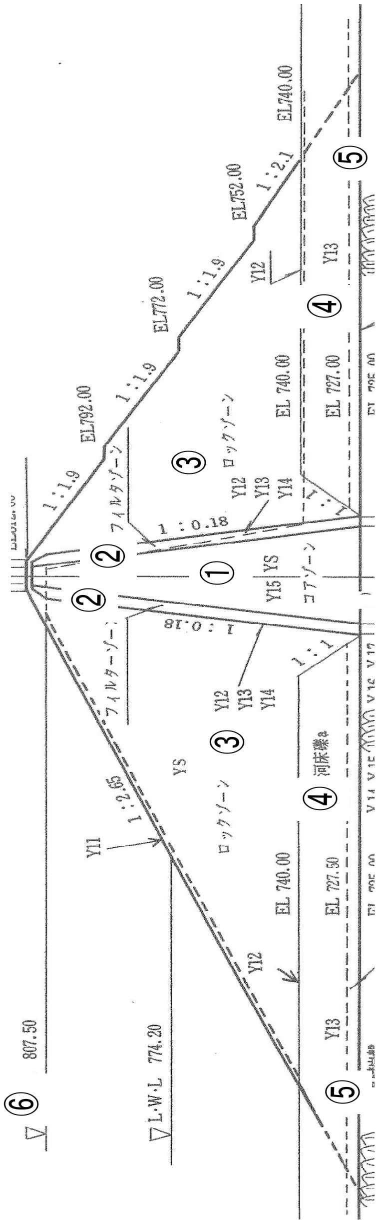

Fig. 7
Standard cross section of dam B
Coupe standard du barrage B

1	Core zone
2	Filter zone
3	Rock zone
4	Riberbed gravel a
5	Riverbed gravel b
6	Normal water level

1	*Zone centrale*
2	*Zone de filtre*
3	*Zone d’enrochement*
4	*Gravier lit rivière a*
5	*Gravier lit rivière b*
6	*Niveau d'eau normal*

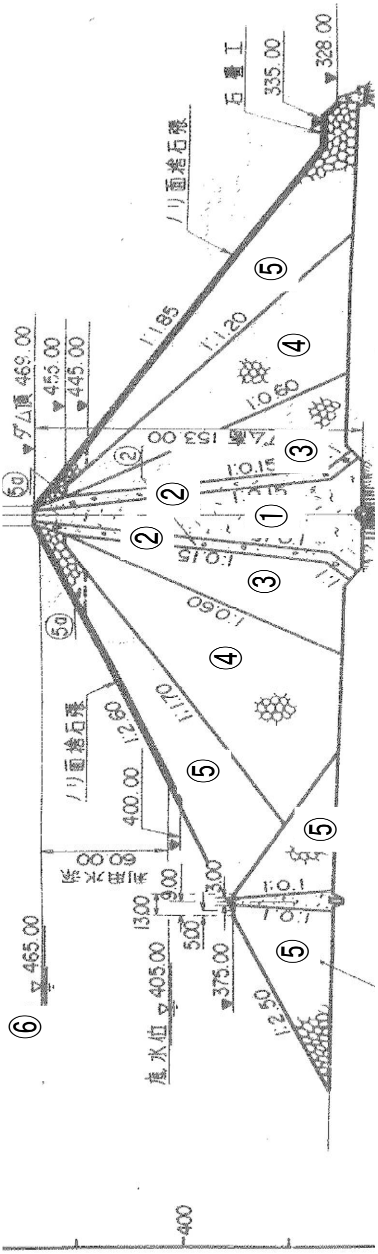

Fig. 8
Standard cross section of dam C
Coupe standard du barrage C

1 Core zone
2 Filter zone
3 Inner rock zone
4 Inner rock zone II
5 Outer rock zone
6 Normal water level

1 Zone centrale
2 Zone de filtre
3 Zone d'enrochement intérieure
4 Zone d'enrochement intérieure II
5 Zone d'enrochement externe
6 Niveau d'eau normal

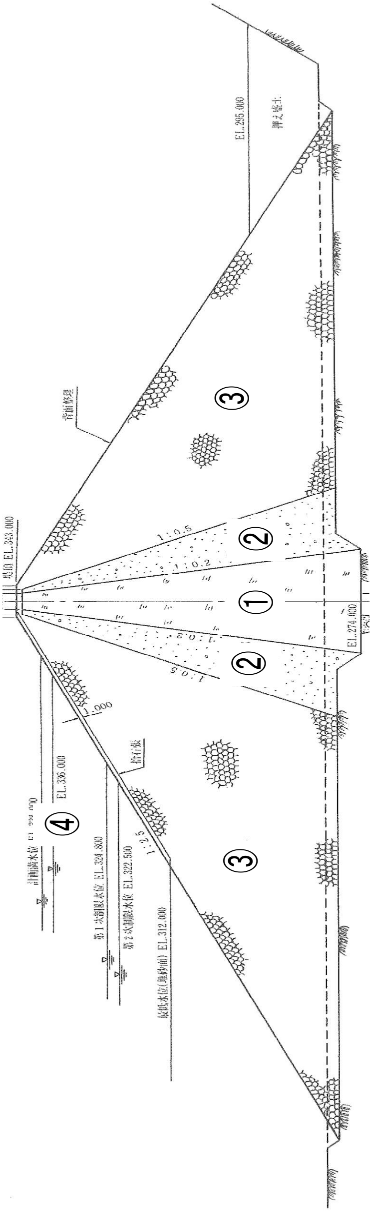

Fig. 9
Standard cross section of dam D
Coupe standard du barrage D

1	Core zone
2	Filter zone
3	Outer rock zone
4	Normal water level

1	*Zone centrale*
2	*Zone de filtre*
3	*Zone d'enrochement externe*
4	*Niveau d'eau normal*

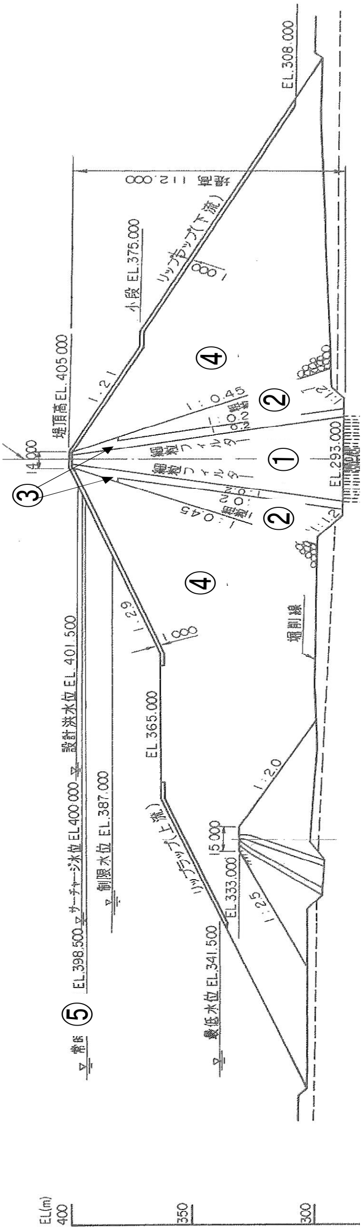

Fig. 10
Standard cross section of dam E
Coupe standard du barrage E

1	Core zone
2	Coarse filter zone
3	Fine filter zone
4	Rock zone
5	Normal water level

1	*Zone centrale*
2	*Zone de filtre grossier*
3	*Zone de filtre fin*
4	*Zone d’enrochement*
5	*Niveau d'eau normal*

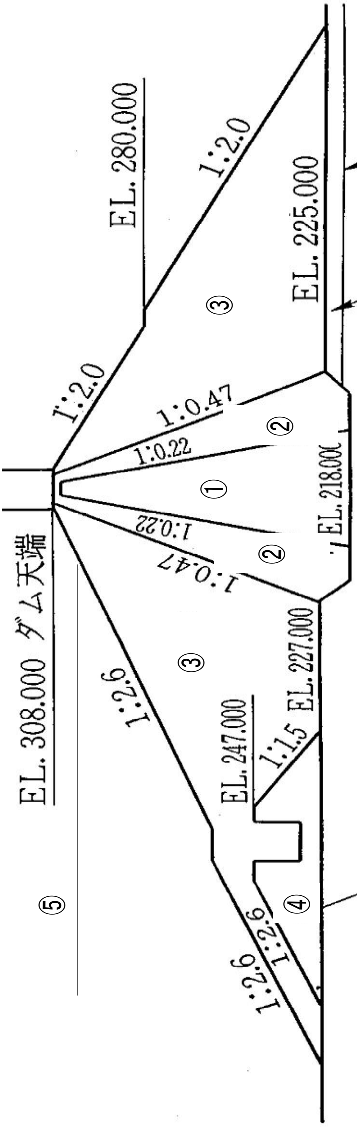

Fig. 11
Standard cross section of dam F
Coupe standard du barrage F

1	Core zone
2	Filter zone
3	Rock zone I
4	Rock zone II
5	Normal water level

1	*Zone centrale*
2	*Zone de filtre*
3	*Zone d’enrochement I*
4	*Zone d’enrochement II*
5	*Niveau d'eau normal*

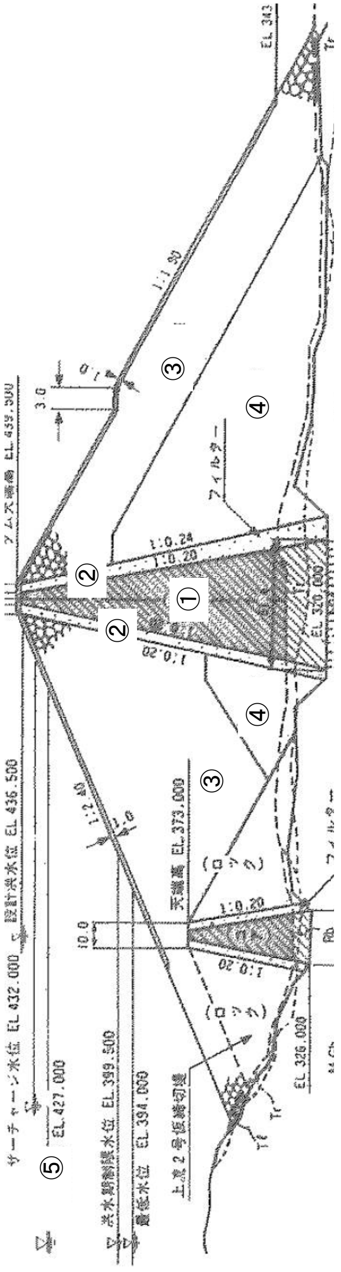

Fig. 12
Standard cross section of dam G
Coupe standard du barrage G

1	Core zone
2	Filter zone
3	Rock zone I
4	Rock zone II
5	Normal water level

1	*Zone centrale*
2	*Zone de filtre*
3	*Zone d’enrochement I*
4	*Zone d’enrochement II*
5	*Niveau d'eau normal*

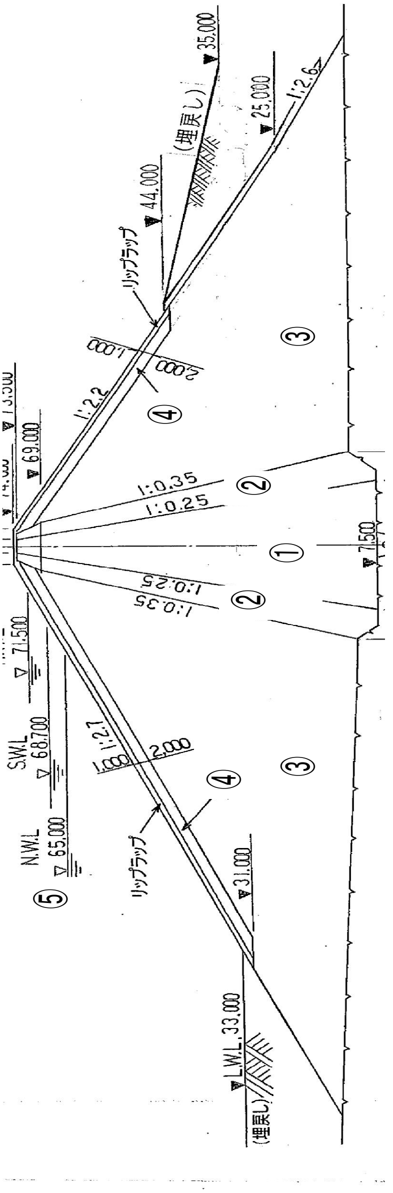

Fig. 13
Standard cross section of dam H
Coupe standard du barrage H

1 Core zone
2 Filter zone
3 Inner rock zone
4 Outer Rock zone
5 Normal water level

1 Zone centrale
2 Zone de filtre
3 Zone d'enrochement intérieure
4 Zone d'enrochement extérieure
5 Niveau d'eau normal

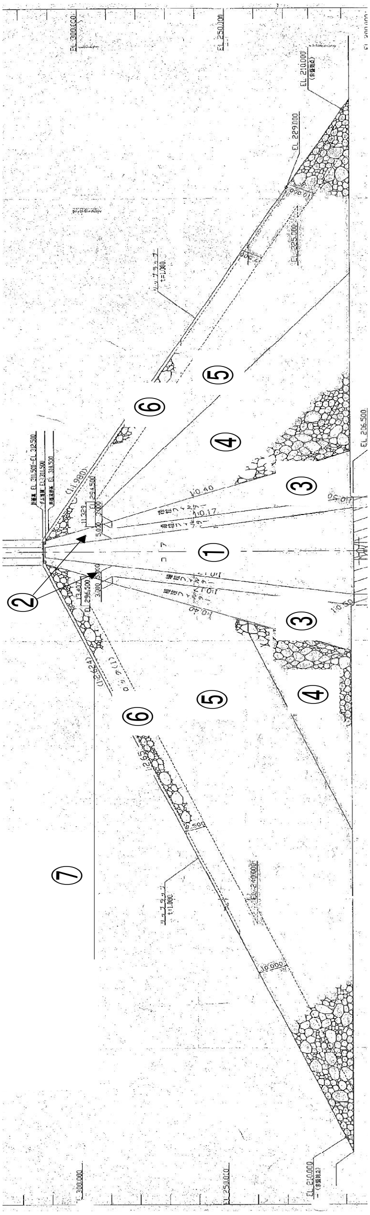

Fig. 14
Standard cross section of dam I
Coupe standard du barrage I

1 Core zone
2 Fine filter zone
3 Corse filter zone
4 Rock zone II
5 Rock zone II(inner)
6 Rock zone I
7 Normal water level

1 Zone centrale
2 Zone de filtration fine
3 Zone de filtre grossier
4 Zone d’enrochement II
5 Zone d’enrochement II (intérieur)
6 Zone d’enrochement I
7 Niveau d'eau normal

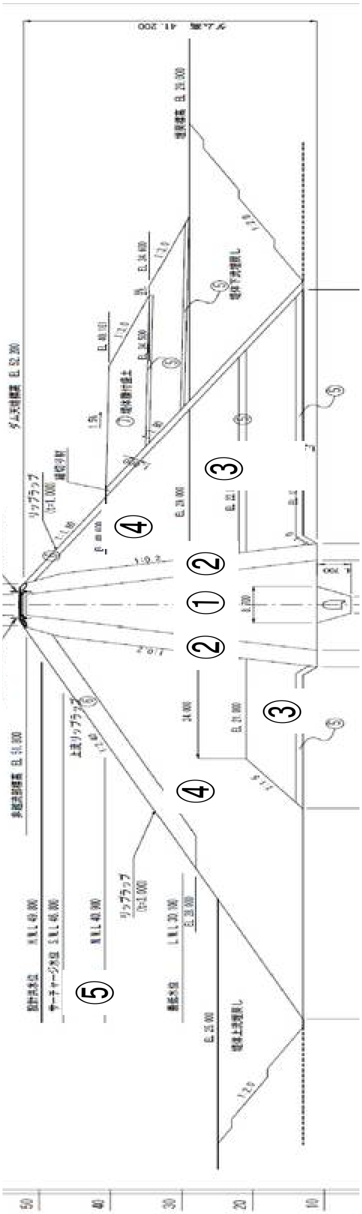

Fig. 15
Standard cross section of dam J
Coupe standard du barrage J

1 Core zone
2 Filter zone
3 Rock zone I
4 Rock zone II
5 Normal water level

1 Zone centrale
2 Zone de filtre
3 Zone d’enrochement I
4 Zone d’enrochement II
5 Niveau d'eau normal

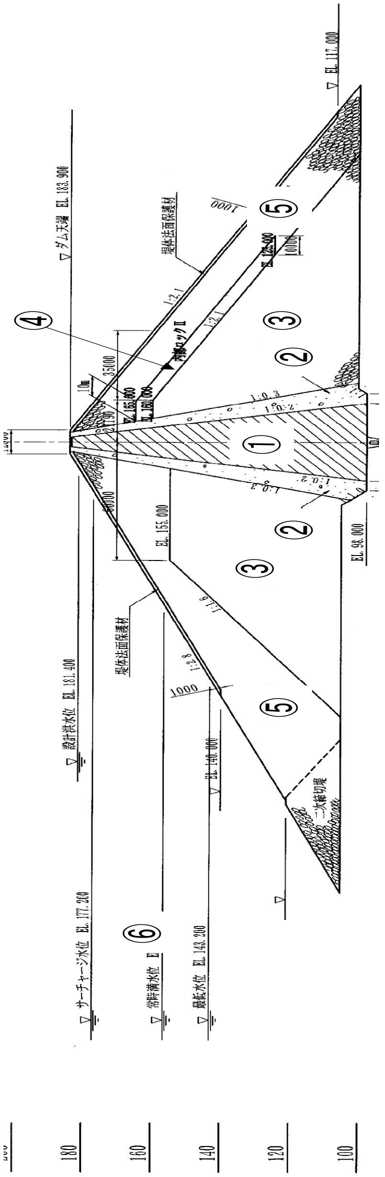

Fig. 16
Standard cross section of dam K
Coupe standard du barrage K

1	Core zone
2	Filter zone
3	Inner rock zone
4	Inner rock zone II
5	Outer rock zone
6	Normal water level

1	*Zone centrale*
2	*Zone de filtre*
3	*Zone d’enrochement intérieure*
4	*Zone d’enrochement intérieure II*
5	*Zone d’enrochement externe*
6	*Niveau d'eau normal*

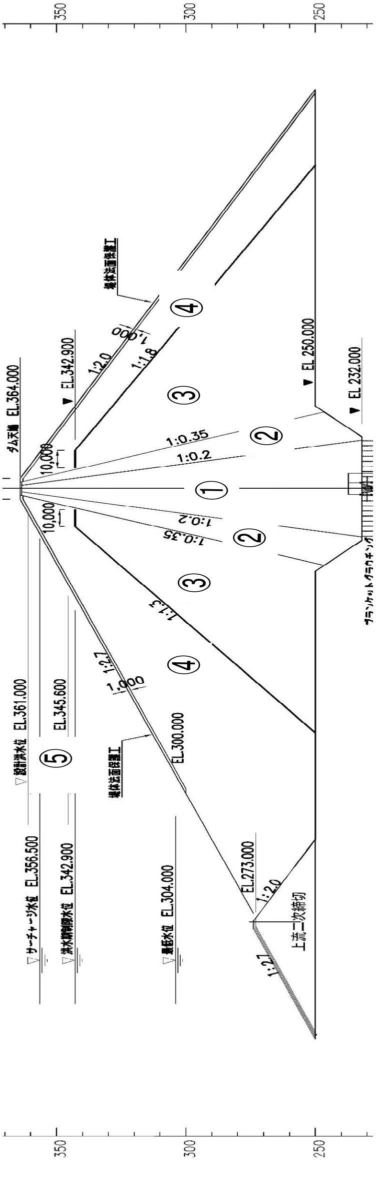

Fig. 17
Standard cross section of dam L
Coupe standard du barrage L

1 Core zone
2 Filter zone
3 Inner rock zone
4 Outer rock zone
5 Normal water level

1 Zone centrale
2 Zone de filtre
3 Zone d’enrochement intérieure
4 Zone d’enrochement externe
5 Niveau d'eau normal

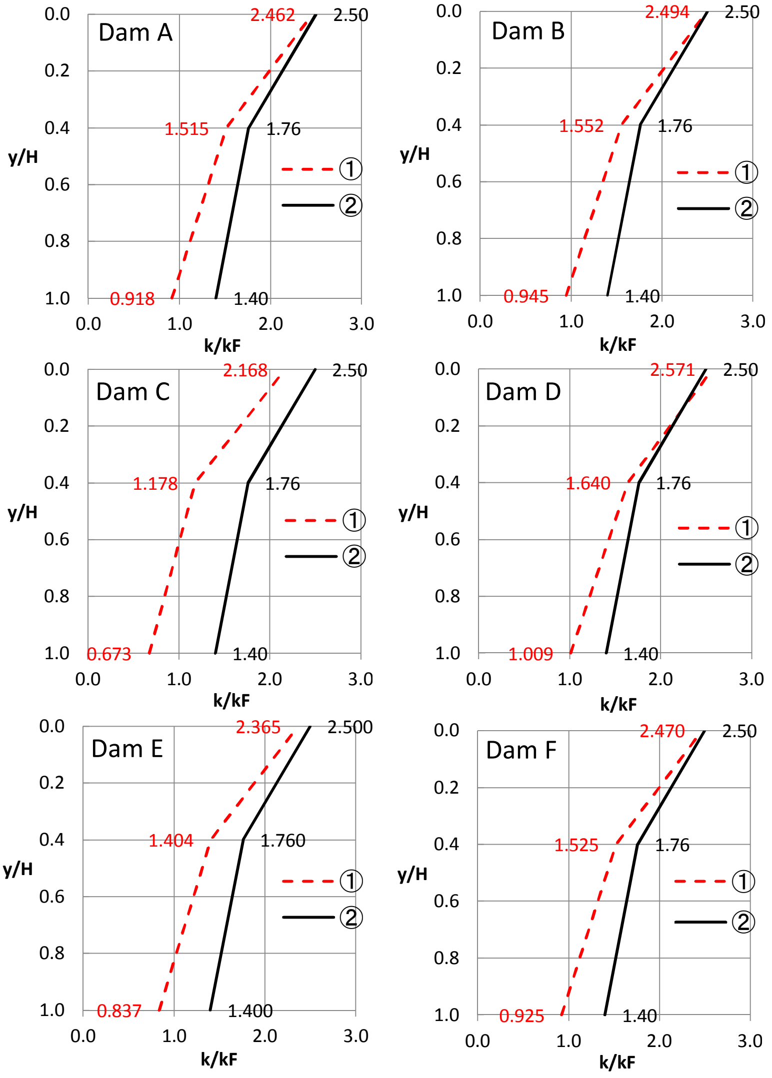

Fig. 18

Comparison of seismic force coefficients from dam A to dam F

Comparaison des coefficients de force sismiques des barrages A à F

1	Revised seismic force coefficients	*1*	*Coefficients de force sismique révisée*
2	Seismic force coefficients in the Draft of the Guidelines	*2*	*Coefficients de force sismiques dans le projet de lignes directrices*

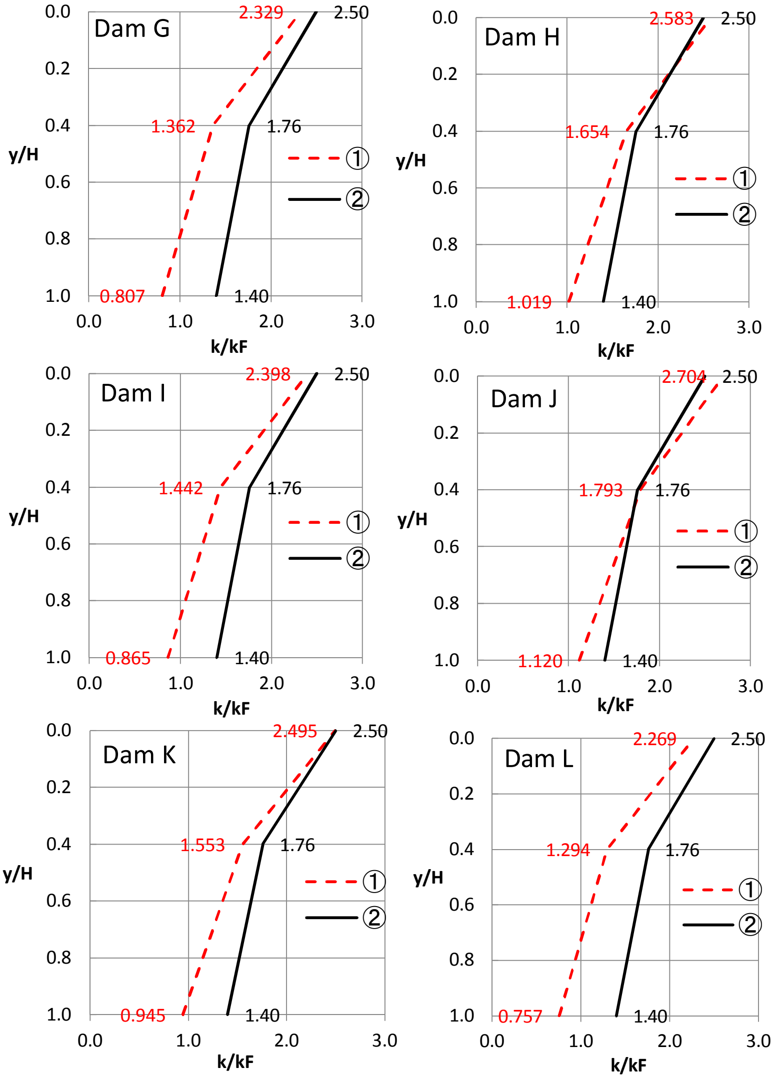

Fig. 19
Comparison of seismic force coefficients from dam G to dam L
Comparaison des coefficients de force sismiques des barrages G à L

1	Revised seismic force coefficients	*1*	*Coefficients de force sismique révisés*
2	Seismic force coefficients in the Draft of the Guidelines	*2*	*Coefficients de force sismiques du projet de lignes directrices*

Table 4
Comparison of minimum safety factors of 12 existing dams

Name of dam	Height (m)	Completion year	Minimum safety factor				Remarks
			Upstream		Downstream		
			The Draft of Guidelines	Revised seismic force coefficient	The Draft of Guidelines	Revised seismic force coefficient	
A	91.7	1974	1.811	2.025	1.938	2.131	
B	85	1975	1.148	1.199	1.284	1.323	
C	153	1979	1.511	1.822	1.545	1.899	
D	69	1981	1.431	1.564	1.742	1.919	
E	112	1990	1.477	1.624	1.629	1.783	
F	90	1991	1.426	1.593	1.641	1.706	
G	119.5	1993	1.319	1.512	1.374	1.440	
H	66.5	2004	1.425	1.515	–		*1
I	105	2006	1.206	1.445	1.283	1.467	
J	41.2	2009	1.252	1.420	–		*1
K	84.9	2012	1.222	1.505	1.280	1.436	
L	132	2013	1.214	1.473	1.328	1.541	

**1 Stability analysis of downstream side was not conducted because zoning was relatively complicated.*

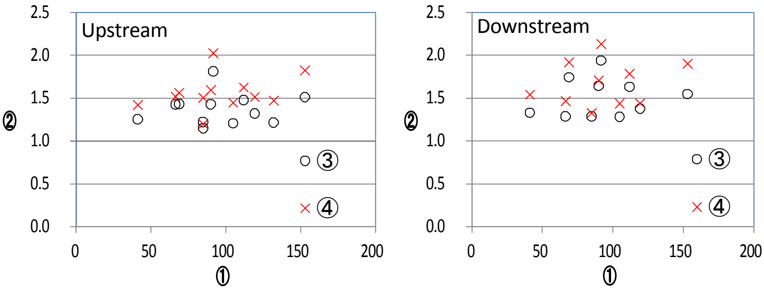

Fig. 20
Dam height and minimum safety factors
Hauteur de barrage et facteurs de sécurité minimale

1	Dam height (m)	*1*	*Hauteur de barrage (m)*
2	Minimum safety factors	*2*	*Facteurs de sécurité minimale*
3	Seismic force coefficients in the Draft of Guidelines	*3*	*Coefficients de force sismique du projet de lignes directrices*
4	Revised seismic force coefficients	*4*	*Coefficients de force sismique révisés*

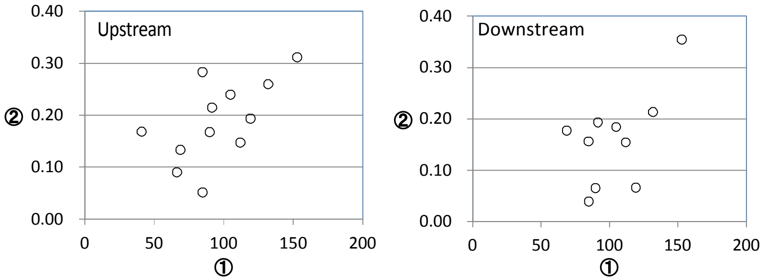

Fig. 21
Dam height and differences of minimum safety factors
Hauteur de barrage et différences de facteurs de sécurité minimale

1	Dam height (m)	*1*	*Hauteur de barrage (m)*
2	Difference of minimum safety factors	*2*	*Différence de facteurs de sécurité minimale*
3	Seismic force coefficients in the Draft of Guidelines	*3*	*Coefficients de force sismique du projet de lignes directrices*
4	Revised seismic force coefficients	*4*	*Coefficients de force sismique révisés*

4. CONCLUSION

We use 55 recent seismic motion records more than 0.1 m/s^2 including the 2011 Tohoku Earthquake and re-examined seismic force coefficients of modified seismic coefficient method for embankment dams. We propose a revised seismic force coefficient based on the seismic response analysis and it can also be applicable for embankment dams higher than 100 m. We conduct stability analysis based on the modified seismic coefficient method using our proposed revised seismic force coefficient and the seismic force coefficient in the Draft of Guidelines. Following conclusions are obtained in this paper.

(1) We have proposed a revised seismic force coefficient for modified seismic coefficient method as linear equations with the dam height, based on the results of seismic response analysis using 55 input seismic motions. Our proposed seismic force coefficient is applicable for embankment dams higher than 100 m. Our proposed seismic force coefficient becomes smaller when the dam height is higher. The Draft of Guidelines indicates that seismic force may be able to reduce from the value of the Draft of Guidelines if dam is higher than 100 m because of the nonlinear behavior of large embankment dams during earthquakes. Our proposed seismic force coefficient meets the indication of the Draft of Guidelines.

(2) Stability analysis is conducted based on the modified seismic coefficient method according to the Draft of Guidelines. We investigate the effects of the differences of the seismic force coefficients of the revised and the original on the minimum safety factors. The minimum safety factors using the revised seismic force coefficient are almost same or larger than those using original one. Differences of minimum safety factors tend to be larger when dam is higher.

We continue to investigate other existing embankment dams to check the applicability of the revised seismic force coefficient by comparing minimum safety factors of stability analysis by modified seismic coefficient method using the revised seismic force coefficient and the original one in the Draft of Guidelines.

REFERENCES

[1] River Development Division, River Bureau, Ministry of Construction, Draft of Guidelines for Seismic Design of Embankment Dams, 95p., 1991 (in Japanese).

[2] Sasaki T., Satoh H., Sakamoto H., Aoi K. and Yamaguchi Y. Modified Seismic Coefficient Method Reviewed by Recent Seismic Records for Embankment Dams. *Proceeding of the 81st Annual Meeting of ICOLD*, 2013.

[3] River Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Guidelines for Seismic Performance Evaluation of Dams against Large Earthquake (Draft), 2005 (in Japanese).

SUMMARY

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 a 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 in Japan with a height less than 100 m, in which the vertical distribution of seismic force was determined with taking the seismic response of a dam body into account. Based on seismic response analysis using 55 observed seismic records, we have been proposed revised seismic force coefficients which can be applicable to embankment dams higher than 100 m. In this paper, to investigate the effects of the seismic force coefficients on minimum safety factor, we conducted stability analysis for 12 existing rockfill dams by the modified seismic coefficient method using seismic force coefficients defined by the Draft of Guidelines and our proposed coefficients. The minimum safety factors using the revised seismic force coefficient are almost same or larger than those using original one. We think we propose better seismic force coefficients which consider the nonlinear behavior of higher embankment dams during earthquakes.

RÉSUMÉ

En 1991, le « Projet de lignes directrices pour la conception sismique de barrages en remblais » a été rédigé en japonais. Ce projet est destiné à la fois aux méthodes de conception de nouveaux barrages et aux méthodes d'évaluation de la performance sismique des barrages existants. Dans le projet de lignes directrices, une méthode du coefficient sismique modifié est proposée comme méthode d'évaluation de la performance sismique des barrages en remblai de hauteur inférieure à 100 m au Japon. La distribution verticale de la force sismique a été déterminée en tenant compte de la réponse sismique d'un corps de barrage. En nous basant sur l'analyse de la réponse sismique de 55 observations enregistrées, nous avons proposé une version révisée des coefficients de force sismique qui peuvent être appliqués aux barrages en remblai de plus de 100 m de haut. Dans cet article, afin d'étudier les effets des coefficients de force sismique sur le facteur de sécurité minimale, nous avons effectué une analyse de stabilité pour 12 barrages en enrochement existants par la méthode du coefficient sismique modifié en les comparant avec les coefficients de force sismique définis par le projet de lignes directrices. Les facteurs minimaux de sécurité calculés à partir du coefficient de force sismique révisé sont presque identiques ou supérieurs aux coefficients d'origine. Nous pensons que nous proposons un meilleur coefficient de force sismique tenant compte du comportement non linéaire des grands barrages en remblai lors des tremblements de terre.