Behavior of Dams during the 1995 Hyogoken-Nambu Earthquake and Earthquake Resistance of Dams

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ABSTRACT: The Hyogoken-Nambu Earthquake of January 17, 1995 inflicted severe damage in the Hanshin and Awaji areas such as has never been seen in Japan in recent years. The safety inspections of the dams conducted in the area by site offices and dam experts immediately after the earthquake showed that there was no damage affecting the safety of the dams, although slight damage was observed in several dams. The investigation also revealed that the peak accelerations at dam sites were much smaller than those at soil sites.

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1. INTRODUCTION

In the early morning of January 17, 1995, the Hyogoken-Nambu Earthquake whose epicenter was in the northern Awaji Island, inflicted severe damage in the Hanshin and Awaji areas. In some parts of the areas, a seismic intensity of 7 was recorded by the Japan Meteorological Agency. Many buildings collapsed during the earthquake or were consumed in the fire, which followed it. The Hanshin expressway, the Shinkansen line, lifelines such as gas and water, and many other public facilities were also destroyed. **Table 1** shows the outline of the Hyogoken-Nambu Earthquake and **Figure 1** shows the distribution of the seismic intensity recorded by the Japan Meteorological Agency.

About 50 dams are located within 50 km of the epicenter of the earthquake. **Figure 2** shows the distribution of the horizontal peak accelerations recorded at the dam foundations during the earthquake. The dam closest to the earthquake fault, called the Nojima Fault, was the Tokiwa Dam (about 800 m from the Nojima Fault). There are also many old dams in Kobe City, where the earthquake damage was most severe. The Gohonmatsu Dam,

Table 1. *Outline of Hyogoken-Nambu Earthquake.*

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Epicenter Depth	14 km
Magnitude	7.2 (Japan Meteorological Agency)

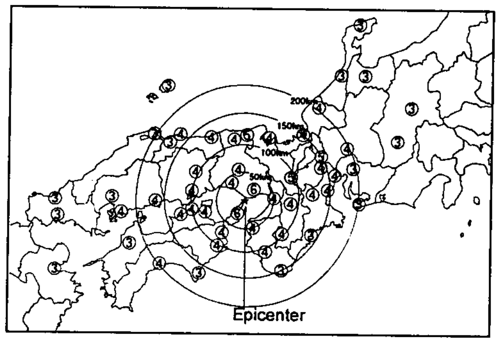

Figure 1. *Map of seismic intensity by Hyogoken-Nambu Earthquake (Values reported by Japan Meteorological Agency).*

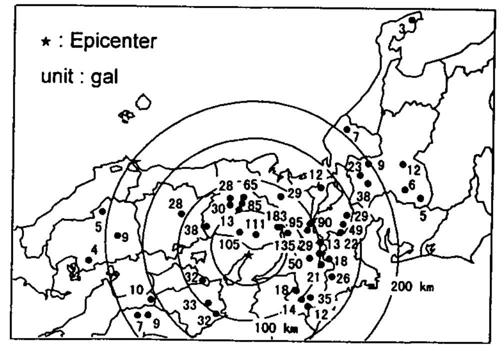

Figure 2. *Map of horizontal peak acceleration at dam foundation.*

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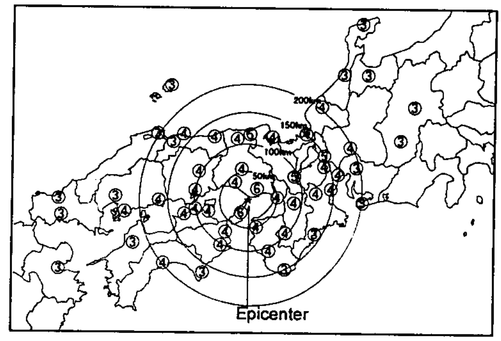

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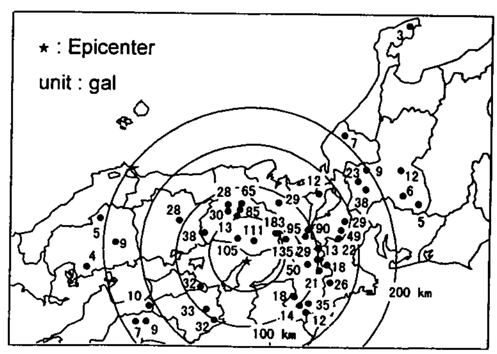

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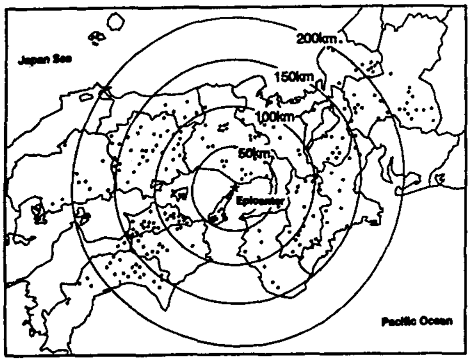


Figure 3. *Locations of dams inspected by site offices.*

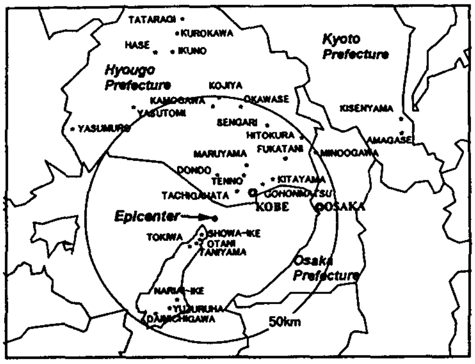


Figure 4. *Location of dams inspected by Ministry of Construction.*

which was built in 1900 as the first concrete gravity dam (rubble masonry structure) in Japan, is located about 19 km from the epicenter.

Immediately after the earthquake, the site offices of the dams carried out special safety inspections of the dams within about 200 km of the epicenter. The Ministry of Construction also dispatched dam experts immediately after the earthquake in order to inspect the dam safety and to collect the acceleration records. The inspections confirmed that no dams suffered severe damage that required emergency protective countermeasures, while some dams were slightly damaged.

In view of the extensive damage caused by the earthquake, the Ministry of Construction organized the Committee on Evaluation of Earthquake Resistance of Dams [1] to examine the safety of dams designed with the present design criteria for dams in Japan [2].

This paper presents the results of the on-site investigation, the characteristics of the acceleration records obtained during the earthquake and the results of the examination of the earthquake resistance of dams designed with the present design criteria.

2. INSPECTION OF DAMS AFTER EARTHQUAKE

2.1. *SPECIAL SAFETY INSPECTION*

Immediately after the earthquake, the special safety inspections of dams were carried out by the site offices within the river reaches administered under the River Act. The special safety inspections consisted of primary and secondary inspections; the former consisted of visual inspections immediately after the earthquake, and the latter consisted of detailed visual inspections and safety check using the data measured by installed instruments. Special safety inspections were conducted at a total of 251 dams. The locations of the inspected dams are shown in **Figure 3**.

The special safety inspections of dams were completed by January 21. The results confirmed that no dams were severely damaged that required emergency protective countermeasures, while some dams had slight damage such as minor cracks in the pavement at their crest. The amount of drainage water also increased slightly after the earthquake at 8 dams, but the amount of water was small enough and has decreased or stabilized.

2.2. *DETAILED INSPECTION*

The Ministry of Construction carried out detailed on-site inspections of dams, including the dams where minor damage was reported, through the special safety inspections by site offices, and analyzed the details of damage and gathered the acceleration records. **Figure 4** shows the locations of the 28 dams inspected and **Table 2** summaries the survey results. The survey results are outlined below.

(1) Yuzuruha Dam

The Yuzuruha Dam, a concrete gravity dam with a height of 42 m, is located about 43 km from the epicenter. **Figure 5** shows the cross section of the dam. According to the report by the site office, concrete fragments fell down from the upstream face of the dam. However, the on-site inspection revealed that repair mortar spread at the surface of the dam had fallen down and there was no damage in the dam body itself (see **Photo 1**).

(2) Tokiwa Dam

The Tokiwa Dam, a zoned earthfill dam with a height of 33.5 m, is located about 10 km from the epicenter and only 800 m from the Nojima Fault, the earthquake fault. **Figure 6** shows the cross section of the dam. A few cracks were observed in the crest

Table 2. *Main features of dams investigated by PWRI and a summary of results.*

(a) Dams within river reaches administered under the River Law.

Name of dam	Name of river	Type of dam	Height of dam (m)	Depth of reservoir water during earthquake (m)	Year of completion	Damage	Distance from epicenter (km)
Hitokura	Ina	Concrete gravity dam	75.0	38.4	1983	·No damage to dam body ·Fall of rock fragments from reservoir shore	47
Minoogawa	Minoo	Rockfill dam with central core	47.0	24.5	1983	·No damage	49
Yuzuruha	Yuzuruha	Concrete gravity dam	42.0	25.1	1974	·Slight spalling of mortar of upstream face finish	43
Dainichigawa	Dainichi	Concrete gravity dam	43.5	18.0	1964	·No damage	48
Tenno	Tenno	Concrete gravity dam	33.8	13.9	1980	·No damage to dam body ·Fall of rock fragments at abutment	16
Tachigahata	Ishii	Masonry dam	33.3	24.2	1905	·No damage	15
Sengari	Hatsuka	Masonry dam	42.4	27.6	1919	·No damage	39
Maruyama (No.1)	Funasaka	Concrete gravity dam	31.0	18.4	1977	·No damage	31
Nariai-ike	Nariai	Masonry dam	33.0	19.4	1950	·No damage	42
Tokiwa	Nojima	Zoned earthfill dam	33.5	20.9	1974	· Transverse cracking at crest near abutments	10
Taniyama	Kusumoto	Zoned earthfill dam	28.2	19.8	1974	·Minor transverse cracking at crest	7
Dondo	Yamada	Concrete gravity dam	71.5	42.8	1989	·No damage	19
Kojiya	Shidehara	Rockfill dam with central core	44.1	16.7	1991	·No damage	48
Kamogawa	Kamo	Concrete gravity dam	43.5	16.3	1951	·No damage	37
Okawase	Tojyo	Concrete gravity dam	50.8	36.0	1990	·No damage	40

(b) Dams not within river reaches administered under the River Law.

Name of dam	Name of river	Type of dam	Height of dam (m)	Depth of reservoir water during earthquake (m)	Year of completion	Damage	Distance from epicenter (km)
Otani	Kusumoto	Zoned earthfill dam	16.6	–	1968	·Minor cracking at crest near spillway	7
Showa-ike	Uzaki	Earthfill dam	16.0	–	1942	·Slight bulging of upstream slope protection ·Longitudinal hairline cracking on crest	4
Gohonmatsu	Ikuta	Masonry dam	33.3	24.6	1900	·No damage to dam body ·Fall of rock fragments at abutment	19
Fukatani	Sakase	Rockfill dam with inclined core	41.0	24.0	1971	·Slight settlement near spillway ·Cracking on splitter of spillway ·Transverse hairline cracking at crest	33
Kitayama (No.1)	Shuku	Homogeneous earthfill dam	24.5	16.2	1968	·Shallow sliding of upstream surface	31

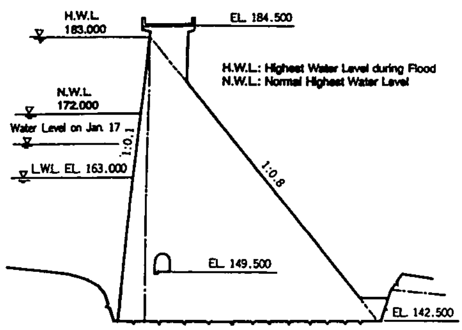


Figure 5. *Cross section of Yuzuruha Dam.*

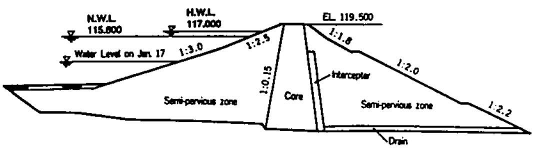


Figure 6. *Cross section of Tokiwa Dam.*

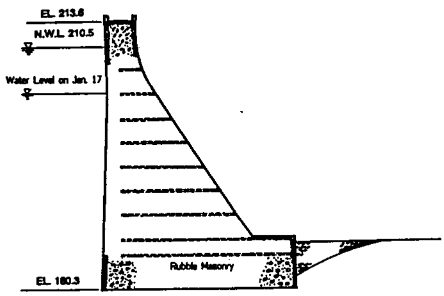


Figure 7. *Cross section of Gohonmatsu Dam.*

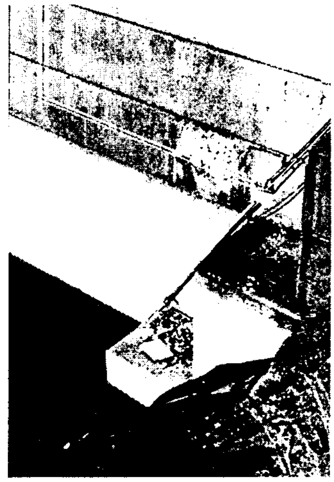


Photo 1. *Yuzuruha Dam : Spalling of mortar on the upstream face.*

Photo 2. *Tokiwa Dam : Cracking at the crest.*

pavement near both abutments; two of cracks had a width of 25 mm and a length of 5 m (see **Photo 2**). Excavation by the dam owner revealed later that one of the cracks extended to the top of the core zone but within the freeboard.

(3) Gohonmatsu Dam

The Gohonmatsu Dam, Japan's first concrete gravity dam (rubble masonry structure) with a height of 33.3 m and completed in 1900, is located about 19 km from the epicenter. **Figure 7** shows the cross section of the dam. Rock fragments fell from the left abutment into the spillway, but the spillway was not damaged. Hairline cracks were observed in the capping concrete on the crest railing, but no cracks were observed in the dam body.

(4) Kitayama Dam

The Kitayama Reservoir is formed by five homogeneous earthfill dams, Dams No.1 to No.5. The reservoir is located about 31 km from the epicenter. **Figure 8** shows the cross section of Dam No.1. This 24.5-high dam was constructed using decomposed granite soil as fill material and was embanked on a foundation of weathered granite. A shallow sliding occurred in the upstream surface (see **Photo 3**). Later examination revealed that the sliding was shallow and did not affect the safety of the dam.

3. CHARACTERISTICS OF EARTHQUAKE MOTION AT DAM SITES

3.1. *MAXIMUM ACCELERATION AT DAM FOUNDATIONS*

3.1.1. *Attenuation of Peak Acceleration*

The horizontal peak accelerations observed during the earthquake are shown in **Figure 9**, and the vertical peak accelerations are shown in **Figure 10**.

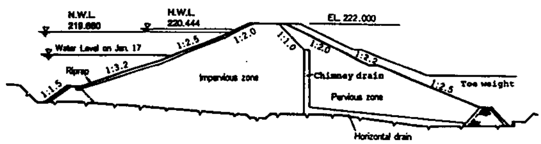


Figure 8. *Cross section of Kitayama Dam No.1.*

The figures consist of the accelerations observed at the dam sites [1] and at soil sites [3]. The accelerations at the dam sites include the values obtained at the gallery at the bottom of embankment dams or at the lowest gallery in concrete dams. The maximum acceleration at soil sites was 818 gal. The figures indicate that the peak accelerations at dam sites are substantially smaller than those at soil sites at the same distance from the epicenter.

Figure 11 shows the horizontal peak accelerations at dam sites with distance from the earthquake source fault [1]. The location of the earthquake source fault was estimated from the distribution of epicenters of aftershocks on the day of the main earthquake (Jan. 17) in the Hanshin area, and coincides with the Nojima Fault in the Awaji area.

Photo 3. *Kitayama Dam No.1 : Shallow sliding at the upstream slope.*

The acceleration records at 8 dams were obtained within a distance of 50 km from the earthquake fault, and the maximum horizontal acceleration at dam sites was 183 gal (10 km from the earthquake source fault). After the overall assessment of the acceleration records shown in **Figure 11** and other records at rock sites similar to dam sites, the Committee estimated that the maximum horizontal

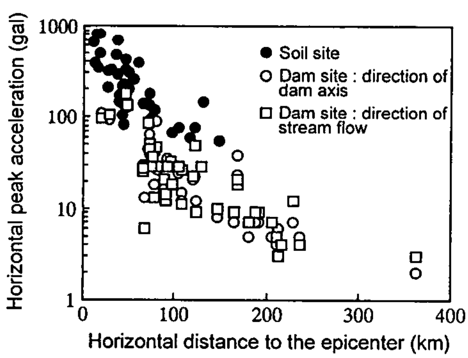


Figure 9. *Attenuation of horizontal peak accelerations with distance to the epicenter.*

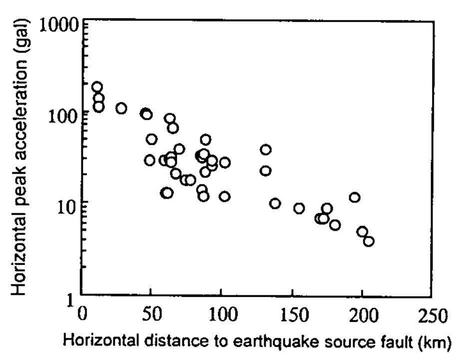


Figure 11. *Attenuation of horizontal peak accelerations with distance to earthquake source fault.*

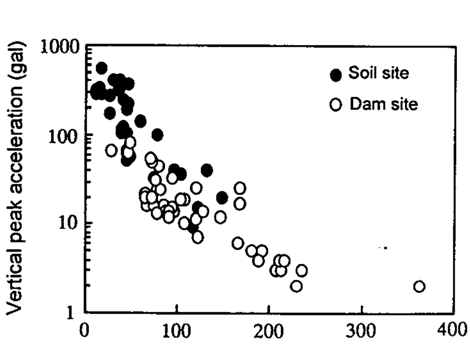


Figure 10. *Attenuation of vertical peak accelerations with distance to the epicenter.*

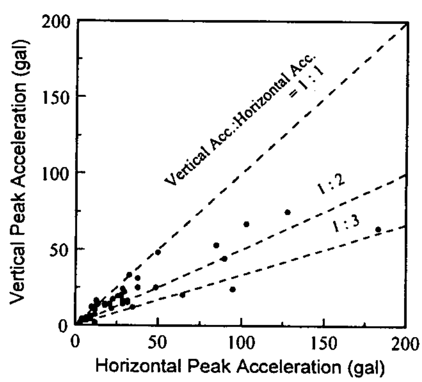


Figure 12. *Horizontal peak acceleration versus vertical peak acceleration.*

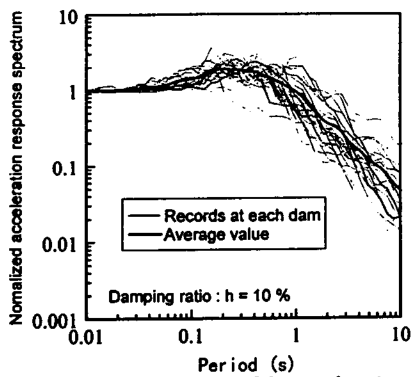


Figure 13. *Response spectrum of the acceleration observed at dam foundations.*

acceleration induced by the earthquake was about 220 gal at rock sites where dams might be built [1].

3.1.2. *Horizontal Peak Acceleration versus Vertical Peak Acceleration*

Figure 12 shows the relationship of the horizontal peak acceleration with the vertical peak acceleration observed at dam sites during the Hyogoken-Nambu Earthquake [1]. The ratio of the vertical peak acceleration to the horizontal peak acceleration ranges from 1/3 to 1/1. This ratio tends to decrease as the horizontal peak acceleration increases.

3.2. *ACCELERATION RESPONSE SPECTRUM*

Figure 13 shows the response spectrum of the acceleration at a damping ratio of 10% in the stream direction observed at 25 dam foundations during the Hyogoken-Nambu Earthquake [1]. Each spectrum is normalized so that the maximum observed acceleration is equal to 1. The average value of the response spectra for the natural period ranging from 0.1 to 0.6 seconds is about 2. The response spectra decreases rapidly when the natural period exceeds about 0.6 seconds.

4. EARTHQUAKE RESISTANCE DESIGN OF DAMS IN JAPAN

The earthquake resistance of dams is designed using the Seismic Coefficient Method under the present design criteria for dams in Japan [2]. The lowest limit of seismic coefficient is as stipulated in **Table 3** according to the type of the dam and its location.

The Seismic Coefficient Method is considered not to represent the actual behavior of dams during earthquakes because the distribution of the seismic coefficient is assumed to be uniform in the dam body. However, the dams designed with the Seismic Coefficient Method have not suffered any damage affecting their structural safety during previous earthquakes. It is considered that the following safety requirements of dams compensate for the defect of the above assumption.

Table 3. *Seismic coefficient in design criteria for dams in Japan.*

Type of Dam	Seismic Coefficient (Lowest Limit)		
	Low*	Medium*	High*
Concrete Gravity Dam	0.10	0.12	0.12
Concrete Arch Dam	0.20	0.24	0.24
Rockfill Dam	0.10	0.12	0.15
Earthfill Dam	0.12	0.15	0.15

* *Low : Low Seismic Activity Zone*
Medium : Medium Seismic Activity Zone
High : High Seismic Activity Zone

(1) Structural Safety Requirements of Concrete Dams

1. No tensile stress in the vertical direction should exist at the upstream face of the dam.
2. The safety factor against sliding of the dam should be no smaller than 4.
3. The stress in the dam should be within the allowable stress of concrete. The allowable compressive stress of concrete should be no larger than one quarter of the compressive strength of the standard specimen of concrete.

(2) Structural Safety Requirements of Embankment Dams

1. The safety factor against sliding of any part of the dam should be no smaller than 1.2. The shear strength of rock materials and filter materials can be obtained from triaxial compressive tests, but apparent cohesion should be ignored in the design of dams.

5. EVALUATION OF EARTHQUAKE RESISTANCE OF DAMS

5.1. *ACCELERATION USED IN THE ANALYSIS*

The Hyogoken-Nambu Earthquake did not inflict any severe damage on dams requiring safety countermeasures. However, many other structures suffered severe damage due to the earthquake. The earthquake resistance of dams designed with the present design criteria was therefore reviewed.

The maximum horizontal acceleration during the Hyogoken-Nambu Earthquake was estimated to be 220 gal at rock sites where dams might be built. The maximum horizontal acceleration of 250 gal was, however, used in the analysis in order to allow an adequate margin of safety. Four acceleration records

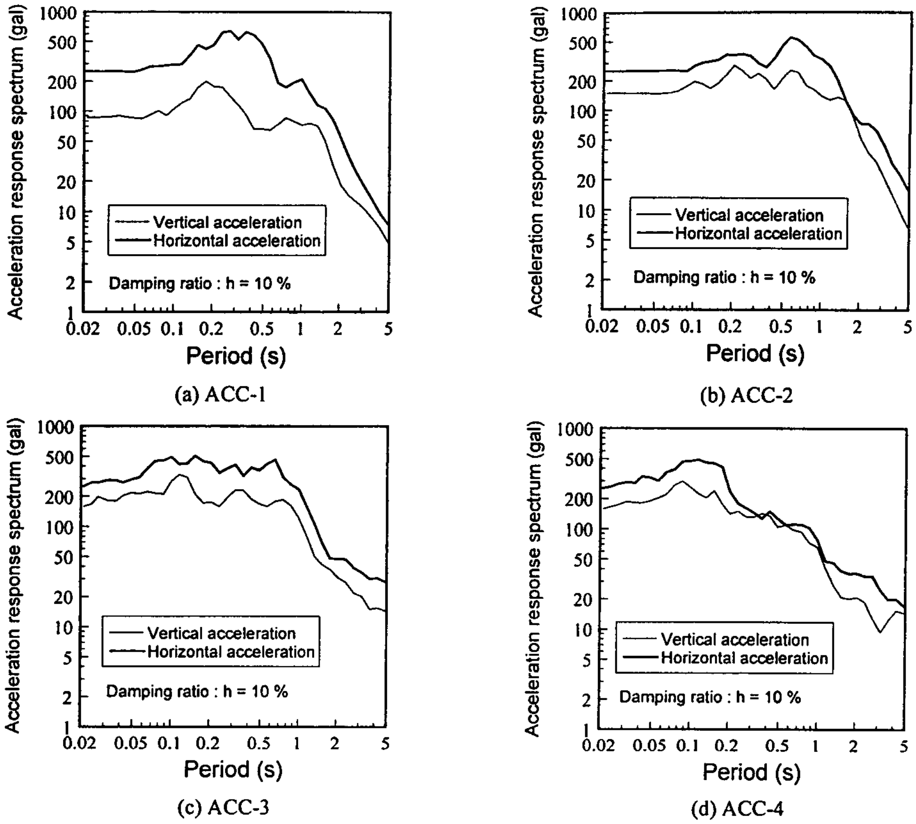


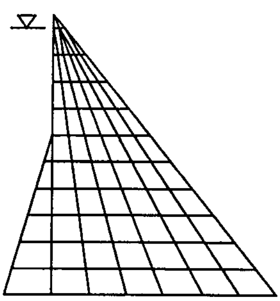
Figure 14. *Response spectrum of the input accelerations.*

at dam sites near the epicenter were selected, and they were amplified to have a peak accelerations of 250 gal. **Figure 14** shows the response spectrum of acceleration ACC-1 to ACC-4 for the damping ratio of 10% [1]. The analysis also considered the vertical acceleration, and the vertical acceleration was increased at the same rate as the horizontal acceleration.

5.2. *CONCRETE GRAVITY DAMS*

5.2.1. *Conditions of Analysis*

The model dams used in the analysis were concrete gravity dams with a typical cross section in accordance with the present design criteria. The downstream slope of the dams was 1:0.8, and the upstream slope was vertical with an additional triangle of slope of 1:0.3. The height of the dams ranged from 25 m to 150 m. **Figure 15** shows the finite element model of the dams. The effect of the reservoir was accounted for as the added mass matrix [4] assuming water to be an incompressible fluid. **Table 4** shows the physical properties of the material.



Firure 15. *FEM model of concrete gravity dam.*

Table 4. *Physical properties of material (Concrete gravity dam).*

Elastic Modulus (N/mm^2)	3.0×10^4
Poisson's Ratio	0.2
Density (kg/m^3)	2300
Damping Ratio (%)	10

Table 5. *Physical properties of materials (Rockfill dam).*

Zoning	Wet Density (kg/m³)	Saturated Density (kg/m³)	Strength Parameter*	
			A (or c)	b (or ϕ)
Rock	1880	2080	A = 1.128	b = 0.804
Filter	2130	2240	A = 0.808	b = 0.908
Core	2220	2230	c = 0.098 N/mm²	ϕ = 35°

* $\tau = Po \cdot A \cdot (\sigma/Po)^b$ or $\tau = c + \sigma \tan\phi$, where τ is the shear strength, σ is the normal stress on the sliding plane, and Po is 1 N/mm².

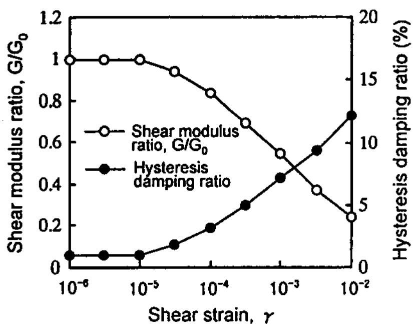
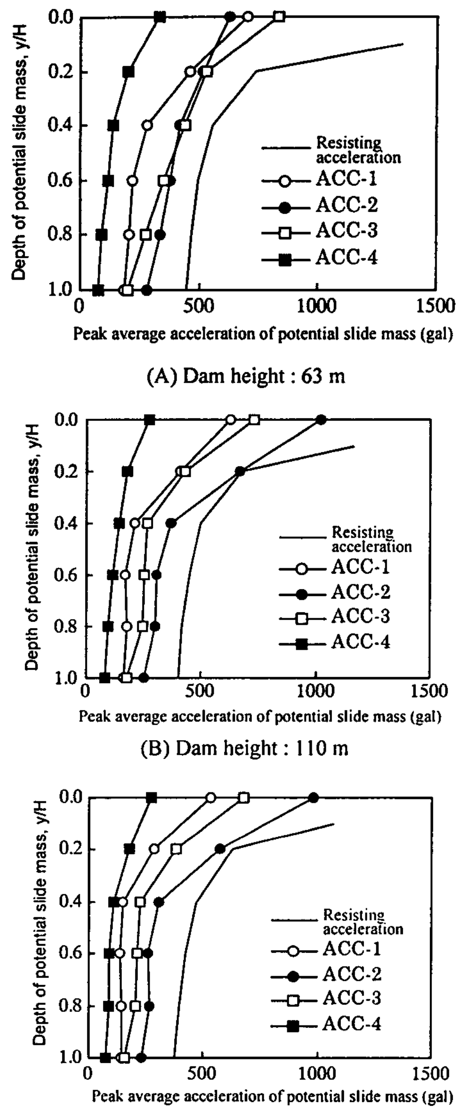


Figure 20. *Shear strain versus shear modulus ratio and hysteresis damping ratio.*

5.3.2. *Results of Analysis*

The potential sliding circle was assumed to pass through the center of the crest of dams in **Figure 18**, where the potential slide mass was expressed by the relative depth y/H. The peak average acceleration can be calculated as the total peak seismic inertia force moment of the potential sliding mass divided by the mass moment of potential sliding mass.

Figure 21 shows the relationship of the peak average acceleration of the sliding mass for a given y/H with the critical acceleration. Here, the critical acceleration is defined as the acceleration which causes the potential sliding mass to begin to slide. The critical acceleration was calculated using the shear strength of the materials shown in **Table 5**. The figure shows that the peak average acceleration is larger in the upper part of the dam, but that the value is still within the critical acceleration in all cases. This reveals that the rockfill dam is safe against sliding.



(A) Dam height : 63 m

(B) Dam height : 110 m

(C) Dam height : 150 m

Figure 21. *Peak average acceleration of potential slide mass.*

6. CONCLUSIONS

The Hyogoken-Nambu Earthquake of January 17, 1995 inflicted severe damage in the Hanshin and Awaji areas such as has never been experienced in Japan in recent years. The safety inspections of dams conducted by site offices and dam experts immediately after the earthquake, however, showed that there was no severe damage affecting the safety of the dams, although slight damage was observed in several dams. The investigation after the earthquake showed that the peak accelerations at dam sites were much smaller than the accelerations at soil sites. The dams were constructed on hard bed rock, which contributed to the safety of the dams during the earthquake.

The Ministry of Construction organized the Committee on Evaluation of Earthquake Resistance of Dams after the earthquake to examine the earthquake resistance of dams designed with the present design criteria. The Committee confirmed that dams designed with the present design criteria are safe.

In Japan, dam sites are selected after a detailed geological survey. The dams are designed with careful structural analyses based on the design criteria, and are constructed under strict management with high quality of materials. This careful effort in survey, design and construction helps to ensure the safety of the dams. However, dams are large and important structures, which must not fail, so the earthquake resistance design of dams should be improved by further with the reinforced measurement system of the earthquake motion.

This paper was prepared based on the Report of the Committee on Evaluation of Earthquake Resistance of Dams [1]. The author expresses the gratitude to all members of the committee for their invaluable efforts.

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[2] Cabinet Order Concerning Structural Standards for River Administration Facilities, etc., 1976.

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