Factor Analysis of Damage to Small Earth Dams Due to the 1995 Hyogoken-Nambu Earthquake

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ABSTRACT

Damage to small earth dams due to the Hyogoken-Nambu Earthquake of January 17, 1995 is discussed. Investigations of 266 dams were conducted in the area where the JMA seismic intensity was 5 or higher, and which were located within about 50 kilometers from the earthquake source fault. Small earth dams suffered various forms of damage such as longitudinal cracking, transverse cracking, settlement and deformation of the dam body. The damage to small earth dams was classified into five grades from no damage to severe damage such as a complete failure. The damage grade was analyzed by several factors such as distance from the fault, topography and geology, intensity of quake motion, direction of dam axis against the fault, year of completion, and height of dam. The characteristics of factors affecting damage to small earth dams were evaluated.

KEYWORDS

Dam, Damage, Earthquake, Fault, Geology, Site-Investigation

INTRODUCTION

The Kobe area of Japan was struck by a major earthquake, the Hyogoken-Nambu Earthquake, with a Japan Meteorological Agency (JMA) magnitude of 7.2 on January 17, 1995. This earthquake was a large intra-plate earthquake. A JMA seismic intensity of 7 was recorded in the Kobe urban area and in the northern part of Awaji Island for the first time since the Fukui Earthquake in 1948. The maximum horizontal acceleration of 818 gal was recorded on the stiff ground (JMA Kobe station) a few hundred meters near the source fault. From the observed records, the maximum earthquake motions observed in the earthquake source field within ten kilometers were 300 to 800 gal in acceleration and 80 to 180 kine in velocity on the soft ground, and acceleration of 400 to 820 gal in acceleration and velocity of 40 to 90 kine in velocity on the stiff ground (Iwasaki, 1996).

Buildings and infrastructures suffered severe damage on the strong quake zones while soil structures such as banks, small earth dams and river levees also suffered damage over a wide area. We analyzed the factors that affected the damage to small earth dams. We documented the performance of and damage to earth dams caused by the event. The earth dams we investigated are small-scale embankment dams for mainly irrigation, and do not include rockfill dams and large dams higher than twenty meters under the River Law of Japan. Most of damaged dams were earth dams lower than fifteen meters. The well engineered dams with a height of more than twenty meters, that were designed and constructed by the recent design criteria, did not suffer serious damages which affected their safety (Matsumoto *et al.*, 1996).

Numerous small earth dams are distributed throughout Awaji Island (about 24,000 dams), the Kako river basin in the west of Kobe City, and the Muko river and Ina river basins in the east of Kobe City. Since the strong quake zones in which the JMA seismic intensity of 7 was recorded were in urban areas, there were few earth dams in the areas. An earth dam, Niteko Dam, near the zone of seismic intensity 7 collapsed. In the Kako river basin that is located in the west of Kobe City, small earth dams were severely damaged, although little damage to buildings and other infrastructures was found. In Awaji Island, many small earth dams were damaged in Hokudan-cho where passed the Nojima Fault and in Ichinomiya-cho leaded from the southern end of the fault. Damage to earth dams in Sumoto City was comparatively slight in spite of an observed seismic intensity of 6. In Honshu Island (Main Island), damage to earth dams was concentrated in the source fault area of Itami City, Takarazuka City, Nishinomiya City and the plain of Akashi City, Kakogawa City and the western part of Kobe City. In the northern area of Rokko mountain region, damage was relatively slight.

The materials of most of the investigated small earth dams were silty sand or clayey sand, mostly composed of decomposed granite. The levels of the reservoir of most earth dams were very low, since the event occurred in the farmer's slack season. Damage to the small earth dams would have been severer if the reservoir level had been higher in the farmer's busiest season. An earth dam in Awaji Island failed due to the liquefaction and overtopped shown in Photo.1. The sand boils were found out at the bottom of the reservoir. We could find sand boils at the reservoir bottom of other dams, yet it was not clear that damage to these dams occurred because of the liquefaction.

In northern Awaji Island, inflow to several dams rapidly increased probably because of groundwater fluctuations after the event. In several earth dams on the mountainous slopes in Tsuna-cho, cracks occurred on the bottom of the reservoirs and then the reservoirs became empty, in spite of no damage to the dam bodies themselves. According to the owners of the reservoirs, the same phenomenon had been happened just after the Nankai Earthquake that occurred about 150 km south of Awaji Island in December, 1946.

OUTLINE OF INVESTIGATIONS

We investigated small earth dams in the area where the seismic intensity was 5 or higher, and which were located within about 50 kilometers from the earthquake source fault.

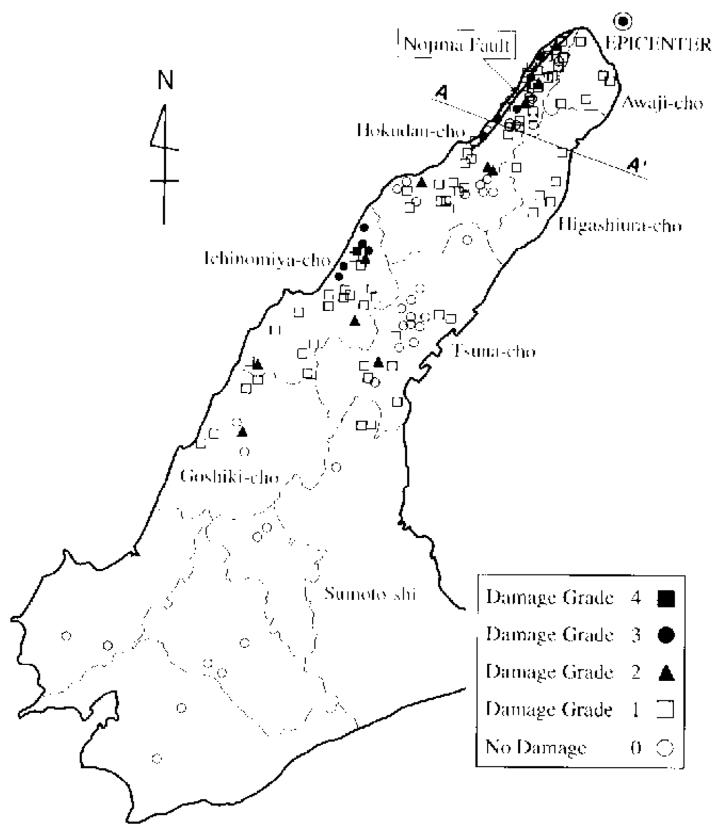

Fig. 1(a) Locations and damage grade of investigated earth dams in Awaji Island

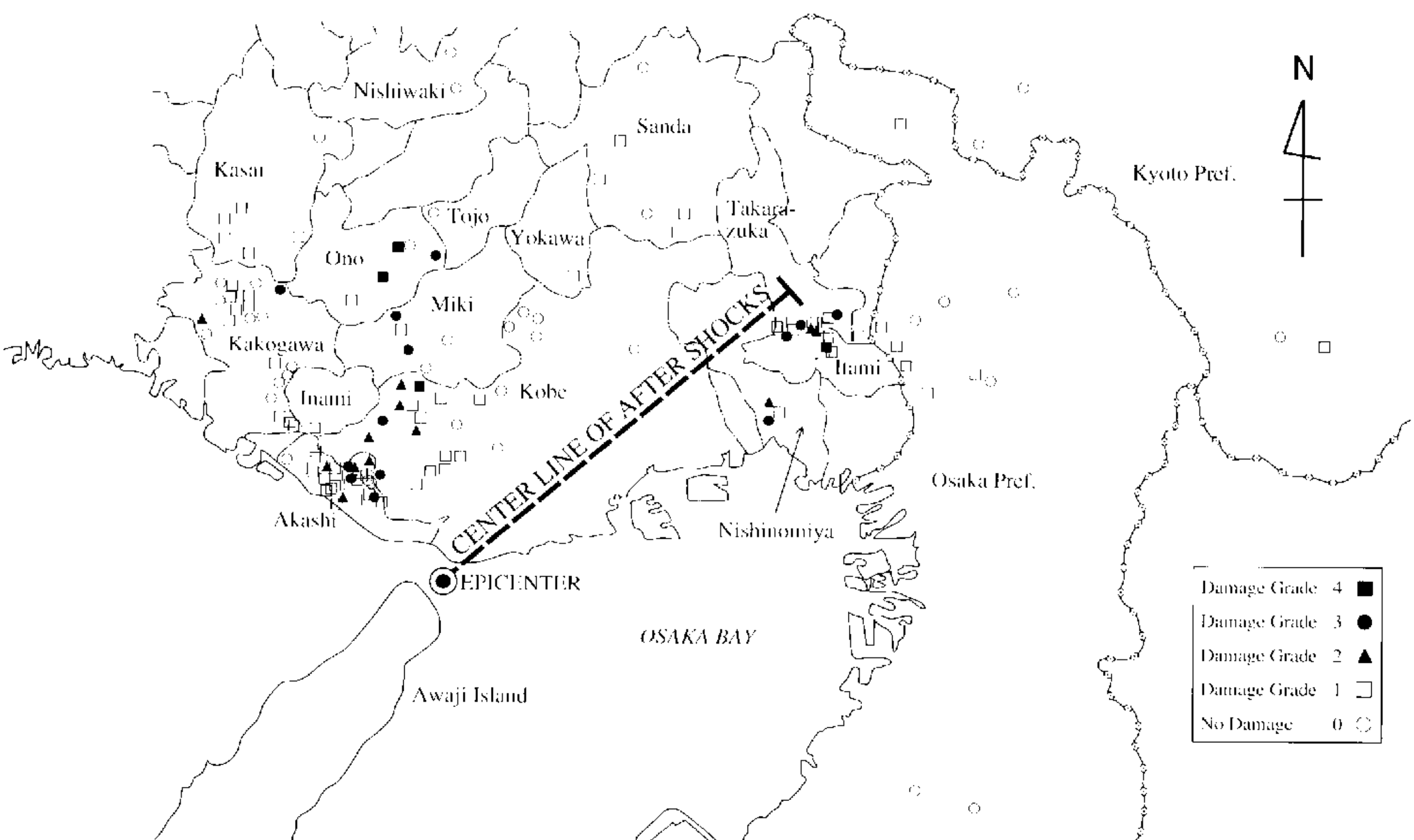

Fig. 1(b) Locations and damage grade of investigated earth dams in Honshu Island

Table 1 Criterion for evaluation of damage grade of small earth dams

Form	Classification		Grade	Notes
Longitudinal crack	Deep crack	Over 20 cm wide or Differential settlement of over 30 cm	4, 3	•Large-scale slide •Collapse of a part of dam (Grade 4)
		10 to 20 cm wide or Differential settlement of 20 to 30 cm	2	
		Under 10 cm wide and Differential settlement of under 15 cm	1	
	Shallow crack	Over 10 cm wide or Differential settlement of over 15 cm	2	•Small-scale slide •Shallow slide
		Under 10 cm wide and Differential settlement of under 15 cm	1	
Transverse crack	Leakage route due to continous cracks from upstream to downstream	(Over 20 cm wide or Differential settlement of over 30 cm)	4, 3	•Overall judgment from condition of leakage •Collapse of a part of dam (Grade 4)
		(10 to 20 cm wide or Differential settlement of 15 to 30 cm)	2	
	Discontinuous cracks from upstream to downstream	(Under 10 cm wide and Differential settlement of under 15 cm)	1	
Settlement • Deformation	Large deformation		4, 3	•Liquefaction •Collapse of a part of dam (Grade 4)
	Uniform settlement	Settlement of over 100 cm	3	
		Settlement of 50 to 100 cm	2	
		Settlement of under 50 cm	1	
Damage to appurtenant works	Severe damage		3	•Appurtenant works indicate spillway, sluice way, slope protection, etc. •Judgment considering aging of structures
	Medium damage		2	
	Slight damage		1	
Leakage	Increase of drainage Leakage due to piping		4~1	•Overall judgment with other damage factors

Here, the earthquake source faults are the Nojima Fault in Awaji Island and the aftershocks area in Honshu Island. It is estimated that maximum acceleration on the ground in the investigated area exceeded 100 gal from the observed records. We gathered little data on undamaged or slightly damaged earth dams far from the source fault, because of giving priority to investigation of severely damaged earth dams. A total of 266 small earth dams was investigated in detail; 143 in Awaji Island and 123 in Honshu Island. The locations of the investigated earth dams are shown in Fig. 1. We collected the following data; the survey of main descriptions such as heights, widths and lengths of the crest, slope gradients, axial directions, years of completion, etc., the inspection of slope protections, spillways, sluice ways, leakage and reservoir slopes, the observation of the materials of dams and the geology of foundations and abutments, the measurement of settlements, the mapping of cracks and bulging, and the finding of sand boils. We also sampled the soil materials of the several dam bodies and examined various soil tests on the samples.

We also investigated the performance of tombstones during the Hyogoken-Nambu Earthquake to estimate the distribution of the intensity of the earthquake motion in the northern part of Awaji Island (details in Iwashita *et al.*, 1996). We surveyed the state of 3545 overturned tombstones for a total of 79 graveyards. We selected only rectangular-shaped tombstones and excluded special shaped and structured ones. We calculated the ratio of overturned tombstones for each graveyard and estimated the intensity of the quake motion at each site.

FACTORS AFFECTING DAMAGE TO DAMS

We classified the damage to small earth dams into five grades from no damage (Grade 0) to failure (Grade 4). The classification of the damage grades was conducted on the basis of the damage criterion shown in Table 1. This criterion was modified from that of the earthquake induced damage of the river levees in "Technical Manual for Earthquake Disaster Restoration on Civil Engineering Structures (draft)" (Ministry of Construction, 1986). Typical views of damaged dams classified as Grade 4, 3 and 2 are shown respectively in Photographs 1, 2, 3 and 4. We describe the analysis results of several factors affecting damage to small earth dams in the following.

Forms of Damage

Earth dams suffered various forms of damage such as longitudinal cracking, transverse cracking, settlement and deformation of the dam body, liquefaction, etc. The piping of

Photo. 1 Liquefied earth dams of Grade 4 (Ichinomiya-cho in Awaji Island)

Photo. 2 Slid earth dams of Grade 4 (Ono City in Honshu Island)

Photo. 3 Damaged earth dams of Grade 3 (Ichinomiya-cho in Awaji Island)

Photo. 4 Damaged earth dams of Grade 2 (Akashi City in Honshu Island)

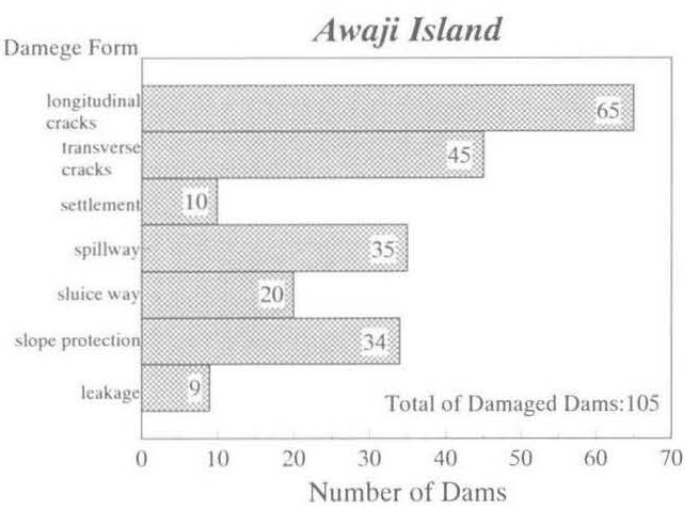

Fig. 2(a) The number of earth dams for each damage form in Awaji Island

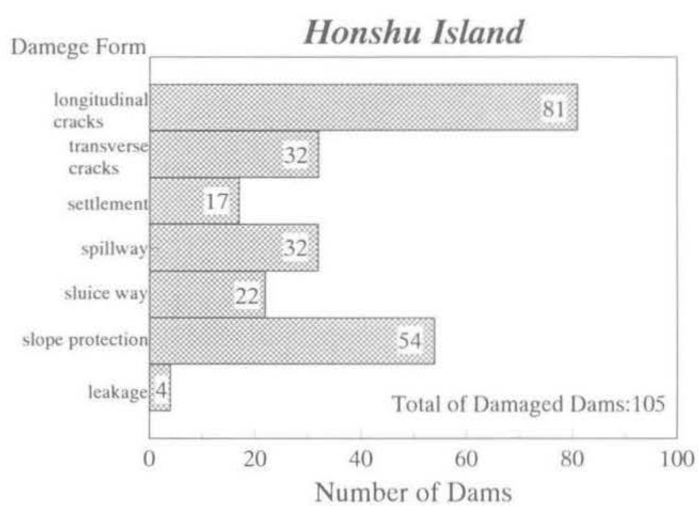

Fig. 2(b) The number of earth dams for each damage form in Honshu Island

the dam body and foundation occurred due to a failure of aged sluice ways.

We classified the forms of major damage to small earth dams into seven types: longitudinal cracks, transverse cracks, settlement, damage of spillways, damage of sluice ways, damage of slope protections, and leakage. Figure 2 shows the number of dams for each damage form; (a) indicates in Awaji Island and (b) in Honshu Island. The most popular form of damage was longitudinal cracks. Over sixty percent of damaged earth dams occurred longitudinal cracks. Most of the dams damaged severely (over Grade 3) were those of the longitudinal cracks. The damage of the dams in the area over 30 km away from the aftershocks area on Honshu Island was

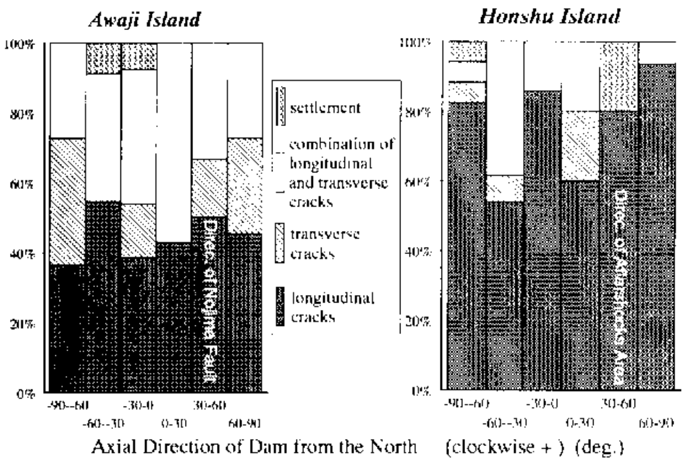

Fig. 3 Relations of damage forms with axial direction of damaged earth dams

Table 2 Geological classification in the investigated area

Geological time		Stratum			Rock	Outcrop area
Quaternary	Holocene	Alluvium	a		Clay, Sand, Gravel	Hyogo Pref. Osaka Pref. Awaji Island
	Pleistocene	Terrace deposit	t			
	Pleistocene ~Oligocene	Osaka group	Og			
Tertiary	Miocene	Kobe group	K		Mudstone, Sandstone, Conglomerate	Kobe
					Tuff	Kobe, Awaji Island
Cretaceous		Rokko granite	Ng	PrT	Biotite granite	Kobe
		Ryoke granite	Nrg		Granite, Granodiorite	Awaji Island
		Izumi group	Ial		Sandstone, Shale	Awaji Island
		Arima group	A		Rhyolite, Pyroclastic rock	Hyogo Pref.
Jurassic ~ Carboniferous		Tanba group	T		Sandstone, Slate, Shale	Hyogo Pref.

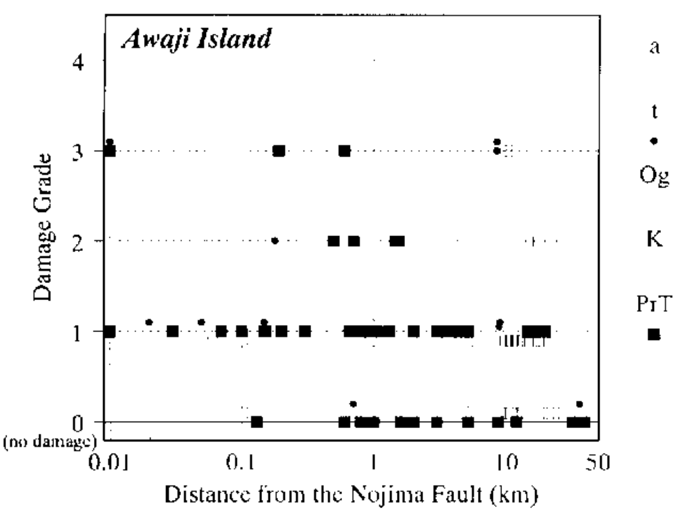

Fig. 4(a) Relations of damage grade of earth dams with distance from the fault and geological stratum of dam foundation in Awaji Island

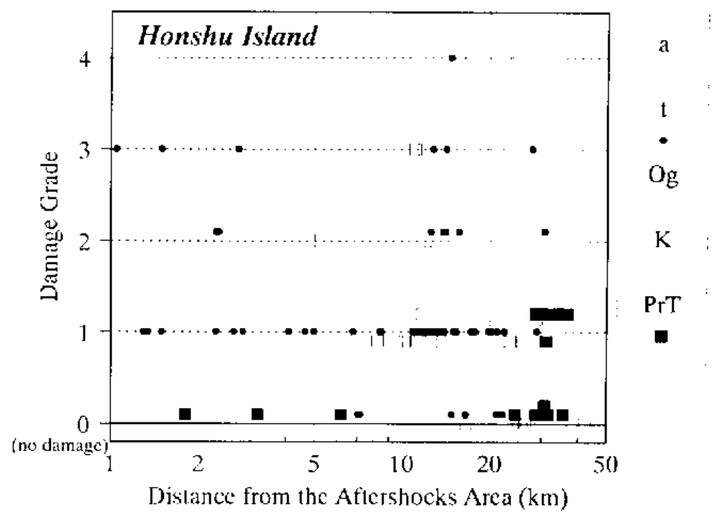

Fig. 4(b) Relations of damage grade of earth dams with distance from the fault and geological stratum of dam foundation in Honshu Island

mainly to slope protections, but the damage was slight (Grade 1).

Figure 3 shows the percentage of each major damage form for each range of axial direction of dam. It seems that there is no special relationship between the form of damage and axial direction of dams.

Effect of Distance from the Fault

Figure 4 shows the relations between damage grade of earth dams and the closest horizontal distance from the fault; (a) indicates in Awaji Island and (b) in Honshu Island. The lateral axis in Fig. 4 indicates the distance from the Nojima Fault in Awaji Island, and the distance from the center line of the aftershocks area in Honshu Island. Symbols in Fig. 4 differ by the geological stratum of the foundation of each dam shown in Table 2.

Awaji Island The damage grade of dams decreases with increase in distance from the fault, for the dams on the stratum prior to the Osaka group over 10 km away from the fault. Even within a few kilometers of distance from the fault, there was no dam damaged in Grade 4 severely, and some of these dams suffered no damage. The earthquake ruptures of the Nojima Fault passed just near about ten earth dams. In spite of the location, these ten dams suffered damage, the grades of which were only Grade 1 to 3. None of the dams collapsed. Some of the dams were undamaged. A small dam was directly above the Nojima Fault. It suffered a failure of the spillway and only a medium damage to the downstream body.

Honshu Island The attenuation of damage to dams was not observed clearly because we focused our investigation on severely damaged earth dams far away the fault. In spite of the long distance from the fault, several dams on alluvium, terrace deposit and diluvium of the Osaka group suffered severe damage. Three earth dams on the Osaka group of 20 to 30 km away from the fault suffered large-scale slides (Damage Grade 4). The view of one of them is shown in Photo. 2. These dams were constructed over 70 years ago and had shapes with steep slopes.

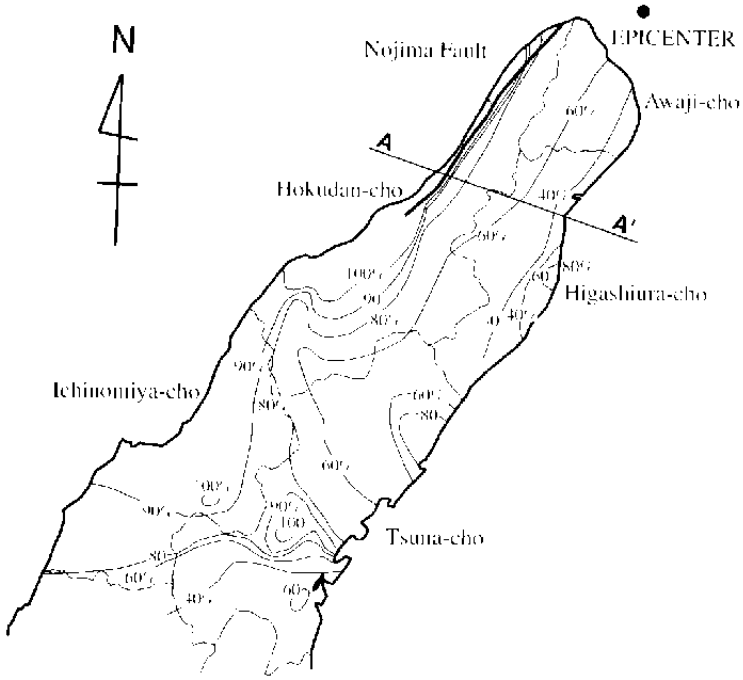

Fig. 5 Distribution of the ratio of the overturned tombstones against a total of the tombstones surveyed at each graveyard in the northern part of Awaji Island

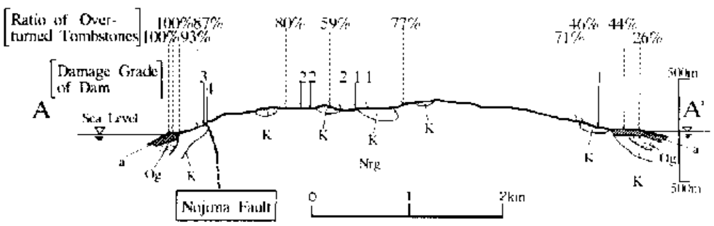

Fig. 6 Distribution of damage grade of earth dams and the ratio of the overturned tombstones in the geological cross section (Mizuno et al., 1990) of line A-A' shown in Fig. 1 (a) and Fig.5 of north Awaji Island

Effect of Geological Stratum of Foundation

The geological classification of the investigated area is indicated in Table 2. An earthquake motion due to the rupture of fault progresses up to the ground surface. The earthquake motion amplifies during progression through the ground. Generally, the response of the motion becomes larger in a softer ground layer, that is a younger stratum. Therefore, the geological stratum of a dam foundation affects the intensity of the incident quake motion of the dam. The following can be said from Fig. 4 that shows the attenuation of damage grade for each geological stratum of dam foundation.

Awaji Island There are few earth dams on alluvium or terrace deposits, which is of young geological age, because the distribution of the alluvium and terrace deposits in Awaji Island is limited to narrow areas. The younger the geological stratum of a dam foundation and the longer the distance from the Nojima Fault to the dam, the severer the damage to the dam, for the dams on the stratum of the Pre-Quaternary Age.

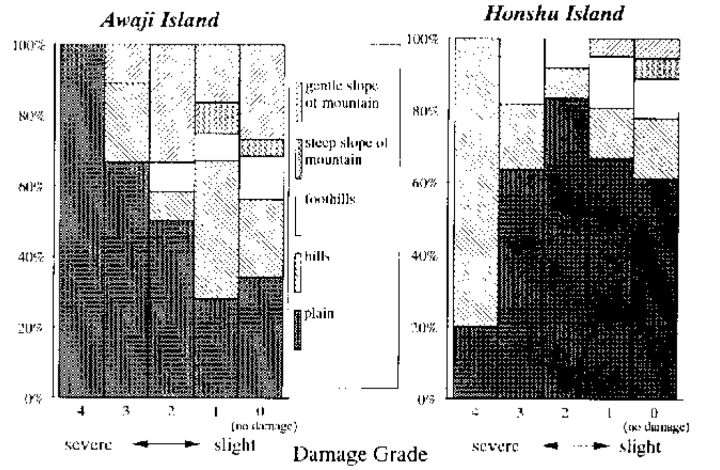

Fig. 7 Relations of damage grade of earth dams with topology at dam sites

Next, the dams with a foundation prior to the Tertiary Age suffered only slight damage of under Grade 1 if over two kilometers from the Nojima Fault.

Honshu Island The earth dams with higher damage than Grade 2 were limited to those constructed on alluvium, terrace deposits and the Osaka group. The earth dams with geological foundations prior to the Tertiary Age were not damaged or limited to slight damage.

Effect of Intensity of Earthquake Motions

Figure 5 shows the distribution map of the ratio of overturned tombstones obtained from our investigation at the northern part of Awaji Island. The geological cross section (Mizuno *et al.*, 1990) of the line A-A' drawn in Fig. 1 (a) is shown in Fig. 6. The damage grades of earth dams and the percentages of overturned tombstones at graveyards near the line A-A' are also shown in Fig. 6. We compared Fig. 5 with the distribution map of damaged dams in Fig. 1(a) and evaluated Fig. 6. The percentages of overturned tombstones exceeded eighty percent in the areas where the damage to dams was over Grade 3. This suggests that very strong earthquake motions were experienced in the areas.

Effect of Topography

We classified the topography of dam sites into plains, hills, foothills, steep slopes of mountain, and gentle slopes of mountain. Figure 7 shows the percentage of each topography for each damage grade.

Awaji Island The damage to earth dams was severer in the order of plains > hills > gentle slopes of mountain > foothills > steep slopes of mountain from Fig. 7, although the number of investigated dams is different for each topography. Damaged dams of over Grade 3 are concentrated in plains and hills, which is also related with their geology.

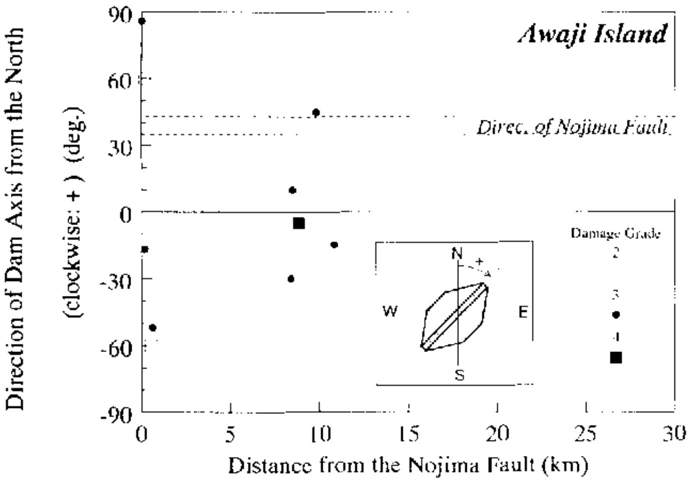

Fig. 8(a) Distribution of axial direction of damaged earth dams in Awaji Island

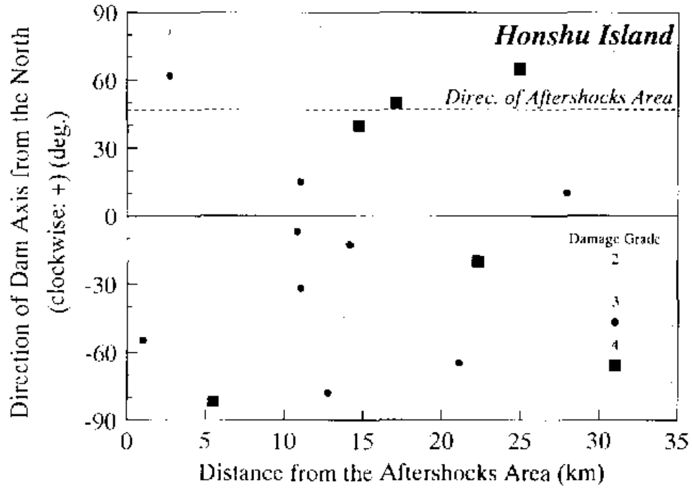

Fig. 8(b) Distribution of axial direction of damaged earth dams in Honshu Island

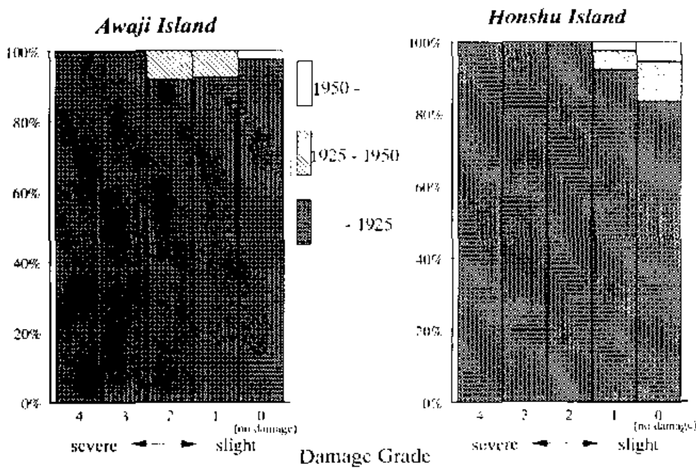

Fig. 9 Relations of damage grade of earth dams with year of completions

Honshu Island Most of the damaged dams were ones constructed in plains or hills. Earth dams at gentle slopes and steep slopes of mountains suffered practically no damage, although few dams investigated at the topographical areas. Topography of plains reflects that the foundation geology is the alluvium deposit.

Effect of Axial Direction of Dam

Figure 8 shows the relations between axial direction of dam and distance from the fault with damage grade of 2 or higher. The axial direction of dams indicates the differential direction from the north. The differential direction ranges within ± 90° ; a plus sign indicates clockwise from the north and a minus sign counterclockwise.

Awaji Island The axial directions of damaged dams were concentrated in the direction of around 30° to 40° from the north even for the dams over ten kilometers away from the fault, with the exception of the damaged dams within a few kilometers from the fault. These directions agree well with the direction of the Nojima Fault. The predominant directions of the earthquake motions due to the rupture of the fault make right angles with the fault. Hence, Fig. 8 (a) indicates that the predominant direction of earthquake motions agreed with the stream direction of the dams.

Honshu Island The axial direction of dams was not clearly related with the damage to dams in Fig. 8 (b) about Honshu Island.

Effect of Year of Completion

The construction method of an earth dam and the structure of a dam body depend on banking techniques, tools and machines available at the time of the construction of dams. The year of completions of an earth dam can thus be used as an index for evaluating the dam structure, construction method and especially the degree of compaction. We divided it roughly into three periods of before 1925, 1925 to 1950 and after 1950. Figure 9 shows the percentages of the period of the completion year for each damage grade.

Awaji Island The small earth dams damaged in Grade 3 or higher were old dams constructed before 1925.

Honshu Island The small earth dams damaged in Grade 2 or higher were old dams constructed before 1925. Two dams on the alluvium deposit in Kakogawa City suffered the damage of longitudinal cracks at the crest and suffered damage of Grade 1, although they were constructed after 1950. Both of them had heights of lower than three meters and steep slopes of sixty to a hundred in a hundred.

The old small earth dams constructed before the early twentieth century were banked by human-power under inadequate construction management and have steep slopes in their cross sectional shapes, that is poorly engineered. The relatively recent earth dams constructed after the 1950's were compacted probably by machines and well engineered. Hence, they were not damaged or very slightly damaged (Grade 1) in spite of the few number of investigated dams.

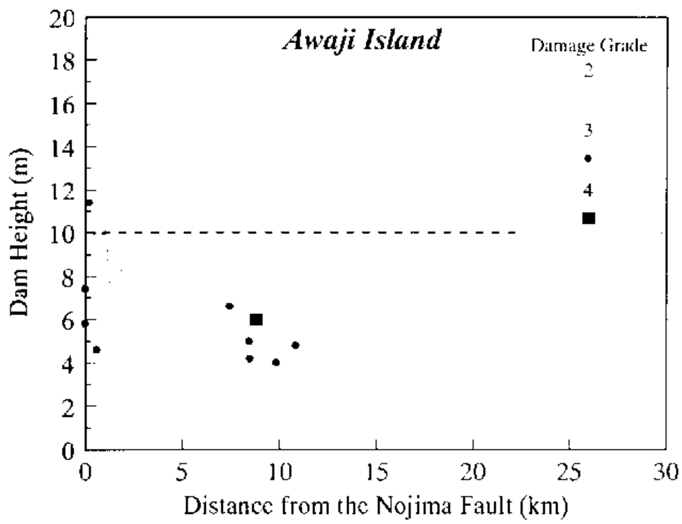

Fig. 10(a) Relations of damage grade of earth dams with dam height in Awaji Island

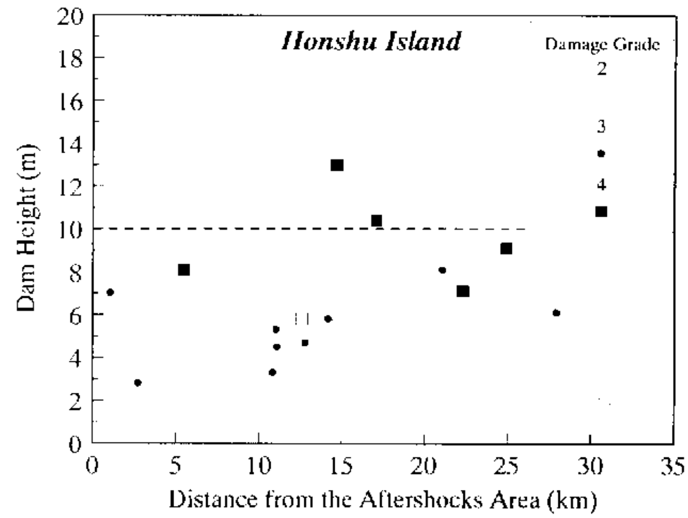

Fig. 10(b) Relations of damage grade of earth dams with dam height in Honshu Island

Effect of Dam Height

Figure 10 shows the relations between height of dams, damage grade and distance from the fault for the damaged dams of over Grade 2.

Awaji Island The dams damaged severely of over Grade 3 were limited to the dams with a height of under ten meters excluding the dams just near the Nojima Fault.

Honshu Island Most of the damaged earth dams exceeding Grade 2 were under 10 m in height. Although two earth dams with a height of over 10 m suffered severe damage of Grade 3, both of them had extremely steep slopes of sixty to seventy in a hundred. One of the two had a thick extra-banking on the dam body itself for a crest road.

Most of the severely damaged earth dams were limited to those with a height of under about 10 m. The high earth dams were not damaged or very slightly damaged except for a few special dams mentioned above. This was because the structure and banking method of large earth dams are different from those of low and small dams with a height of under 10 m.

CONCLUSIONS

We investigated damage to small earth dams due to the Hyogoken-Nambu Earthquake. We evaluated the effect of several factors on the characteristics and grades of the damage to dams. The findings are summarized in the following.

(1) Longitudinal cracking was the most popular form of damage to small earth dams.

(2) The earth dams constructed on old geological foundations of the Pre-Quaternary Age suffered little damage. The dams on young geological foundations such as the alluvium or diluvium of the Osaka group suffered severe damage.

(3) The earth dams in low lands of plains or hills were seriously damaged. The earth dams in mountainous areas suffered little or only slight damage. This reflects the foundation geology stated in (2)

(4) Almost all the severely damaged earth dams in Awaji Island and Honshu Island were low dams with a height of lower than ten meters and were old dams constructed before the 1920's. The dams constructed after the 1950's were undamaged or very slightly damaged.

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