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Earthquake Damage to Fill Dams in Japan

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Abstract

Earthquakes have caused considerable damage to fill-type dams. Research into earthquake damage has contributed to the study of earthquake resistance of dams. However damage to fill dams occurred almost only in the case of small-scale earth dams, especially in the few cases of serious damage. This report describes the damage and performance of earth dams and fill dams more than 15 m high during earthquakes, based on literature data as well as field surveys. The results indicated that even stronger earthquakes than the designed earthquake intensity did not cause heavy damage to large well-constructed modern dams. The above analysis of the performance of fill dams during earthquakes shows that large-scale dams are earthquake-proof.

Discipline: Agricultural engineering
Additional key words: earth dam

Introduction

A survey conducted in 1978 showed that there are more than 250,000 fill dams in Japan, 75% of the dams are more than 100 years old and generally small, and 80% are less than 10 m high. Fig. 1 shows the distribution of earth dams and fill dams. Like other soil structures, fill dams have experienced damage in past earthquakes. Analytical geotechnical/soil-engineering surveys of earthquake damage to fill dams have provided useful information for implementing measures against earthquake damage. The surveys revealed that the majority of the fill dams which experienced earthquake damage were small-scale earth dams, while no large-scale fill dams higher than 15 m, except for the "Manno-ike" dam (which was damaged in the 1854 "Ansei Nankai" earthquake), experienced serious damage[2]. This report summarizes the behavior of fill-type dams higher than 15 m during earthquakes, including cases where fill dams were damaged.

Earthquake damage to earth dams

Earthquake damage to fill dams in Japan has paralleled the history of fill dam construction. "Manno-ike" dam is the first reported case of earthquake damage to fill dams. The Manno-ike dam was damaged presumably due to the phenomenon referred to as "piping" that occurred one month after the Ansei Nankai earthquake (1854). The Nohbi earthquake (1891) damaged the "Iruka-ike" dam (Aichi Prefect.). The first post-earthquake survey was performed after the Kitatango earthquake (1927). Table 1 reviews the earthquake damage to earth dams since 1927. The damage by Oga earthquake (1939) was surveyed by Akiba[1]. The major conclusion was that earth dams with embankments of sandy soil experienced severe damage, suggesting that "liquefaction" could have been incriminated. Subsequently, detailed surveys of earth dam damage were conducted after the past several earthquakes[5,6].

Fig. 2 shows the relationship between the damage rate of earth dams and the average distance from the epicenter of the affected districts in the case of Hyogoken Nambu earthquake. The solid line in the Figure represents the maximum value for the relationship between the damage rate and distance from the epicenter. Although this relationship differs depending on the conditions of the ground and dam bodies, the line in the Figure represents the maximum values of the distance from the epicenter and the reservoir damage rate, which was attributable to the earthquake.

Fig. 3 depicts the relationship between the average distance from the epicenter and estimated maximum damage rate as a function of the magnitude for the Tokachi-oki, Niigata, Nihonkai Chubu, and Hyogoken Nambu earthquakes shown in Table 1. Since the degree of damage and ground and dam conditions were not taken into account, the estimates are merely conservative.

Fig. 4 shows the relationship between the earthquake magnitude (M_J) and the earth dam farthest from the epicenter, which was damaged by the earthquake

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Fig. 1. Distribution of earth dams and fill dams in Japan

(hereafter referred to as "critical distance from epicenter"). Using past data, the relationship between M_J and the critical distance from the epicenter can be expressed as:

$$R = 11 \qquad 5 < M_J < 6.1 \text{.........}(1)$$

$$\log R = 0.846\, M_J - 4.14 \qquad 6.1 \leqq M_J < 8 \text{ ....}(2)$$

where M_J: magnitude, R: critical distance from epicenter (km).

This relationship is indicated by the solid line in the Figure, which also delineates the boundary of the damaged area. The upper area did not sustain any damage and the lower area shows the zone where damage is likely to have occurred. Therefore, the damage rate increased in a downward direction in the Figure. It should be noted that the critical distance from the epicenter represents the distance from the epicenter shown in Fig. 4 at which the damage rate became zero. The value of Equation (1) depends on the properties of the earthquake, ground conditions, and earth dam conditions. However, the approximate distance from the epicenter at which damage starts to occur can be determined by calculating the distance from the epicenter and the magnitude.

Table 2 summarizes the outline of earth dam damage caused by 5 past earthquakes. The damage can be divided into the damage to the dam body and dam facilities (spillway, outlet works). In addition, the dam body damage can be classified into functional defects (crack, settlement, slip) and failure which prevents water storage. These damages may occur at the same time: e.g. settlement occurs along with slip, or settlement and crack may occur independently. Table 2 lists all the possible damages.

As for the cracks, most of them are longitudinal cracks parallel to the dam body axis. They are frequently generated on upper slopes and crests of dam, presumably due to the difference in stability between upper and lower slopes. Lateral cracks in the direction perpendicular to

Table 1. Earth dam damage caused by several earthquakes

No.	Name of earthquakes	Occurrence time			Magnitude (M_J)	Number of earth dams damaged
1	Kitatango	Mar.	7,	1927	7.5	90
2	Oga	May	1,	1939	7.0	74
3	Niigata	Jun.	16,	1964	7.5	146
4	Matsushiro	Aug. Dec.	1965~ 1970		Max. 5.4	57
5	Tokachi-oki	May	16,	1968	7.9	202
6	Miyagiken-oki	Jun.	12,	1978	7.4	83
7	Nihonkai Chubu	May	26,	1983	7.7	238
8	Chibaken Toho-oki	Dec.	17,	1987	6.7	9
9	Kushiro-oki	Jan.	15,	1993	7.8	1
10	Notohanto-oki	Feb.	7,	1993	6.6	21
11	Hokkaido Nansei-oki	July	12,	1993	7.8	18
12	Hokkaido Toho-oki	Oct.	4,	1994	8.1	0
13	Sanriku Haruka-oki	Dec.	28,	1994	7.5	7
14	Hyogoken Nambu	Jan.	17,	1995	7.2	1,362
16	Sorachichuo	Sep.	23,	1995	5.6	1
17	Miyagiken Hokubu	Sep.	11,	1996	5.9	5
18	Kagoshimaken Satsuma(1)	Mar.	16,	1997	6.3	1
19	Kagoshimaken Satsuma(2)	May	13,	1997	6.1	2
20	Yamaguchiken Hokubu	July	15,	1997	6.1	2

the dam axis can be associated with serious damage because water may leak from the dam bodies although such cracks occur only at a low rate. Most of the lateral cracks cross the dam body. In the Nihonkai Chubu earthquake, lateral cracks were generated on the border between the abutment and dam body, and near outlet works at a rate of about 50%. The same phenomenon was noted in the survey of Oga earthquake. This trend may be due to the difference in the behavior between the abutment and dam body, and between the dam body and outlet works.

Type of earth dam damage

For grouping the type of damage in Nihonkai Chubu earthquake, a classification was carried out on the basis of the major causes of damage, according to the damage classification for river dikes and railway embankments. Fig. 5 shows the classification of damage types. Table 3 shows the types of damage. Types I and III accounted for

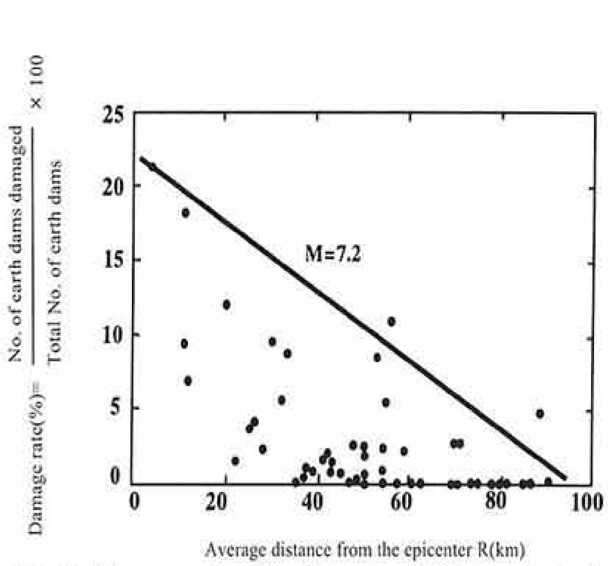


Fig. 2. Average epicenter distance and damage rate of earth dams in the case of Hyogoken Nambu earthquake

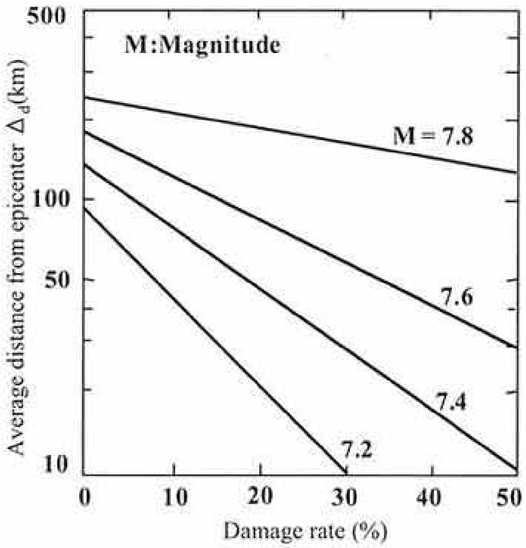


Fig. 3. Relationship between average distance from epicenter and damage rate based on past earthquake data

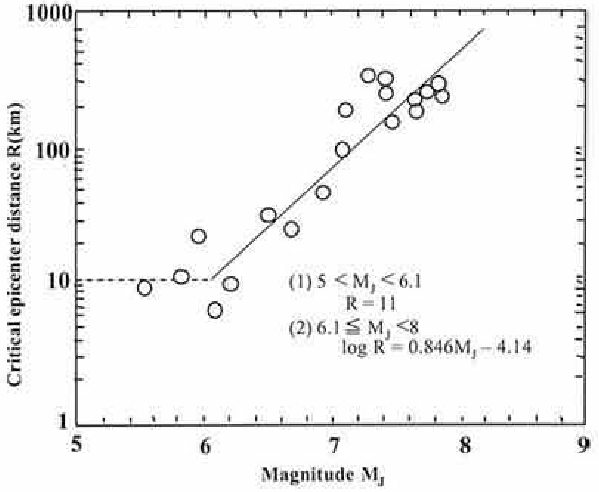


Fig. 4. Relationship between magnitude M_J and critical distance from epicenter R

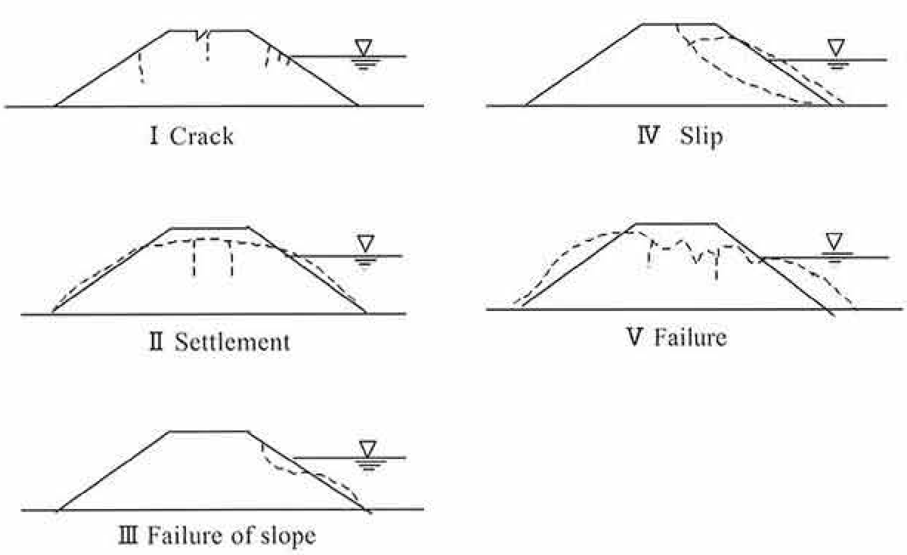
30% respectively, followed by Types II, IV and other types. Type V accounted for only 1.8%. In Type I (crack) the shape of the dam body was maintained with little settlement and cracks alone were generated. This type is characterized by the fact that many dam bodies are made of clay on good foundation ground. There were 3 examples of cracks generated along the line grouted in the past. In Type II (settlement) the shape of the dam body was maintained with accompanying cracks, and the major cause was attributed to the settlement of the foundation ground. Type III (failure of slope) and Type IV (slip) showed basically the same type of damage, but in Type III the damage was less severe than in Type IV. Most of the dam body remained sound and serious damage was not observed in Type III. A slip was recognized in Type IV, though this type accounted for only a few cases. Most part of the dam body experienced settlement by slip in Type IV, frequently causing large damage such as failure. In Type V, the dam body and the foundation ground were broken. Though the number of cases was very low, earth dam failure occurred in many cases like in Type III. The estimated causes included liquefaction of the dam body and foundation ground. In addition, outlet works, spillway, abutment break, and damage to only the covering block accounted for about 10% of the total.

Table 4 shows the number of cases with damage and

Table 2. Outline of earth dam damage

Name of earthquakes	Number of surveyed earth dams	Damage of dam body									
		Damage of function of dam									
		Crack			Slip			Settlement	Failure	Outlet works	Spillway
		Lateral	Longitudinal	Both	Upper slope	Lower slope	Both				
Oga	58 (6)	43	0	5	17	6	6	42	12	9	6
Niigata	123(37)	87	3	8	34	16	1	30	7	38	7
Tokachi-oki	93 (8)		– 24 –		25	10	4	8	10	–24–	
Miyagiken-oki	83 (5)		– 49 –			–17–		7	0	– 6–	
Nihonkai Chubu	218(15)	138	3	16	32	21	10	79	10	50	28

( ): Number of earth dams with a height above 10 m.



I Crack

Ⅳ Slip

Ⅱ Settlement

V Failure

Ⅲ Failure of slope

Fig. 5. Classification of damage types

Table 3. Relationship between the type of damage and soil type in the case of the Nihonkai Chubu earthquake

Type of damage		I	II	III	IV	V	Dam facilities
		Crack	Settlement	Failure of slope	Slip	Failure	
Number of cases		69	47	62	13	4	23
Material of embankment	Sandy soil	4	11	8	2	3	5
	Clay soil	57	30	48	11	1	17
	Others	8	6	6	0	0	1
Rate (%)		31.6	21.6	28.4	6.0	1.8	10.6

Table 4. Relationship between soil type of dam body and damage of earth dam in the case of the Nihonkai Chubu earthquake

Soil type	Number of dams	Number of cases	Number of cases with serious damage [a)]	Rate (total) (%)	Rate (serious damage) (%)
Sandy soil	215	43	10	20.0	4.7
Clay soil	1,258	130	5	10.3	0.4
Gravel clay soil	287	40	1	13.9	1.4
Others	74	5	0	6.8	0
Total	1,834	218	16	11.9	0.9

a) : Serious damage refers to failure or settlement above 1.0 m.

damage rate for each dam body soil obtained from a questionnaire for 218 damaged earth dams and 1,834 non-damaged earth dams in Nihonkai Chubu earthquake. The cases of damage in clay and gravely clay soil accounted for 80% in comparison with sandy soil. On the other hand, the damage rate of sandy soil against all earth dams including non-damaged earth dams was as high as nearly 20%, which was nearly twice the rate of that in the case of clay and gravely clay. This tendency was more obvious for the damage rate of earth dams with serious damage. Dam body soil was sampled in 39 areas of damaged earth dam and in 18 areas of non-damaged earth dam, and subjected to physical soil tests. As for the non-damaged earth dams, those located in a similar region, which showed similar geographic characteristics and height were selected as far as possible.

Damage to fill dams more than 15 m high

Table 5 shows the time of construction of fill dams for irrigation, with heights of more than 15 m prior to 1985. The total number of fill dams was 1,872, with 1,506 earth dams and 438 were very old, being constructed before the Meiji era (1868~1911). Most of these were brought into service during the Edo period (1603~1867). The following refers to the damage of fill dams with heights of 15–30 m in Japan. Table 6 lists major earthquake damage to fill dams with heights of 15–30 m in Japan[7]. This table shows that no large-scale fill dams with a height of 15–30 m had experienced serious earthquake damage, except for the Manno-ike dam. Table 7 shows observations made during earthquakes in typical large fill dams with heights of more than 30 m in Japan. The table includes the Akita-Toho earthquake (1970) with M_J=6.5 where the "Ainono Dam" was damaged. This dam was completed in 1961. It showed a uniform type and was 41 m high. This dam had a seismometer installed at the dam site. It was reported that the seismometer swung outside the scale, thus failing to register the earthquake intensity. An attempt to calculate the earthquake intensity, from an epicenter distance of 15 km, indicated that the maximum input acceleration of seismic waves transmitted to the bedrock was around 150 gal. The post-earthquake survey report disclosed that major damage occurred on the crest of the dam in the form of several vertical cracks extending over 40 m, each 5 to 25 cm in width.

The Nihonkai Chubu earthquake was recorded at the

Table 5. Time of construction of fill dams with height above 15 m

Construction time	~ 1867	1868 ~ 1945	1946 ~ 1950	1951 ~ 1960	1961 ~ 1970	1971 ~ 1980	1981 ~ 1985	Under construction	Planned	Total
Number	438	610	51	189	193	148	18	186	39	1,872 [a)]
	(23.4)	(32.6)	(2.7)	(10.1)	(10.3)	(7.9)	(1.0)	(9.9)	(2.1)	(100)

a) : 1,506 earth dams.

Table 6. Observations of earthquake damage to fill dams with height of 15 – 30 m in Japan

Earthquake	Date	Magnitude (Mj)	Name of dam	Date of completion	Height (m)	Type of dam	Characteristics of damage	Degree of damage
Ansei Nankai	Jul. 24 , 1854	8.4	Manno-ike	Around 700	23	Earth	One month after the earthquake, leakage was reported in the embankment. Failure occurred 6 days later.	Serious(Failure)
Nobi	Oct. 28, 1891	8.4	Iruka-ike	1633	29	Earth	Longitudinal cracks on the crest.	Slight
Kanto-dai	Sept. 1, 1923	7.9	Ohno Reservoir	1914	34	Earth (concrete core)	Crest settlement of 24 cm. Lateral cracks on the crest.	Medium
			Maruyama					
			Upper	1923	24	Earth	Crest settlement of 20 cm.	Slight
			Lower	Under Construction	16(33)	Earth	Longitudinal cracks on the crest.	Slight
Oga	May 1, 1939	7.0	Iwakura Tameike	1931	17	Earth	Longitudinal cracks on the crest.	Slight
Matsushiro	Aug. 1965 ~Dec. 1968	Max. 5.4	Ohike	1927	16	Earth	Longitudinal cracks.	Slight
			Shionoiri	1936	25		Longitudinal cracks.	Slight
Niigata	Jun. 16, 1964	7.5	Takinosawa	1954	15	Earth	Cracks on the slope.	Slight
			Fujita	1952	18	Earth	Cracks on the slope and crest.	Slight
			Bajin	1950	22	Earth	Cracks on the crest.	Slight
			Hasa-ike	1953	16	Earth	Leakage from downstream slope.	Slight
			Ohkura	1807	16	Earth	Cracks on the crest.	Slight
			Hirusawa	1948	24	Earth	Cracks on the crest.	Slight
			Kamonotani	1933	15	Earth	Heavy leakage from the bottom.	Serious
			Nishino	1935	18	Earth	Cracks on the crest.	Slight
			Shekishiba	1958	30	Earth	Unknown.	—
			Bakura	1931	21	Earth	Leakage from the bottom of the embankment.	Medium
Tokachi-oki	May 16, 1968	7.9	Tanosawa	1626	23	Earth	Cracks on the crest, settlement.	Medium
			Koganezawa	1938	21	Earth	Cracks on the crest.	Slight
Akita Toho	Oct. 26, 1970	6.5	Yunosawa	1930	27	Earth	Slide cracks on the crest.	Medium
							Cracks on the crest (20 cm wide).	Slight
Miyagiken-oki	Jun. 12, 1978	7.4	Ushino	1965	23	Rock-fill	Slide of upstream surface.	Slight
			Irusawa	1948	24		Lateral cracks.	Slight
Nihonkai Chubu	May 26, 1983	7.7	Megurisekida	—	18	Earth	Cracks, leakage from the bottom.	Slight
			Hongo	1956	17	Earth	Crest settlement of 50 cm.	Medium
			Higashidaisa	1970	17	Earth	Leakage from the bottom.	Slight
			Ohzutsumi	1940	15	Earth	Cracks on the surface block.	Slight
Chibaken Toho-oki	Dec. 17, 1987	6.7	Konaka Tameike	1936	21	Earth	Cracks on the crest.	Slight

Table 7. Observations of earthquake damage to fill dams with height above 30 m in Japan

Earthquake	Date	Magnitude (M_J)	Name of dam	Date of completion	Height (m)	Type of dam	Epicenter distance	Maximum acceleration at the dam site (gal)	Characteristics of damage	Degree of damage
Kanto-dai	Sept. 1, 1923	7.9	Chino	1914	37	Earth (concrete core)	—	330 (based on post-earthquake toppled gravestone survey)	Crest settlement of 24 cm Lateral cracks perpendicular to the dam axis.	Slight
Akita Nanseibu	Oct. 26, 1970	6.5	Ainono	1962	41	Earth	15	150 (estimated from seismometer readings and other data)	Longitudinal 5 ~ 25 cm wide and 40 m long cracks.	Slight
Nihonkai Chubu	May 26, 1983	7.7	Namioka	1982	52	Rock fill (central core)	160	94 (estimated from seismometer in the upstream/downstream direction within the bedrock of the dam. Observed max. acc. Was 223 gal at the crest.)	Maximum crest settlement 6 cm. Earthquake at lowest water level	Slight
Naganoken Seibu	May 26, 1984	6.9	Makio	1961	106	Rock fill (central core)	29	500 ~ 600 (estimated from seismometer readings and other data)	Longitudinal cracks on the crest. Sliding of surface rock near the edge of crest.	Slight ~ Medium
Chibaken Toho-oki	Dec. 17, 1987	6.7	Nagara	1985	52	Earth (sloping core)	29	262 (estimated from seismometer in the upstream/downstream direction within the bedrock of the dam. Observed max. acc. was 369 gal on the crest.)	Cracks on the crest pavement. Crest settlement of 20 mm During reservoir testing.	Slight

Table 8 . Earthquake damage to fill dams worldwide

Year	Magnitude (Ms)	Name of dam	Date of completion	Height (m)	Type of dam	Intensity of shock	Characteristics of damage	Degree of damage
1906	7.8	San Andreas	1870	33	Earth	10[a]	A single longitudinal crack 2 to 3 in. wide near the center of the crest.	Slight
		Upper Crystal Spring	1887	47	Earth		Longitudinal transverse cracks. Offset about 8 ft on the crest.	Slight
		Pilarcitos	1874	29	Earth		No damage	No
1925		Sheffield	1918	15	Earth	9[b]	Complete failure due to liquefaction of the lower portion of the embankment or the upper part of the foundation.	Serious (Failure)
1930		Chatsworth No.2	1918	11	Earth (hydraulic-fill)	7[a]	Longitudinal 1/4 to 3 in. wide cracks over the full length of the dam. Crest settlement of 1 to 3 in.	Medium
1952	7.8	South Haiwee	1912	27	Earth (hydraulic-fill)	10[a]	Several longitudinal cracks of 1/4 to 1 in. wide near the upstream edge of the crest. Total crest settlement of 1 in. in 2 weeks.	Slight
		Dry Canion	1912	17	Earth (hydraulic-fill)		Several longitudinal cracks on the crest. No further damage after sealing.	Slight
1955		Contra Costa	1928	15	Earth (concrete core)	7[a]	Longitudinal 0.1 to 0.2 ft. wide cracks near the crest. center just above the concrete cutoff wall.	Medium
1959		Hebgan	1914	27	Earth (concrete core)	10[a]	Crest settlement of 6 ft. near the middle of the dam. Overtopping at least four times due to a number of landslides around the reservoir edge.	Medium
1971	6.5	Lower San Fernando	1918	50	Earth (hydraulic-fill)	Max. Acc. ≒ 0.5 g	Upstream slope failure.	Heavy
		Upper San Fernando		27		Max. Acc. ≒ 0.5 g	Large downstream movement.	Heavy
1990	7.8	Pantabangan (Philippines)	1974	107	Rock fill	Max. Acc. ≒ 0.3~0.4 g	Cracks settlement of 10 in. Longitudinal 1 ft. wide and 20 ft. long cracks.	Slight

a) : Modified Mercalli scale, b) : Rossi-Forel scale.

Namioka dam, 146 km from the epicenter. The recorded data showed that the maximum input acceleration of seismic waves transmitted to the bedrock was 94 gal, with the embankment crest exhibiting a seismic response of 223 gal. The earthquake occurred when the dam was empty, and only slight damage occurred. The Naganoken Seibu earthquake (1984; M_J=6.9) did not result in severe damage of the Makio dam close to the epicenter. This dam was completed in 1961 as a central core-type rock fill dam with a height of 105 m. The dam was equipped with strong-motion earthquake response seismometers, with a maximum scale limit of 300 gal, one on the top and another in the bedrock. It was suggested that the earthquake motion could have exceeded the scale, possibly reaching 500 to 600 gal. A post-earthquake investigation revealed that the downstream crest slipped along the slope over a width of 20–50 cm, and a height of 10–50 cm, without causing serious damage. The Makio dam design included protection against a horizontal seismic intensity of Kh = 0.15, and a minimum safety factor of 1.40. The Chibaken Toho-oki earthquake (1987; M_J=6.7) damaged the Nagara dam. This dam was completed in 1985, and was an earth dam 52 m high, located at a distance of 29 km from the epicenter. The earthquake caused a maximum input seismic wave acceleration of 262 gal propagating in the bedrock in the upstream/downstream direction, and 365 gal recorded on the crest where only cracks occurred. The Hyogoken Nambu (Great Hanshin-Awaji) earthquake (1995; M_J=7.2) damaged many soil structures but there was no serious damage affecting large fill dams. Taniyama Dam is located at a distance of about 7 km from the epicenter and as close as 3 km for the Nojima Fault.

These instances show that fill dams characterized by modern geotechnical/soil engineering designs are earthquake-proof and are not subject to heavy damage. Dams experienced only slight damage even with seismic intensities above that considered in the dam designs.

Some instances of earthquake damage to typical fill dams outside Japan are depicted in Table 8. In the United States, the Santa Barbara earthquake (1925) damaged the Sheffield dam[3,4]. The banks of this dam were 11 m high and were insufficiently compacted. They failed to withstand the rise in pore water pressure in the lower part of the dam and collapsed. The San Fernando earthquake (1971) caused serious damage to both the Lower San Fernando dam with a bank height of 43 m and the Upper San Fernando dam with a bank height of 25 m. These 2 dams had been constructed according to a hydraulic-fill process, and were in the neighborhood of a fault. Therefore they experienced damage. Recently, the Loma Prieta earthquake (1989) has caused slight damage to 9 earth dams. The seismic data from the Lexington dam show that the dam abutment (approximately corresponding to the bedrock) experienced a maximum seismic wave input acceleration of 452 gal.

The center of Luzon Island, Philippines, had an earthquake with a magnitude of 7.8 on July 16, 1990, and the Pantabangan (107 m high) and Masiway dams (25 m high) near the epicenter were damaged. The damage to the Pantabangan dam was relatively slight, including a settlement of the crest (25 cm) and the release of joints in the upstream concrete wall with gaps in some joints. Masiway dam suffered more severe damage than the Pantabangan dam. The earthquake caused a settlement of 1.5 m on the crest near the spillway. However, the dam remained safe to use in terms of leakage and sliding surface. Considering the distance of this dam from the epicenter, and the magnitude of the earthquake, it is estimated that the maximum input acceleration of the seismic waves transmitted to the dam was approximately 300 to 400 gal. These values clearly exceeded the design criteria for earthquake intensities, but no serious damage occurred.

These findings based on earthquake surveys show that large-scale fill dams have never experienced serious damage, suggesting that current dam design methods (material characteristics and slope stability analysis method) are technologically sound.

Conclusion

We have compiled data on earthquake damage to fill dams in Japan and in other countries. The majority of the fill dams that experienced earthquake damage were small, and fill dams for which modern geotechnical/soil engineering designs were applied did not experience serious damage even with earthquake intensities above the design criteria. Therefore, it is considered that large-scale fill dams are markedly resistant to earthquakes. The conclusions are as follows.

1) For small earth dams

(1) Based on the data of 5 earthquakes, the distance from the epicenter at which earth dam damage occurs is expressed using magnitude as follows;

$$R = 1155 \qquad 5 < M_J < 6.1 \text{ ....(1)}$$

$$\log R = 0.846\, M_J - 4.14 \qquad 6.1 \leqq M_J < 8 \text{ ....(2)}$$

where M_J : magnitude, R: critical distance from epicenter (km).

(2) Most cracks generated on dam bodies are longitudinal cracks parallel to the dam body. There are few lateral

cracks perpendicular to the dam body and they occur frequently on the border of the abutment and near outlet works.

(3) As for the physical properties of the dam body, the damage is serious for sandy soil dams, particularly in the case of failure. It is estimated that liquefaction was the major cause of damage for many dams.

2) For large fill dams

(1) The only case of earthquake damage to a fill dam with a bank height of more than 15 m is that experienced by the Manno-ike dam.

(2) Earthquakes have subjected fill dams to maximum input accelerations of 260 to 600 gal. Conversion to static earthquake intensity shows that these values exceed the earthquake magnitudes considered in design criteria. It is evident that even such high intensities do not cause serious damage to large-scale fill dams.

(3) Although fill dams with heights above 15 m in the United States have experienced serious damage, it must be noted that they were constructed based on the hydraulic-fill process. The above review indicates that large fill dams with heights above 15 m and constructed with the current dam designs exhibit a high earthquake resistance and provide sufficient safety against earthquakes.

References

1) Akiba, M. & Senba, H. (1941): The Oga earthquake and its influence on earth dam. *J. Jpn. Soc. Agric. Eng.*, **13** (1), 31–59 [In Japanese].
2) Manno-ike irrigation association (1929): Construction history of Manno-ike dam [In Japanese].
3) Seed, H. B. (1979): Consideration in the earthquake resistant design of earth and rock-fill dams. *Geotechnique*, **29** (3), 215–263.
4) Sherard, J. R. et al. (1963): Earth and earth-rock dams. John Wiley and Sons, Inc., 156–170.
5) Takase, K. (1967): Statistic study of earth dam damage. Doctoral Dissertation [In Japanese].
6) Tani, S. & Hasegawa, T. (1988): Earthquake damage on earth dam by the 1983 Nihonkai Chubu earthquake. *J. Jpn. Soc. Agric. Eng.*, **55** (10), 17–25.
7) Tani, S. (1991): Consideration of earthquake damage to earth dam for irrigation in Japan. *In* Int. Conf. Geotech. Earthquake Eng. Soil Dyn., 1137–1144.

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