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SYNOPSIS Earthquakes have caused much damage to fill type dams. Research into earthquake damage has contributed to the study of earthquake resistance of dams. However damage to fill dams occuurred almost only to small scale earth dams, especially the few cases of heavy damage. This report describes the damage and performance of fill dams more than 15m-high during earthquakes, drawn from literature, data, and field surveys. The results indicate that even stronger earthquakes than the design 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 resistant.

INTRODUCTION

A 1978 survey 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% have a height of less than 10m. Like other soil structures fill dams have suffered from damage in past earthquakes. Analytical geotechnical/soil-engineering surveys of earth-quake damage to fill dams have provided usefull suggestions for determining measures against earthquake damage. The surveys have found that the majority of fill dams which have suffered earthquake damage are small-scale earth dams , and no large-scale fill dams higher than 15m, except "Manno-ike" dam (which was damaged in the 1854 "Ansei Nankai" earthquake), have suffered serious damage.

This report summarizes the behavoir of fill type dams higher than 15m during earthquakes including cases where fill dams were damaged.

1. EARTHQUAKE DAMAGE TO FILL DAMS IN JAPAN

Earthquake damage to fill dams in Japan has paralleled the history of fill dam construc-tion. "Manno-ike" dam is the first reported case of earthquake damage to fill dam. the Manno-ike was possibly damaged due to a phenomenon termed "piping" that emerged one month after the Ansei-Nankai Earthquake (1854). The Nohbi Earhquake (1891) damaged " Irukaike" dam (Aichi Pref.). The first post earthquake survey was performed after the North Tango Earthquake (1927).

The damage by Oga Earthquake (1939) was surveyed by Akiba. The major conclusion is that a large damage occur to the earth dams with embankments of sandy soil. The conclusion suggests that "liquefaction" could have subjected such embankments to serious damage. Later, detailed surveys of earth dam damage took place after the Niigata Earthquake (1964), Tokachi-Oki Earthquake (1968), Miyagi-Oki Earthquake(1978), Mid Japan Sea Earthquake (1983), and the Chiba-Tohooki Earthquake (1987).

Table 1 Time of Constructionf of Fill Dams with Height of More Than 15 m

Construction Time	~1867	1868 ~1945	1946 ~1950	1951 ~1960	1961 ~1970
Number	438 (23.4)	610 (32.6)	51 (2.7)	189 (10.1)	193 (10.3)

1971 ~1980	1981 ~1985	Under construction	planned	Total
148 (7.9)	18 (1.0)	186 (9.9)	39 (2.1)	1,872* (100)

*1,506 earth dams

Table I shows the time of construction of fill dams for irrigation, with heights of more than 15m constructed prior to 1985. The total number of fill dams is 1,872, with 1,506 earth dams; 438 are very old, constructed before the Meiji era. Most of these were brought into service during the "Edo" period. The following refers to damage of fill dams with heights of 15-30m in Japan.

Table 2 details major earthquake damage to fill dams with heights of 15-30m in Japan. This table shows that no large scale fill dam with height of 15-30m have suffered heavy earthquake damage, except the case of Manno-ike.

Table 3 shows observations during earthquake of typical large fill dams with heights of more than 30 m in Japan. Thetable includes the Akita-Toho Earthquake (1970) with Mj=6.5 where the "Ainono Dam" suffered damage. This dam was completed in 1961.It is uniform type ,41m 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. Anattempt to calculate the earth-quake intensity, from an epicenter distance of 15 km, suggested that the maximum input acceleration of seismic waves transmitted to the bedrock was around 150gal. The post earthquake survey report disclosed that major damage showed at the crest of the da m in the form of several vertical cracks ext end- ing over 40m, each 5 to 25cm wide.

The Mid Japan Sea Earthquake was recorded at Namioka Dam 146km from the epicenter. The recorded data showed that the maximum input acceleration of seismic waves transmitted to the bedrock was 94gal, with the embankment crest exhibiting a seismic response of 223 gal. The earthquake occurred when the dam was empty, and only slight damage occured.

The Naganoken-Seibu Earthquake (1984; MJ= 6.9) subjected the Makio Dam close to the epiceter to non-serious damage. This dam was completed in 1961 as a center core type rock fill dam with a height of 105m.The dam was equipped strong-motion earthquake response seismometers, with a maximum scale limit of 300gal, one at the top and another in the bedrock. It was suggested that the earthquake motion could have gone beyond the scale, possibly reaching 500 to 600 gal. A post-earthquake investigation found that the downstream crest slippeds along the slope over a width of 20-50cm, and a height of 10-50cm, without causing serious damage,

Table 2 Observations of Eathquake Damage to Fill Dams with Heights of 15-30m In Japan

Earthquake	Date	Magni-tude(Mj)	Name of Dam	Date of Completion	height	Height of Dam	Paticulars of Damage	Degree of Damage
Ansei -Nankai	Jul.24 1854	8.4	Manno Ike	Around 700	23	Earth	·1 month after the earthquake, leakage was reported in the embankment.Failure occured 6 days later.	·Failure
Nobi	Oct.28 1891	8.4	Iruka Ike	1633	29	Earth	·Longitudial cracks on the crest.	·Slight
Kanto -Dai	Sept.1 1923	7.9	Ohno Reservoir	1914	34	Earth (concret core)	·Crest settlement of 24cm. Lateral cracks on the crest.	·Medium
			Murayama Upper	1923	24	Earth	·Crest settlement of 20cm.	·Slight
			lower	Under Construct.	16(33)		·Longitudial cracks on the crest	·Slight
Oga	May I 1939	7.0	Iwakura Tameike	1931	17	Earth	·Longitudial cracks on the crest.	·Slight
Matsushiro	Aug.1965 ~Dec.1968	Max.5.4	Ohike	1927	16	Earth	·Longitudial cracks.	·Slight
			Shionoiri	1936	25		·Longitudial cracks.	·Slight
Nigata	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
			Hase 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.	·Heavy
			Nishino	1935	18	Earth	·Cracks on the crest.	·Slight
			Sekishiba	1958	30	Earth	·Unknown	――
			Bakura	1931	21	Earth	·Leakage from the bottom of the embank.	·Medium
Tokachi -Oki	May.16 1968	7.9	Tanosawa	1926	23	Earth	·Cracks on the crest,settlement	·Medium
			Koganezawa	1938	21	Earth	·Cracks on the crest	·Slight
Akita -Touhou	Oct.26 1970	6.5	Yunosawa	1930	27	Earth	·Slide,cracks on the crest.	·Medium
							·Cracks on the crest(20cm wide)	·Slight
Miyagi -Oki	Jun.12 1978	7.4	Ushino	1965	23	Rock fill	·Slide of upstream surface.	·Slight
			irusawa	1948	24		·Lateral cracks.	·Slight
1983 Mid Japan sea	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	1940	17	Earth	·Leakage from the bottom.	·Slight
			Ohzutsumi	1940	15	Earth	·Cracks on the surface block.	·Slight
Chiba -Touhouoki	Dec.17 1987	6.7	Konaka Tameike	1936	21	Earth	·Cracks on the crest.	·Slight

The Makio Dam design included p roof against a horizontal seismic intensityof K_h= 0.15, and a minimum safety factor of 1.40.

The Chiba-Tohooki Earthquake (1988; MJ=6.7) caused damage to the Nagara Dam. This dam was completed in 1985, and is a 52m high zone type earth dam, 29km 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 at the crest where only cracks occured.

These instances show that fill dams of modern geotechnical/soil engineering designs are earthquake-proof and are not subject to heavy damage. Dams suffer 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; In the United States, the Santa Barbara Earthquake (1925) damaged the Sheffied Dam. The banks of this dam were 11 m high and were insuffi -iently compact. They failed to withstand t e rise in pore water pressure in the lower part of the dam, and collapsed. The San Fernando Earthquake(1971) caused heavy damage to both the Lower San Fernando Dam with a bank height of 43m and the Upper San Fernando dam with a bank height of 25m.These two dams had been constructed with a hydraulic-fill process, and were in the neibourhood of a fault, wherefore these dams suffered such damage.

Recently, the Loma Prieta Earthquake (1989) caused damage to nine earth dams, none critical damage. The seismic data from the Lexington Dam shows that the dam abutment (approximately corresponding to the bedrock) experienced a maximum seismic wave input acceleration of 452gal.

The center of Luzon Island, Philippines, had a magnitude 7.8 eartquake on July 16,1990, and the Pantabangan (107m high)and Masiway Dams (25m high) near the epicenter suffered damage. The damage to the Pantabangan Dam was relatively slight, a settlement (25cm) of the crest and the release of joints in the upstream concrete wall with gaps in some joints. The Masiway Dam suffered shallow slides on both the upstream and downstream slopes and in the bed of a flood spillway , as well as crest settlement.

Masiway Dam suffered heavier damage than the Pantabangan Dam. However, with changed leakage, and dam ruptur examined, it was concluded that the dam has no safety problems. Considering the epicenter distance to this dam, and the magnitude of the earth -quake, it is estimated that the maximum input acceleration of the seismic waves transmitted to the dam, were approximately 300 to 400gal. This clearly exceeds the design criteria for earthquake intensities, but no serious damage occured.
These findings from earthquake surveys show that large-scale fill dams have never suffered critical damage ,allowing the conclusion that current dam design methods (material characteristics and slope stability analysis method) are technologically adequate.

Conclusion

We have summarized earthquake damage to fill dams in Japan, and at earthquakes in other countries. The majority of fill dams

Table 3 Observations of Earthquake Damage to Fill Dams with The Height of More Than 30 m in Japan.

Earth-quake	Date	Magni-tude(Mj)	Name of Dam	Year of Complet.	Height (m)	Type of Dam	Epicent. Dist.	Maxiumum Acceleration at The Dam Site (gal)	Paticulars of Damage	Degree of Damage
Kanto-Dai	Sept.1 ,1923	7.9	Ohno	1914	37	Earth (concrete core)	—	330 (based on post-earthquake toppled tombstone survey)	·Crest settlement of 24 cm. ·Lateral cracks perpendeicular 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)	·Longitudial 5～25cm wide and 40 m long cracks.	Slight
1983 Mid Japan Sea	May.26 ,1983	7.7	Namioka	1982	52	Rock fill (center core)	160	94 (estimated from seisometer in the upstream/downstream direction within the bedrock of the dam. Observed max. acc. was 223gal at the crest.)	·Maximum crest settlement 6cm. ·Earthquake at lowest water level	Slight
Nagano-ken-Seibu	May 26 ,1984	6.9	Makio	1961	106	Rock fill (center core)	29	500～600 (estimated from seismometer readings and other data)	·Longitudial cracks on the crest. ·Sliding of surface rock near the edge of crest.	Slight ～Medium
Chiba-Touhouoki	Dec.17 ,1987	6.7	Nagae	1985	52	Earth (sloped core)	29	262 (estimated from seisometer in the upstream/downstream direction within the bedrock of the dam. Observed max. acc. was 369gal at the crest.)	·Cracks on the crest pavement. ·Crest settlement of 20 mm. ·During reservoir testing.	Slight

suffering earthquake damage are small, and that fill dams employing modern geotechnical /soil engineering designs have not suffered serious damage even with earthquake intensities above the design criteria. In view of this, it is considered that large-scale fill dams are highly earthquake resistant. The following conclusions may be made:

(1) The only case of earthquake damage to a fill dam with a bank height of more than 15 m is that suffered 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 to exceed the earthquake magnitudes considered in design criteria. It is clear that even such high intensities do not cause serious damage to large-scale fill dams.

(3) Although fill dams with heights above 15m in the United States have experienced heavy damage, it must be noted that they are constructed by the hydraulic fill process. The above examination shows that fill dams defined as large, with heights above 15m and constructed with the current dam designs have excellent earthquake resitance and provide sufficient safety against earthquakes.

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Table 4 Earthquake Damage to Fill Dams

Year	Magnitude Ms	Name of Dam	Year of Completion	Height (m)	Type of Dam	Intensity of shock	Particulars of damage	Degree of Damage
1906	7.8	·San Andreas	1870	33	Earth	10※	·A single longitudial crack 2 to 3 in. wide near the center of the crest.	·Slight
		·Upper Crystal Spring	1887	47	Earth		·Longitudial transvers cracks. Offset about 8ft at the crest.	·Slight
		·Pilarcitos	1874	29	Earth		·No damage	·No
1925		·Sheffield	1918	15	Earth	9※※	·Complete failure due to liquefaction of the lower portion of the embankment or the upper part of the foundation.	·Failure
1930		·Chatsworth №2	1918	11	Earth (hydraulic -fill)	7※	·Longitudial 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 number of longitudial 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)		·A number of longitudial cracks on the crest No further trouble after sealing.	·Slight
1955		·Contra Costa	1928	15	Earth(Concrete Core	7※	·A longitudial 0.1 to 0.2 ft. wide cracks near the crest center just above the concrete cutoff wall.	·Medium
1959		·Hebgen	1914	27	Earth(Concrete Core	10※	·Crest settlement of 6 ft. near the middle of the dam. Overtopping at least four times due to a number of landslides around the resorvoir edge.	·Medium
1971	6.5	·Lower San Fernando	1918	50	Earth (hydraulic -fill)	Max. Acc ≒ 0.5g	·Upstream slope failure.	·Heavy
		·Upper San Fernando		27	Earth (hydraulic -fill)	Max. Acc ≒ 0.5g	·Large downstream movement.	·Heavy
1990	7.8	·Pantabangan (Philippine)	1974	107	Rock fill	Max. Acc ≒ 0.3～0.4g	·Crest settlement of 10 in. A longitudial 1 ft. wide and 20 ft. long cracks.	·Slight

※ Modified Mercalli scale ※※ Rossi-Forel scale