International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2001 - Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

28 Mar 2001, 4:00 pm - 6:30 pm

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Recommended Citation

Tani, Shigeru, "Consideration of Earthquake Resistant of Large Fill Dams" (2001). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 1.
https://scholarsmine.mst.edu/icrageesd/04icrageesd/session10/1

CONSIDERATION OF THE EARTHQUAKE RESISTANCE OF LARGE FILL DAMS

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ABSTRACT

There are two approaches for estimating the stability of fill dams during earthquakes. The first method determines the ultimate resistance of dams by using theoretical analyses, such as slide analysis and finite element method. In actuality, fill dams do not immediately collapse even when the safety factor by slide analysis is less than 1.0. The finite element method estimates safety based on displacement, which cannot be accurately determined with analytical methods. The second approach estimates the maximum seismic force fill dams can resist based on past earthquake damage to fill dams. In this study, we used this second method to investigate the earthquake resistance of fill dams, and estimated the earthquake damage to fill dams that are at least 15 m in height and have been built since 1953 based on the modern design standards. We derived the following conclusions:

(1) In Japan, no fill dam of at least 15 m in height that has been built based on the modern design standards has been destroyed by an earthquake. Only earth dams built by using experimental methods have been affected.

(2) Earthquakes have caused maximum input acceleration of 260 to 600 gal at the foundations of fill dams. These values, which may be converted into static intensities, exceed the dam design values, but no dam has been destroyed.

The fact that fill dams have not been destroyed by major earthquakes suggests empirically that large fill dams are highly earthquake resistant and that the conventional dam design system (methods for determining physical values and for evaluating safety) is generally appropriate for investigating earthquake resistance.

KEYWORDS

Large fill dam, earthquake resistance, irrigation

INTRODUCTION

Fill dams may be classified into modern dams constructed based on design standards and small earth dams built based on experience. In Japan, there are approximately 100,000 fill dams and about 1,872 irrigation dams of at least 15 m in height. Most of these 1,872 irrigation dams, 1,688 (89%) are fill-type dams, of which 438 were constructed before 1868. The history of fill dam construction in Japan began approximately 1,600 years ago. After 1945, full-scale design standards were established, and studies on earthquake-resistant design began. There are two approaches for estimating the stability of fill dams during earthquakes. The first method determines the ultimate resistance of dams by using theoretical analyses, such as slide analysis and the finite element method. In actuality, fill dams do not immediately collapse even when the safety factor is less than 1.0. The finite element method estimates safety based on displacement, which cannot be accurately determined with analytical methods. The second approach estimates the maximum seismic force that fill dams can resist based on past earthquake damage to fill dams. In this study, we used this second method to investigate the earthquake resistance of fill dams, and estimated the earthquake resistance of fill dams in Japan that are more than 15 m in height.

DAMAGE TO OLD FILL DAMS

Old fill dams were built based on empirical technology and have been damaged during past earthquakes. There are earth dams that have collapsed, have seriously subsided, and/or have lost the capability of storing water. Our survey and analyses of such dams revealed that the main cause of serious damage was the liquefaction of the foundation ground and/or the embankment. Earth dams having other conditions have also suffered damage but on a lesser scale. Liquefaction is likely the principal cause of serious damage to earthen structures, such as earth dams.

Earthquake damage to fill dams in Japan has paralleled the history of fill dam construction. The Manno-ike Dam was the first reported case of earthquake damage to fill dams. This dam was likely damaged by a phenomenon called "piping" that occurred one month after the Ansei Nankai earthquake (1854). The Nobi earthquake (1891) damaged the Iruka-ike Dam. The first post-earthquake survey was performed after the North Tango earthquake (1927). The damage caused by Oga earthquake (1939) was surveyed by Akiba (1941). The major conclusion was that earth dams with embankments of sandy soil experienced severe damage, suggesting that liquefaction could have been involved. In the Hyogo-ken Nanbu Earthquake, about 1,200 fill dams (small earth dams) were damaged, nine of them seriously.

DAMAGE TO LARGE FILL DAMS

The total number of large fill dams for irrigation is 1,872. Among these are 1,506 earth dams, including 438 very old ones that were constructed before the Meiji Era (1868~1912). Most of these were brought into service during the Edo Period (1603~1867). Most of the dams that have been severely affected by earthquakes were old earth dams although some modern fill dams have also suffered earthquake damage. Of the fill and earth dams that were severely damaged by earthquakes and were of at least 15 m in height built before 1953, most were old earth dams although some modern fill dams also suffered earthquake damage. Table 1 shows the damages to large fill dams in Japan. The Akita-ken Nantobu

Table1 Relationship between design seismic intensity and safety factors

Name of Earthquake	Occurrence	Magnitude (M)	Name of Dam	Type of Dam	Epicent. Dist. (km)	Max. Acc.* (cm/s^2)	Degree of Damage	Design Seismic Factors	Minimum Safety Factors F_s (UP).,(LO)	Destructive Seismic Factors F_{sd}
Akita- antou	1970	6.5	Ainono	Earth	15	(150)*	Slight	0.20	1.56, 1.15	0.267
Nihonnkai-Chyubu	1983	7.7	Namioka	Rock fill	141	94	Slight	0.20	1.20, ---	0.254
			Hongou	Earth	137	(90)*	Slight	0.20	1.22. 1.25	0.30
Nagano-Seibu	1984	6.9	Makio	Rock fill	5	500~600	Slight	0.20	1.35, 1.40	0.254
Chiba-Touhouoki	1987	6.7	Nagara	Earth	29	369	Slight	0.20	1.43, 1.22	0.298
Hokkaido-Nanseioki	1973	7.8	Makomanai	Rock fill	34	(196)*	Slight	0.10	1.20, 1.20	0.154
			Kamiiso	Rock fill	152	215	No	0.20	1.23, 1.33	0.263
Hyougo-Nanbu	1995	7.2	Taniyama	Earth	8	(580)*	Slight	0.20	1.21, ---	0.293
			Tokiwa	Earth	10	(420)*	Slight	0.20	1.21, 1.22	0.293
			Ohtani	Earth	7	(580)*	Slight	0.15	1.50, 1.50	0.372
			Koujiya	Rick fill	134	132	No	0.20	1.21, 1.22	0.257
Kagoshima-Satsuma (No. 1,2)	1997	6.3	Mitarai	Rock fill	7	(290)*	Slight	0.12	1.20, 1.20	0.174
		6.1	Kushikino	Rock fill	19	(135)*	Slight	0.12	1.20, 1.20	0.174

*Max. Acc. = $18.4 \times \Delta^{0.302M} \times \Delta^{0.8}$ (By Iwasaki, 1974) 、 UP : Upper slope; LO : Lower slope

Earthquake (1970, M = 6.5) caused damage to the 41-meter high Ainono Dam, a homogeneous type that was completed in 1961. The seismograph installed at the site could not record the earthquake motion, which exceeded the range of measurement. From the data for the epicentral distance of 15 km, the maximum input acceleration to the foundation is estimated to have been about 150 gal. The earthquake caused several longitudinal cracks of 5 - 25 cm in width and 40 m in length on the dam crest.

The Nagano-ken Seibu Earthquake (1984, M6.9) caused slight damage to the 105-meter high Makio Dam located very near the epicenter. The dam is a central core-type rock fill type that was completed in 1961. Seismographs that could measure up to 300 gal were installed at the dam crest and the foundation ground, but the earthquake motion exceeded this value and was estimated to have been 500 - 600 gal. The earthquake moved some rocks at the downstream-side crest section of the dam body but caused no severe damage. Inspection after the earthquake revealed that there were cracks on the rock section but no crack reached the core. The dam had been designed with horizontal seismic intensity of $k_h = 0.15$ and minimum safety factor of 1.40. Fig. 1,2 shows the heights of fill dams in Japan built before and since 1953, respectively, and their damage levels caused by earthquakes and the maximum horizontal acceleration at the foundation either measured or estimated using Iwasaki's formula.

$$A = 18.4 \times 10^{0.302M} \times \Delta^{0.8} \quad (1)$$

where A= Maximum acceleration (gal), and Δ = Epicentral Distance (km). Damage level was classified into three categories as following. Slight : Crack or Settlement at crest <50cm, Medium: 50< Settlement <100 cm, Serious: Failure or Settlement >100cm. Since there were no fill dam design standards before 1953, the technical background was completely different from those built since 1953. While fill dams constructed after 1953 have scarcely been damaged, some of the dams built before then have been very seriously affected. However, only one dam has failed. The figures, which also include estimated values, show maximum accelerations around 600 gal. Fill dams in Japan that have been constructed based on the modern design method, should sufficiently resist earthquakes that cause such maximum acceleration. Official records (or sometimes estimates) of earthquake motion at dam sites in Japan have shown that at maximum input acceleration of about 600 gal, earthquakes do not seriously affect modern fill-type dams .All fill-type dams that were destroyed or seriously damaged had been built before 1918.

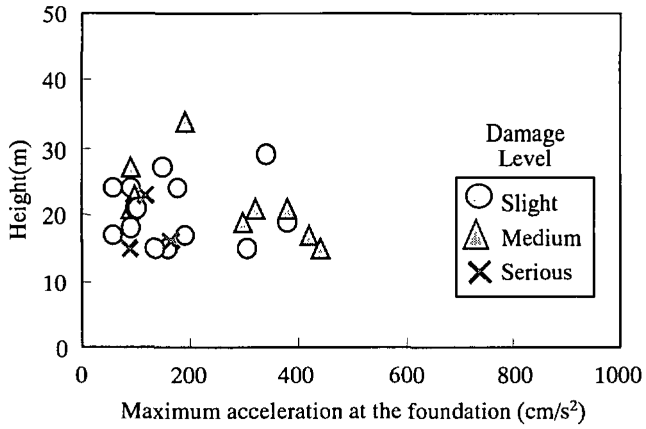

Fig.1 Earthquake damage to large fill dams constructed before 1953 in Japan

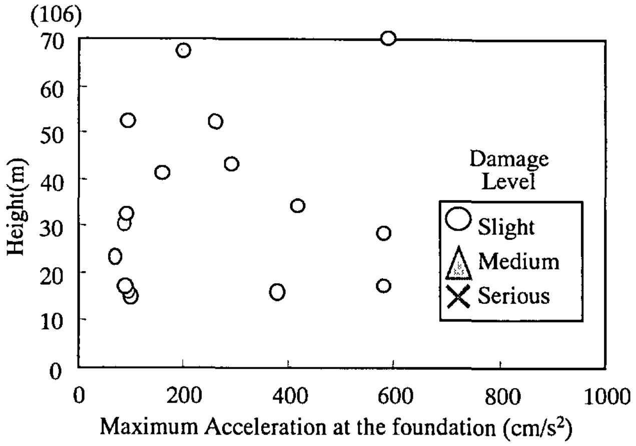

Fig.2 Earthquake damage to large fill dams constructed after 1953 in Japan

Fill dams that have been built based on the design standards have the following characteristics

1) Modern fill-type dams constructed on a firm rock foundation (N value by SPT > 50)
2) Both the strength of core and rock zones are very high since their density is kept to within at least of 95 % of the JIS maximum density
3) By using the circular slip method, modern dams are designed to always retain a slip safety coefficient of Fs=1.20

These characteristics can probably account for the only slight damage that earthquakes have inflicted on modern fill-type dams. The fact that fill dams have not been destroyed by major earthquakes suggests empirically that large fill dams are highly earthquake resistant and that the conventional dam design system (involving methods for determining soil properties and for evaluating safety factors) is generally appropriate for investigating earthquake resistance.

Fig.3 summarizes earthquake damage to dams in other nations and maximum horizontal acceleration at the foundation either measured or estimated by using Gutenberg and Richter's formula (1942)

$$\log A = I_{MM} / 3 - 0.5, \qquad (2)$$

where A= Maximum Acceleration (gal), and I_{MM} = Modified Mercalli Scale. The maximum acceleration measured at the dam site was about 700 gal. Some dams have been seriously affected, mainly by liquefaction. All fill dams that were destroyed or seriously damaged had been built before 1918, and those that had been constructed after 1918 were only slightly affected.

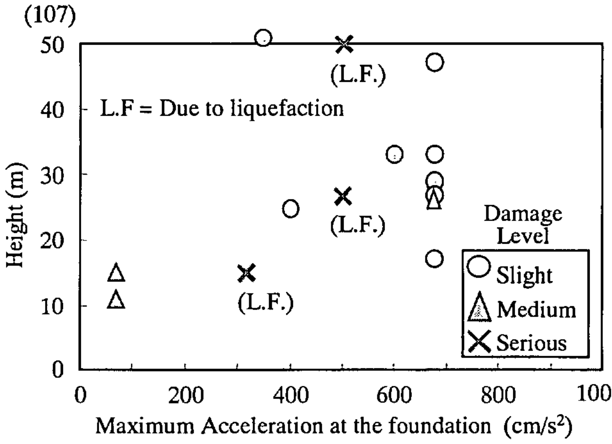

Fig.3 Earthquake damage to large fill dams in the world

SAFETY FACTORS, MAXIMUM ACCELERATION AND HORIZONTAL INTENSITY

Experience has shown that fill dams built with modern design standards should be able to resist a force of up to about 600 gal. Fill dams are designed with a horizontal seismic intensity of 0.10 to 0.20. The relationship between the actual maximum acceleration of seismic waves and the horizontal intensity K_h is generally expressed as:

$$K_h = Cr\, Amax/g \qquad (3)$$

where, Cr is the conversion factor, Amax is the maximum acceleration at the ground surface, and g is the gravitational acceleration (cm/s2).

Koga et al. derived Cr = 0.69 from the concept of cumulative damage. Matsuo et al. inversely analyzed earthquake damage to banks and estimated that the mean horizontal intensity for the slide safety factor of 1.0 was approximately 65% of the estimated maximum acceleration, and derived Cr = 0.65 to 0.69. Noda et al. and Uwabe et al.(1991) studied the relationship between maximum acceleration measurements and the seismic intensity that destroyed embankments, which are shown in Fig.4. Since the relationship between maximum acceleration and destructive intensity varied with the range of maximum acceleration, they proposed the following equations:

$$K_h = \alpha/g \qquad (\alpha<200 \text{ gal})$$
$$= 1/3\,(\alpha/g)1/3 \qquad (\alpha>200 \text{ gal}) \qquad (4)$$

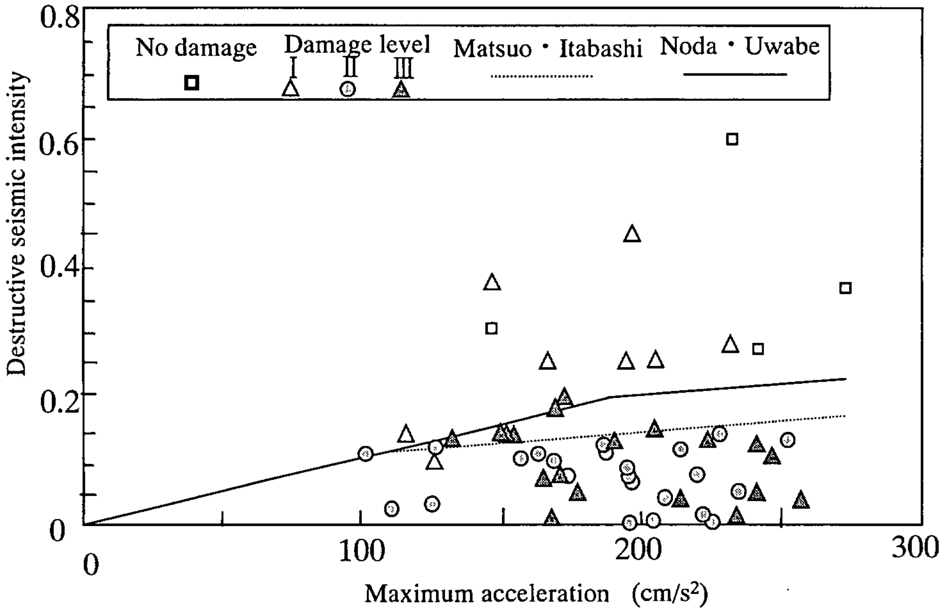

Fig.4 Relationship between maximum acceleration and seismic intensity (T. Uwabe,1991)

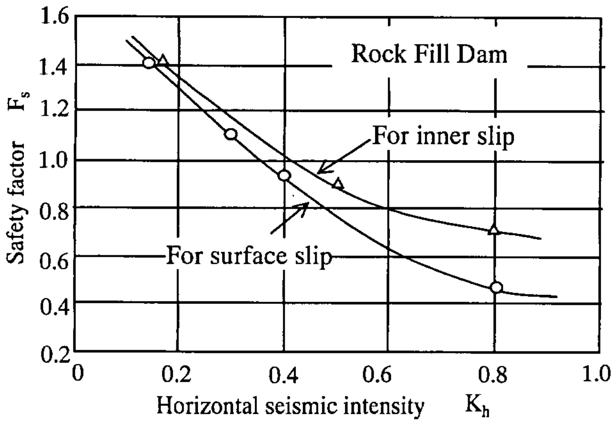

Fig.5 Relationship between safety factor F_s and horizontal seismic intensity K_h (Ōne, 1985)

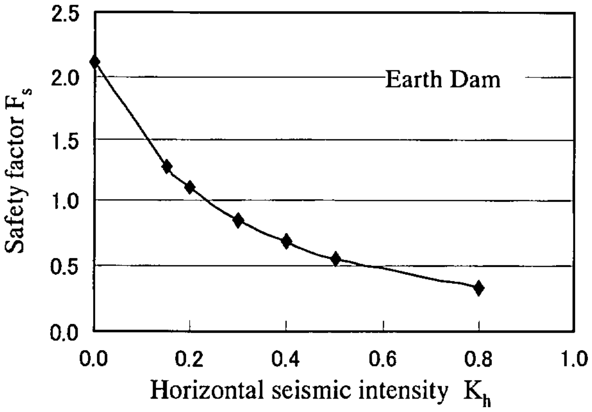

Fig.6 Relationship between safety factor F_s and horizontal seismic intensity K_h (Tani, 2000)

We studied the relationship between the maximum acceleration and the horizontal intensity for fill dams. Fill dams built with modern technology have been damaged only slightly, even by great earthquakes.

The relationship between horizontal intensity and slide safety factor, which One et al. calculated for a rock fill dam is shown in Fig.5. The figure shows that the horizontal intensity K_h is 0.20 when the safety factor is 1.35 and K_h is 0.40 when the safety factor is 1.0. This relationship likely varies with crest height, sectional form, the strength of the materials used, and other factors. Since not all data could be acquired, we could not determine the seismic intensity for the safety factor of 1.0 from slide analysis. Therefore, we approximated the K_{ds} value for the safety factor of 1.0 (□、■ in the Fig.7) by using the relationship for the inner slide of rock-fill dams between the change in horizontal intensity K_h and slide safety factor Fs. The data (K_{ds} values for the safety factor of 1.0) for undamaged and damaged earth dam are also shown in the figure with △ and ▲ by using the relationship between for an earth dams between the change in horizontal intensity K_h and slide safety factor Fs shown in Fig. 6. Fig.7 show the relationship between the maximum acceleration (either measured or estimated from the seismic intensity and epicentral distance) and the destructive horizontal seismic intensity shown in Table1. Assuming that the destructive intensity is the value at safety factor = 1.0, the design and destructive intensities are different

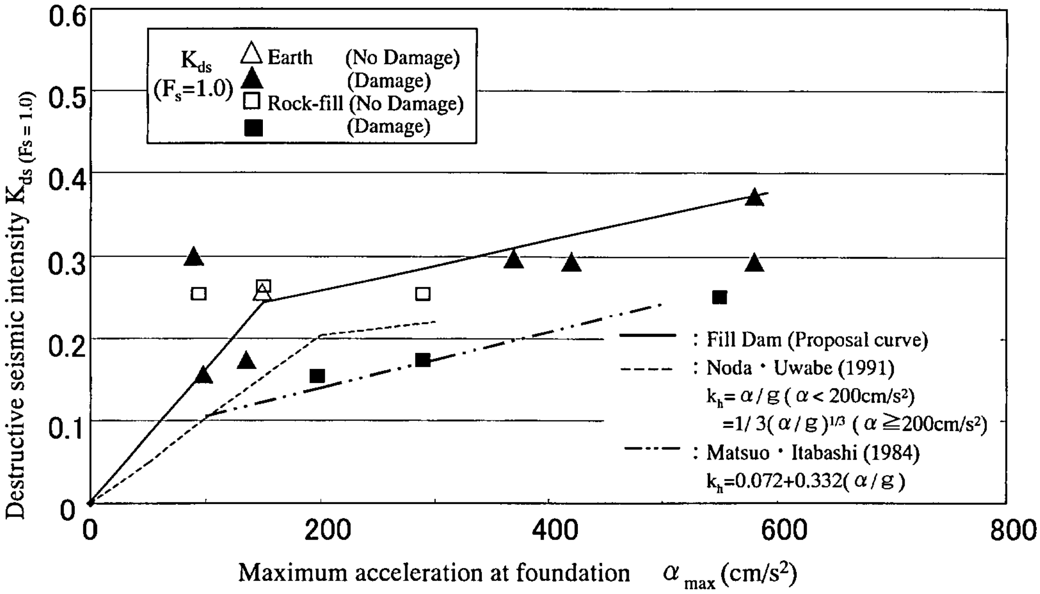

Fig.7 Relationship between destructive seismic intensity and maximum acceleration at foundation

An approximate curve derived by Noda and Uwabe method is shown in Fig.7. The upper limit of damage is shown with a solid line in the Fig.7. Fill dams showed a tendency similar to that of other civil structures. The data for Fill dam were different from others due to the difference of height. Although the number of data is few, the solid line in Fig.7 is believed to show the relationship between the destructive intensity and the maximum acceleration for fill dams. We will collect more data and further study the relationship between destructive intensity and maximum input acceleration to the foundation.

TARGET OF EARTHQUAKE RESISTANCE OF LARGE FILL DAMS

Safety evaluation and disaster prevention of fill dams depend greatly on the established level of the target resistance. For earth dams, the target is that the dams will not collapse during earthquakes. To prevent collapse, the settlement or sliding of the dam body must be controlled within a range such that reserved water does not overflow the levee. Considering the free boards of earth dams (crest height - maximum water level), earth dams must not subside more than 1.0 m.

In Japan, few dams have subsided 1.0 m or more during earthquakes. The main causes for settlement have been 1) soft dam bodies, and 2) liquefaction of sandy soil. Earth dams must be built to settle not more than 1.0 m even on soft ground or other places that may suffer liquefaction. For fill dams built with modern technology, the target earthquake resistance is a debatable topic. The Second Proposal of the Society of Civil Engineers defined that the target resistance of a civil structure against a Level 2 earthquake motion is deformation within the allowable range. However, it may be difficult to determine the allowable settlement of fill dams. To prevent failure, the maximum settlement will have to be controlled within the free boards.

CONCLUSION

Earthquake damage to fill dams was investigated by surveying damage caused by recent earthquakes and analyzing the behavior of the dams during the earthquakes and the causes of damage. In Japan, none of the fill dams constructed with the design standards has been seriously damaged. Most of the dams have suffered only slight damage and have been repaired and restored. Even the recent Hyogo-ken Nanbu Earthquake destroyed no fill dams. We also investigated damage in nations other than Japan and found that no dams other than hydraulic fill dams have been seriously damaged.

Fill dams that have been built based on the design standards have the following characteristics

1) Modern fill-type dams are constructed on a firm rock foundation (N value by SPT > 50)

2) The strength of both core and rock zones is very high since their densities are kept to within at least of 95 % of the JIS maximum density

3) By using the circular slip method, modern dams are designed to always retain a slip safety coefficient of Fs > 1.20

The fact that fill dams have not been destroyed by major earthquakes suggests empirically that large fill dams are highly earthquake resistant and that the conventional dam design system (methods for determining physical values and for evaluating safety) is generally appropriate for investigating earthquake resistance.

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