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Behavior and Damage of Dams Under the 1993 Big Earthquakes in Japan

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Behavior and Damage of Dams Under the 1993 Big Earthquakes in Japan

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SYNOPSIS By analyses of the acceleration records at dams during the two big earthquakes which hit in Hokkaido of Japan in 1993, the maximum acceleration at damsite rock, the maximum acceleration amplification ratios at crest and the natural periods of dam bodies were evaluated and were compared the results with empirical equations. Damage to the dams was described, and the mechanism of the deformations was examined.

1. INTRODUCTION

Two earthquakes hit in Hokkaido of Japan in 1993. The first was the 1993 Kushiro Oki Earthquake on January 15 with its hypocenter at a focal depth of 107 kilometers, and the second was the 1993 Hokkaido Nansei Oki Earthquake on July 12 at a focal depth of 34 kilometers. The magnitude of both earthquakes was 7.8, and a force of 5 or 6 on the seismic intensity scale was observed close to the epicenters of the two earthquakes by the Japanese Meteorological Agency. The earthquakes caused severe damage in terms of human casualties, destruction of dwellings, and damage to public works. Several dams were resultant damaged to varying degrees.

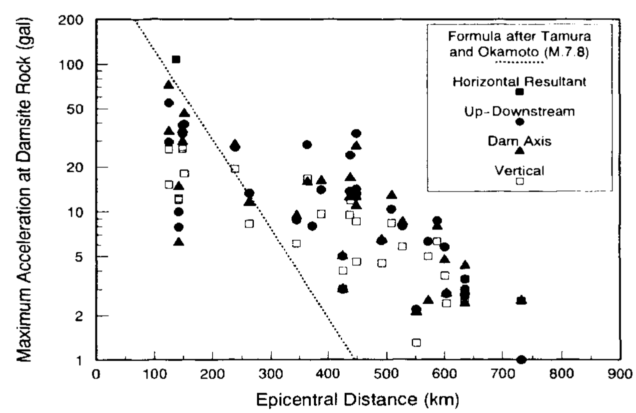
2. EARTHQUAKE MOTIONS OBSERVED AT DAMS AND DAMSITES

2.1 Maximum Acceleration

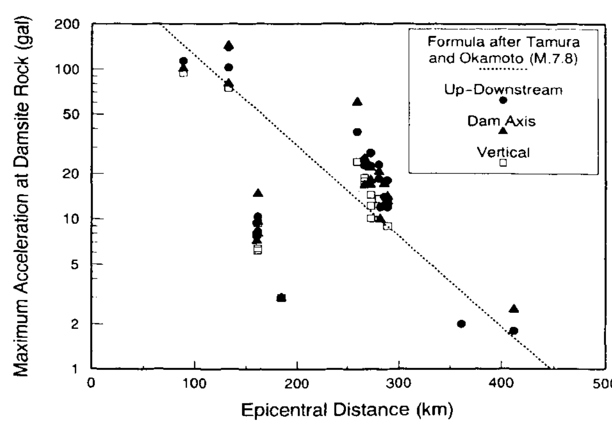
Figures 1 (a) and (b) show the attenuation of the maximum acceleration at damsite rock with the epicentral distance during the two earthquakes. In those figures, a dotted line represents attenuation of the maximum acceleration calculated by the formula of Tamura and Okamoto (1979) expressed as:

$$\log_{10}\frac{a_{max}}{1000}=\frac{\Delta+50}{100}(-4.93+0.89M-0.043M^2) \qquad (1)$$

where, a_{max} is the maximum rock acceleration in gal, Δ is the epicentral distance in km, and M is the magnitude of earthquakes. This attenuation formula was based on seismic records observed in underground rock within an epicentral distance of 280 kilometers. The actual records for the 1993 Kushiro Oki Earthquake tend to be smaller than those estimated by the attenuation formula for dams less than 300 kilometers from the epicenter and larger at dams further than 300 kilometers from the epicenter. In the case of the 1993 Hokkaido Nansei Oki Earthquake, up to an epicentral distance of about 400 kilometers, the actual attenuation is modeled accurately by the attenuation formula of Tamura and Okamoto.



(a) The 1993 Kushiro Oki Earthquake



(b) The 1993 Hokkaido Nansei Oki Earthquake

Fig. 1 Attenuation of the Maximum Damsite Rock Acceleration with Epicentral Distance

2.2 Acceleration Amplification at a Crest

Figure 2 shows the relationship between the maximum acceleration amplification ratio at a dam crest and the maximum acceleration at a base observed at embankment dams. The figure also shows cases of other earthquakes. For all earthquakes, the amplification ratios range from 2 to 8, and decrease as the maximum base accelerations increase. This is thought to be because of the increase of damping as the maximum base accelerations increase, and also because an earthquake event with a maximum base acceleration larger than 100 *gals* has a short epicentral distance and tends to cause earthquake motion with a higher frequency than that of the dam body. The amplification ratios for the up-downstream component tend to be larger than for the dam axis component.

2.3 Natural Period of Rockfill Dams

We calculated the frequency response functions from the time history records of the acceleration at the base and crest of rockfill dams. The predominant period of the functions is nearly equal to the fundamental natural period of the dams. Figure 3 shows the relationship between the natural period

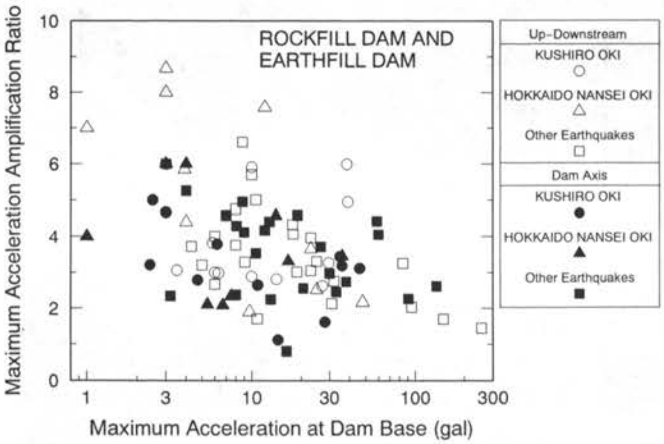


Fig. 2 Acceleration Amplification Ratio at the Crest with the Maximum Acceleration at the Base for Embankment Dams

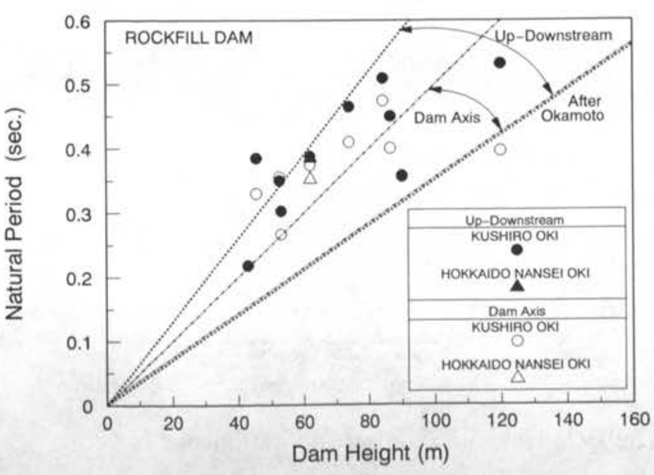


Fig. 3 Natural Period of the Rockfill Dam with Dam Height

and dam height. The natural period increases linearly with the dam height, and most of the plots are within the range of the empirical equation of Okamoto (1984) based on earthquake observations and vibration tests. The natural period in the dam axis component tends to be smaller and to deviate further from the range of the empirical equation than in the up-downstream component. This is thought to be because the shape and binding of the canyon affect the vibration in the direction of the dam axis.

3. DAMAGE TO DAMS DUE TO THE 1993 KUSHIRO OKI EARTHQUAKE

Because no dam with a height of 15 meters or more was located within 100 kilometers of the epicenter, damage to dams was small considering the intensity of the earthquake. Inspections revealed that only the Mombetsu Dam suffered slight damage.

3.1 Mombetsu Dam

The Mombetsu dam is a homogeneous earthfill dam managed by the Mombetsu Land Improvement District. The dam was 180 kilometers from the epicenter.

Owing to the earthquake, deformation of the dam body was caused at protective facing blocks which overlapped one another and rose up about 10 centimeters along the entire dam axis directly below the elevation where the gradient of the upstream slope changed, as shown in Fig. 4. The earthquake is thought to have caused the top one-third of the dam body to settle, applying a compressive force in the slope direction on the facing blocks, thus causing them to buckle. When the inspectors removed the deformed facing blocks to check the surface of the embankment body, they concluded that there was no deformation, and that the safety of the dam was not compromised. Undulating deformation was seen on the facing blocks close to the intake pipe on the upstream concrete part of the left bank.

Fig. 4 Raised Facing Concrete Blocks on the Upstream Slope Protection of Mombetsu Dam

4. DAMAGE TO DAMS DUE TO THE 1993 HOKKAIDO NANSEI OKI EARTHQUAKE

Inspections revealed that of dams with a height of 15 meters or more, the Niwa-Ikumine Dam suffered moderate damage, while minor damage was discovered at the Pirika Dam and the Makomanai Dam. Furthermore, two small irrigation pond dikes less than 15 meters high located only 65 to 70 kilometers from the epicenter at Setana-cho of Hokkaido failed. Settlement or cracking occurred some dikes of this kind along the Japan Sea Coast near the epicenter. We describe the above three damaged dams below.

4.1 Niwa-Ikumine Dam

The Niwa-Ikumine Dam is an earthfill dam managed by the Kita-Hiyama Land Improvement District. It is an old dam completed more than 60 years ago in 1927, and was located 70 kilometers from the epicenter.

Figure 5 is a plane diagram of the dam showing an outline of the damage. The earthquake caused cracking bulging and on the dam body. As shown in Fig. 5, the cracking consisted of five longitudinal cracks at the crest of the dam; the longest crack extended for a length of approximately 120 meters on the crest at a depth of two meters, and settled on the upstream side with a maximum level difference of about one meter, as shown in Fig. 6. The bulge at the upstream toe of the slope was over 40 meters long and with a maximum level difference of about one meter, as shown in Fig. 7. Several cracks were formed with a sand boil extending from the sand layer in a sedimentary mound at the bottom of the reservoir near the upstream toe of the body.

After the earthquake, drilling inspections and soil inspections of the channel excavated as an emergency work against floods were carried out. The dam body was banked on the riverbed deposit between four to five meters thick, and a Setana Formation composed of sandstone with a low degree of consolidation existed beneath it. As shown in Fig. 8, the dam body was a zoned type, which consisted of core zones of clay and silt mixed with gravels, and silty sand zones mixed with gravels. Core zones were divided into two zones: a central core and an inclined core. Thus, the embankment of silty sand between two cores was saturated. The silty sand zone was extremely loose with an N value between two to four and with a compaction degree of 81% based on penetration tests, in-situ density tests, and compaction tests. The riverbed deposit consisted of loose sand and gravel with an N value between three to eight and gravel with an N value of about 20.

We calculated the safety factor against liquefaction: the liquefaction resistant factor F_L based on the Specifications for Highway Bridges of Japan (1990). The factor F_L is given by:

$$F_L = R/L \tag{2}$$

$$R = 0.0279\sqrt{\frac{N}{\sigma'_v + 0.07}} - 0.05\begin{cases} +0.0 & (FC \leq 40\%) \\ +0.004FC - 0.16 & (40\% < FC) \end{cases} \tag{3}$$

$$L = r_d \frac{\alpha_{max}}{g} \frac{\sigma_v}{\sigma'_v} \tag{4}$$

where, σ'_v is the effective overburden pressure in MPa, σ_v is the total vertical loading pressure in MPa, FC is the mass percentage of soil less than 74 μm in diameter, r_d is the

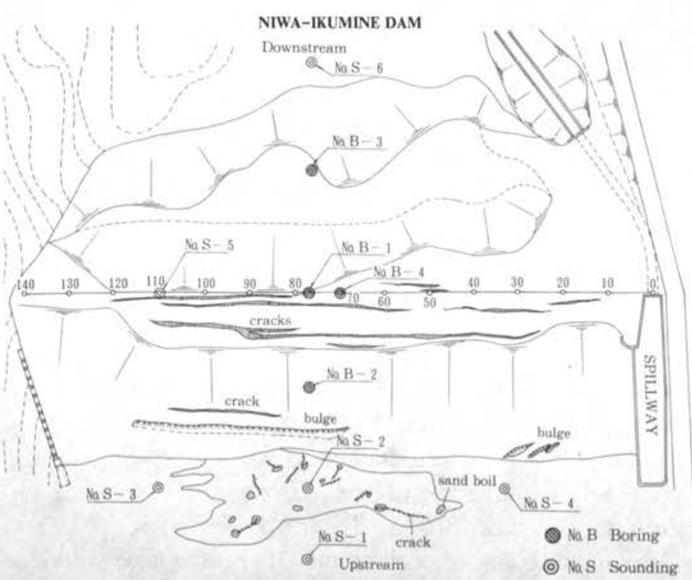


Fig. 5 Plane of Damage to Niwa-Ikumine Dam

Fig. 6 Settlement of the Upstream Side Body of Niwa-Ikumine Dam

Fig. 7 Bulging on the Upstream Slope of Niwa-Ikumine Dam

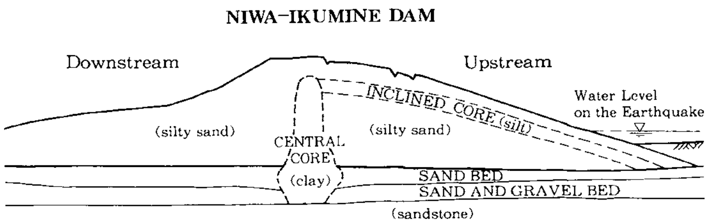


Fig. 8 Cross Section of Niwa-Ikumine Dam

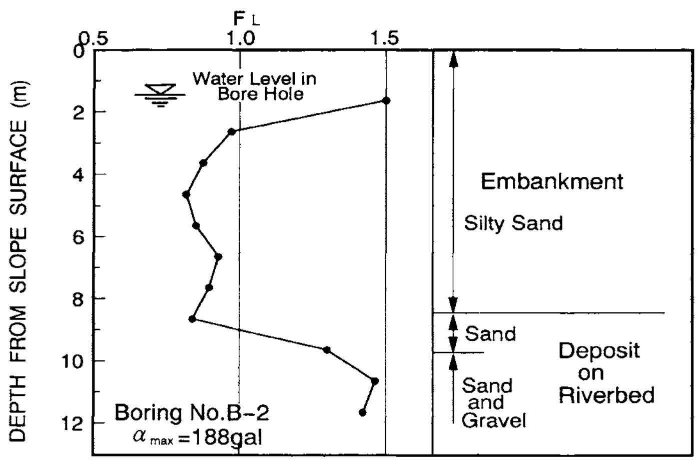


Fig. 9 Liquefaction Resistant Factor at Niwa-Ikumine Dam

reduction coefficient along depth, g is the gravitational acceleration, and α_{max} is the horizontal maximum acceleration, as which we used the value of 188 *gals* from the equation (1). Figure 9 shows the depth distribution of F_L in the drilling hole of the upstream side of the dam. The values of F_L at the embankment and the upper riverbed deposit are smaller than unity, hence the embankment apparently liquefied and the liquefaction caused the upstream dam body to settle. This liquefaction occurred for two reasons; one is the fact that the dam embankment was badly compacted on the loose riverbed deposit, and the second is that the embankment between the two cores without drainage was saturated.

4.2 Pirika Dam

The Pirika Dam, which is managed by the Hokkaido Development Agency, is a combined dam consisting of a concrete gravity dam and a rockfill dam. It was located 89 kilometers from the epicenter.

In the junction between block 0 of the concrete dam body and the connecting corridor tunnel leading to the control office, the floor panel concrete of the connecting corridor was pushed up and spalled over a length of about 1.5 meters due to compression in the axial direction of the dam. This connecting corridor was located on the rock zone of the core wall connected perpendicular to the concrete dam body. Above this junction, the surface paving of the crest road settled, and a gap of the upstream railing opened between the junction. In the nearby square above the junction between block 0 of the concrete dam and the left bank core wall, part of the surface block was lifted. All these deformations were caused by differences in the earthquake response of the concrete dam body and the rock zone of the core wall or the backfilled soil above the core wall. None of them significantly affected the safety of the dam body.

4.3 Makomanai Dam

The Makomanai Dam is a rockfill dam with a central core and a height of 34 meters, managed by the Hokkaido Development Agency. It was completed in 1987, and was located 66 kilometers from the epicenter.

The earthquake caused a slight settlement of the dam body and a slight bulge of the lower part of the body. Thus, the concrete frame on the upstream slope was deformed, and its joints were broken slightly. Several cracks opened up on the sprayed concrete facing in the front of the overflowing wall of the spillway. This is because there were some hollows within the sprayed concrete facing, since the inside backfilled soil had flowed out owing to fluctuation of the reservoir water level. The facing concrete blocks on the right bank were deformed in an undulating fashion. None of these damages significantly affected the safety of the dam body.

5. CONCLUSIONS

The present study confirmed that the dams constructed on rock foundations using modern design and construction technologies were able to survive these powerful earthquakes without any threat to the safety, and that they had remained good condition. However, for an old earthfill dam and small irrigation pond dikes with badly compacted embankments banked using old construction technology on loose riverbed deposit, these earthquakes caused failure or settlement. We must inspect and reinforce the seismic stability of such dams and dikes from now on. Attachments such as facing blocks and corridor tunnels respond differently to earthquakes from the dam body, hence we must design and build dams accordingly.

The earthquake motion and behavior of the dams based on an analysis of acceleration records agreed well with the estimates of empirical formulae of other researchers.

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