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INVESTIGATION OF DAM PERFORMANCE DURING THE NOTO HANTO EARTHQUAKE IN 2007, JAPAN

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ABSTRACT

The Noto Hanto Earthquake, registered by the Japan Meteorological Agency as magnitude (M_j) 6.9, occurred on March 25, 2007 offshore west of the Noto Peninsula facing the Sea of Japan. Two dams, Hakkagawa Dam and Oya Dam, are located within 50 km from the epicenter. We conducted a field survey to investigate the effects of the earthquake on these dams.

Hakkagawa Dam, which is a concrete gravity dam, is located 14 km from the epicenter. The seismometer installed at the dam foundation recorded a peak horizontal acceleration of over 200 gal, which is one of the largest acceleration motions ever recorded at a dam foundation in Japan. The increase in drainage amount and deformation of dam body due to the earthquake was slight. The different behavior between each dam block during the earthquake may have caused friction acting between the contraction joint faces. Such energy dissipation may have resulted in the low amplification and high damping against dam vibration mode shown in the spectral analyses of recorded earthquake motions.

Oya Dam, which is a rockfill dam, is located 48 km from the epicenter. The amount of seepage through the impervious earth core changed due to the earthquake and the monitored data was evaluated. Earthquake-induced settlement was 25 mm at the crest of the maximum cross section. The amount of settlement was evaluated and compared with cases of other embankment dams in Japan and other countries and regions, through the relationship between crest settlement and peak horizontal acceleration at dam foundations. Besides the above, Oya Dam was struck by a large earthquake of M_j 6.6 in 1993, just after completion. The performance of the dam during the two large earthquakes was compared.

INTRODUCTION

The Noto Hanto Earthquake occurred on March 25, 2007. It was the Japan Meteorological Agency (JMA) magnitude (M_j) of 6.9, and its epicenter was located offshore west of the Noto Peninsula in Ishikawa Prefecture. Immediately after the earthquake, emergency inspections were carried out on 108 dams. The inspection results showed that the earthquake did not affect the safety of the dams.

This paper describes the seismic performance of two dams located near the epicenter. The response characteristics of one of the dams (Hakkagawa Dam: concrete gravity dam) were analyzed based on acceleration data recorded at the dam. The other dam (Oya Dam: rockfill dam) was struck by a large earthquake of M_j 6.6 in 1993 immediately after completion; therefore, the performance of the dam during the two large earthquakes was compared.

OUTLINE OF THE EARTHQUAKE

This earthquake occurred at 9:41 a.m. on March 25, 2007. The Japan Meteorological Agency announced that it was a M_j 6.9 earthquake with its epicenter offshore from the Noto Peninsula (37°13.2'N. Lat., 136°41.1'E. Lon.) at a hypocenter depth of 11 km. Exitaions with JMA seismic intensity 6 upper were registered at Nanao City, Wajima City, and Anamizu Town in Ishikawa Prefecture.

The Cabinet Office, Government of Japan (2008) announced that the earthquake resulted in 1 fatality and 356 injuries, 684 houses totally destroyed, 1,733 houses partly destroyed, and 26,935 houses damaged. The earthquake also caused damage to lifelines such as electric power, gas, and water supply.

EARTHQUAKE MOTIONS RECORDED AT DAMS

Maximum acceleration at dam foundations

Seismometers installed at the dam foundation (including at the bottom of the inspection gallery) of 19 dams under the jurisdiction of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) recorded accelerations of 25 gal or larger during the earthquake. The location of each dam is shown in Fig. 1. The relationship between the peak horizontal acceleration at the foundation of these dams and the distance of each dam from the earthquake fault is shown in Fig. 2. This figure also indicates the attenuation relationship for peak acceleration (intraplate earthquake type, M_j 6.9) of dams shown in the *Guideline for the Seismic Performance Evaluation of Dams against Large Earthquake (Draft)* (River Bureau, MLIT, 2005). The shortest distance between the fault and a dam was calculated using the model estimated by the Geographical Survey Institute (2007). Peak accelerations at the dam foundations tend to be larger than the attenuation relationship curve based on the guideline. One of the reasons for this may be that the fault movement that caused this earthquake was reverse faulting and most of these dams were located on the hanging wall where larger movement can be produced compared with that at the footwall.

Figure 3 shows the amplification factors of the peak acceleration at the dam crest against that at the dam foundation. When small earthquake motion is input to dam foundations with a peak acceleration of 50 gal or less, the amplification factors, namely the responses of crests, are widely scattered from one to over ten. However, when the peak acceleration is higher than 100 gal, the response amplification factors and its scattering is small. This same tendency has also been observed in other earthquakes (Nakamura *et al.*, 1994 and Yamaguchi and Iwashita, 2001).

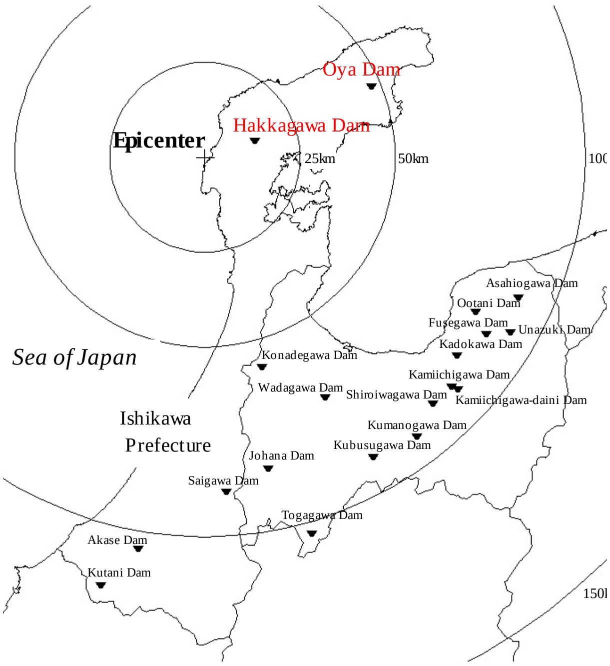


Fig. 1 Location map of dams that recorded an acceleration of over 25 gal at the dam foundation

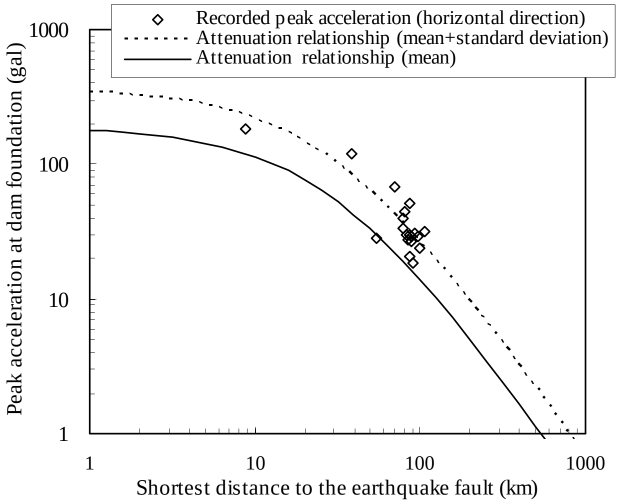


Fig. 2 Attenuation of peak acceleration recorded at dam foundations and the attenuation relationship as per the River Bureau, MLIT (2005)

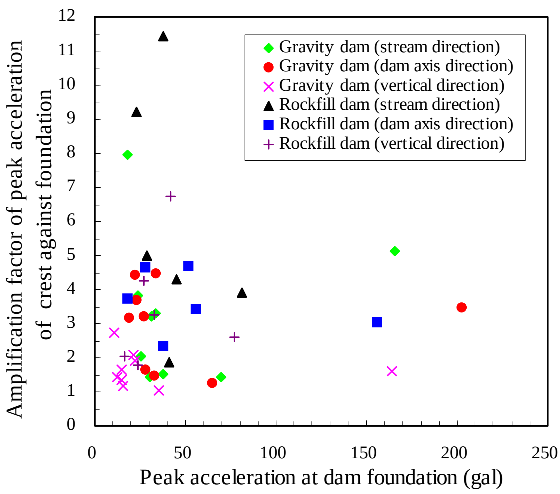


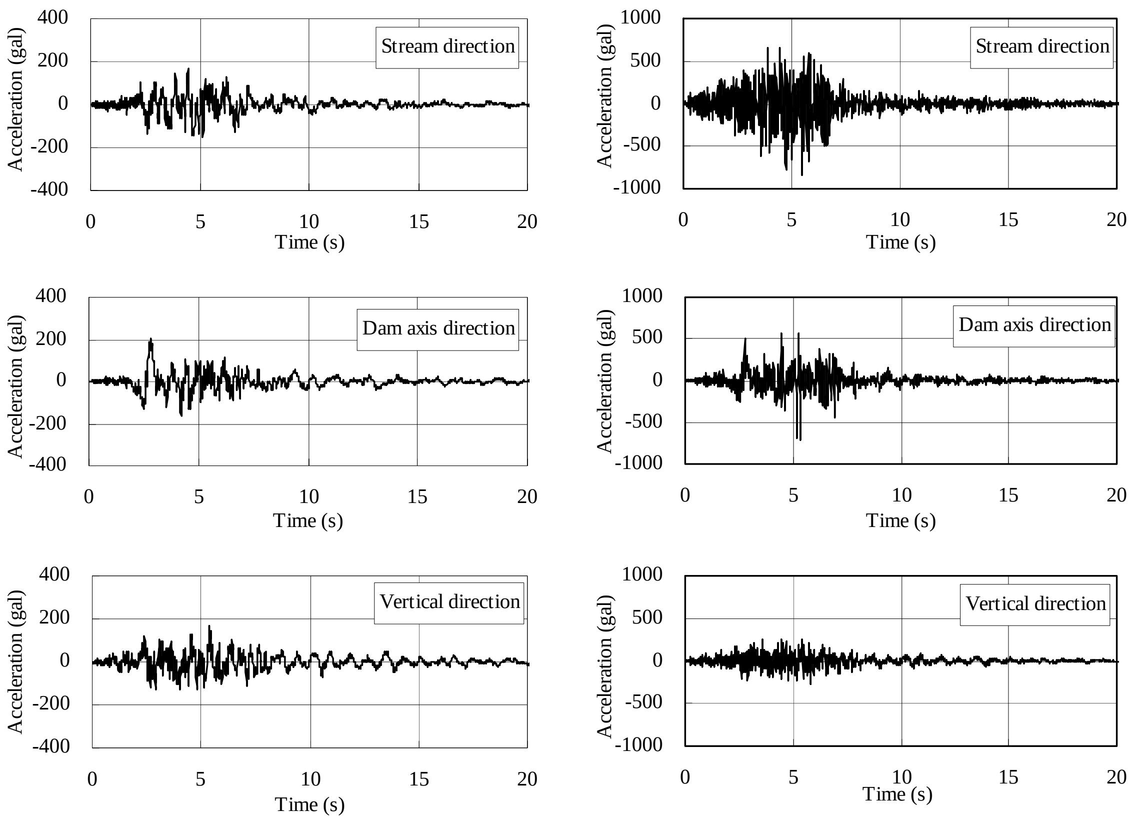
Fig. 3 Amplification factors of peak acceleration at the crest against that at the dam foundation

Acceleration records at the foundation of Hakkagawa Dam

Hakkagawa Dam is a 52.0-m-high concrete gravity dam managed by the Public Works Department of the Ishikawa Prefectural Government. It was completed in 1995 and is located 14 km from the epicenter. The rock foundation of the dam is mainly andesite and volcanic conglomerate with a P-wave velocity of 3.6–4.5 km/s.

Seismometers are installed at the bottom of the inspection gallery and at the crest. The seismometer at the inspection gallery (at the foundation) recorded peak accelerations of 165.7 gal in the stream direction, 202.5 gal in the dam axis direction, and 164.2 gal in the vertical direction. The acceleration time histories and the horizontal acceleration response spectrum are shown in Figs. 4 and 5, respectively. Figure 5 also shows the “Lower-limit acceleration response spectrum for dam seismic evaluation” against “Level 2 earthquake motion (L2 motion)”, provided in the *Guideline for the Seismic Performance Evaluation of Dams against Large Earthquake (Draft)* (River Bureau, MLIT, 2005). L2 motion is equivalent to the maximum credible earthquake motion at the dam site. “Lower-limit acceleration response spectrum for dam seismic evaluation” is considered as the mandatory minimum L2 motion. This minimum response spectrum is determined by taking into consideration the possibility of events occurring beneath the dam site even when no active fault is found near the dam site by geographical survey of the ground surface. The 2007 Noto Hanto Earthquake excitation was caused by an active fault beneath the sea that had not been confirmed. Figure 5 shows that the acceleration response spectra recorded at the foundation of Hakkagawa Dam fall below the “Lower-limit acceleration response spectrum for dam seismic evaluation”.

The Japanese Ministry of Construction (present Ministry of Land, Infrastructure, Transport and Tourism (MLIT)) began monitoring dams under its jurisdiction through the installation of seismometers in 1957. Since then, the number of seismometer-installed dams has increased mainly in newly constructed dams. On the momentum of the experience of severe damage to infrastructures and buildings due to the Hyogoken-Nambu Earthquake in 1995,



(a) Dam foundation (inspection gallery)　　　　(b) Crest

Fig. 4　Acceleration time histories recorded at Hakkagawa Dam

seismometers were installed in all dams under the jurisdiction of the Ministry of Construction by 2000. Table 1 shows several peak horizontal accelerations recorded at dam foundations during major recent earthquakes. The acceleration recorded at the foundation of Hakkagawa Dam is one of the largest peak accelerations ever recorded at a dam foundation in Japan.

PERFORMANCE OF DAMS DURING THE EARTHQUAKE

After the 2007 Noto Hanto Earthquake, emergency inspections were conducted at 108 dams (including weirs). These consist of 3 dams or weirs operated directly by MLIT, 33 dams subsidized by MLIT and 72 other dams. The inspection results revealed that no damage had occurred to threaten the safety of the dams.

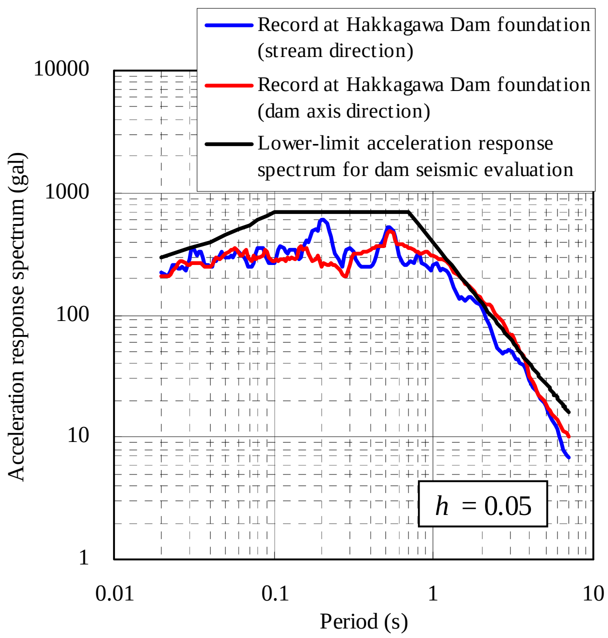


Fig. 5　Acceleration response spectra at the foundation of Hakkagawa Dam

Table 1 Peak acceleration at dam foundation in recent large earthquakes in Japan

Earthquake	Year	Magnitude M_j	Dam (Dam type*)	Epicentral distance (km)	Peak acceleration at dam foundation (gal)	
Hyogoken-Nambu	1995	7.3	Hitokura Dam (PG)	47	183	stream direction
			Minogawa Dam (ER)	48	135	stream direction
Tottoriken-Seibu	2000	7.3	Kasho Dam (PG)	12	569	dam axis direction
Miyagiken-oki	2003	7.1	Tase Dam (PG)	73	232	stream direction
			Hinata Dam (PG)	55	228	stream direction
Tokachi-oki	2003	8.0	Urakawa Dam (PG)	115	103	stream direction
Mid Niigata Prefecture	2004	6.8	Shirokawa Dam (PG)	14	162	stream direction
Noto Hanto	2007	6.9	Hakkagawa Dam (PG)	14	203	dam axis direction
Niigataken Chuetsu-oki	2007	6.8	Kakizakigawa Dam (ER)	31	170	dam axis direction

*) PG: Concrete gravity dam, ER: Rockfill dam

Two dams, Hakkagawa Dam (concrete gravity) and Oya Dam (rockfill), are located within 50 km from the epicenter. The performance of the two dams during the earthquake is explained below based on our surveys and observation data.

Hakkagawa Dam

Figure 6 shows the upstream face of Hakkagawa Dam. Photograph 1 shows the downstream face of the dam body and the location of the crest seismometer. The peak accelerations at the crest (installed in the pier top of the crest bridge shown in Photo. 1) were 848.6 gal in the stream direction, 705.4 gal in the dam axis direction, and 266.9 gal in the vertical direction and those at the dam foundation were mentioned above.

Exterior survey

Our survey found a slight opening of the crest parapet joints corresponding to a contraction joint (J-1) as shown in Photo. 2 and chipping of the concrete between the parapet joints corresponding to contraction joints (J-3 and 8) as shown in Photo. 3. Repair mortar surface between the gallery joints corresponding to contraction joints (J-3, 4, 6, 7 and 8) had flaked inside the inspection gallery, and cracks occurred on the slab concrete of the steps in the gallery along contraction joints (J-6 and 8) as shown in Photo. 4.

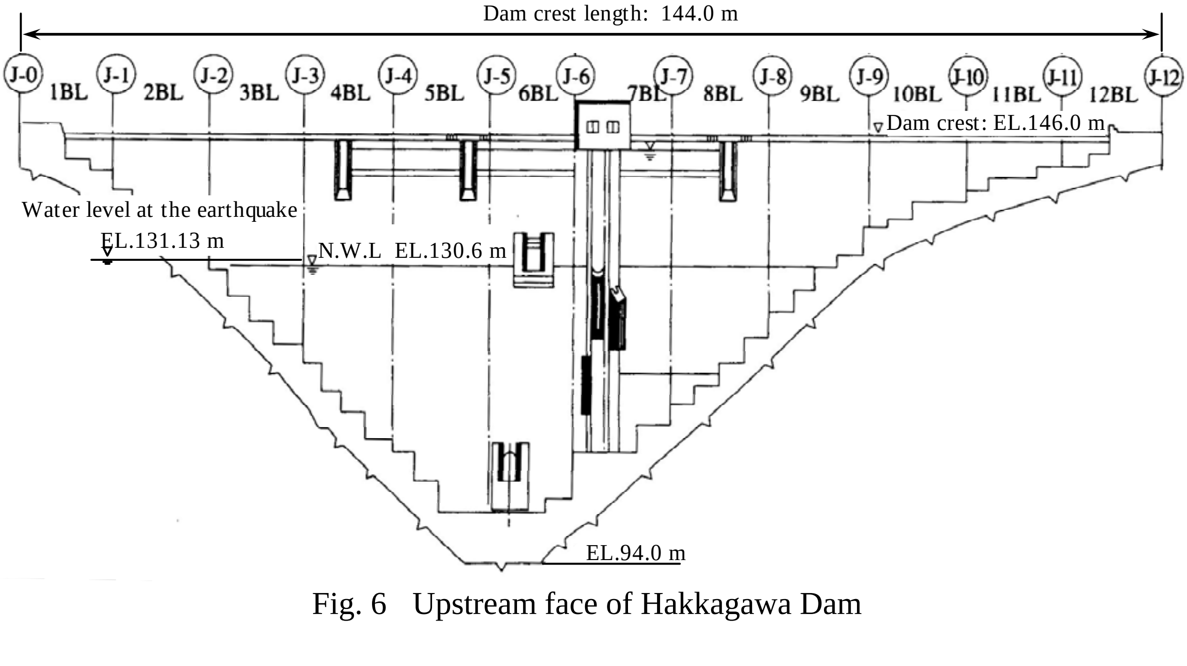


Fig. 6 Upstream face of Hakkagawa Dam

Observation data of dam body

– Drainage

Total drainage, which is the total amount from drilled foundation drain holes and from contraction joints, was 2 liter/min at 9:00 a.m. on March 25 prior to the earthquake. The drainage increased to 4 liter/min. at 10:00 a.m. immediately after the earthquake, but fell to 3 liter/min by 11:00 a.m. and returned to 2 liter/min by 7:00 p.m. on March 26. Later, the lowering of the reservoir water level was accompanied by a decline in total drainage.

– Displacement

A plumb line installed in Block 7 of the dam body revealed slight permanent displacement of 0.5 mm in the downstream direction and 0.2 mm toward the left-bank side immediately after the earthquake. The displacement did not appear to have advanced rapidly.

– Others

Uplift pressure data showed no significant change due to the earthquake.

Response properties of the dam during the earthquake

The dam body continued damped free vibration after the principal earthquake motion. The frequency content of damped free vibration depends on the natural frequency of the dam body. Thus, the natural frequency can be clarified to a certain degree by the spectral analyses

Photo. 1 Downstream face of Hakkagawa Dam

Photo. 2 Opening of crest parapet joints on contraction joint J-1

Photo. 3 Concrete chips between crest parapet joints on contraction joint J-8

Photo. 4 Cracks in concrete steps along contraction joint J-8 in the gallery

of damped free vibration. Figure 7 shows the ratio of Fourier spectrum amplitude of the crest motion to that of the dam foundation motion during damped free vibration. The main shock and three aftershocks were selected for analyses. The earthquake magnitude and peak acceleration at dam foundation of the aftershocks are shown in the legend in this figure. The dam foundation accelerations had fallen to 5 gal or less following the principal motion and were analyzed as damped free vibration. According to Fig. 7, the first and second natural frequencies of the Hakkagawa Dam body can be estimated as 8.5–9.5 and 12–13.5 Hz, respectively.

Figure 8 shows the ratio of Fourier spectrum amplitude of the crest motion to that of the dam foundation motion during the total duration of the earthquake including the principal motions of the main shock and the three aftershocks. Around the first natural frequency of 8.5–9.5 Hz of Hakkagawa Dam estimated by Fig. 7, the spectrum amplitude ratios of the three aftershocks have a clear peak. On the other hand, the spectrum amplitude ratio of the main shock does not have any clear peaks around the first natural frequency range. The different trend in the spectrum ratio for the main shock and the aftershocks around the second natural frequency of 12–13.5 Hz is almost the same as that around the first natural frequency.

As explained above, the external survey of Hakkagawa Dam revealed slight chipping of the concrete at the crest parapet joints and cracking of the slab concrete in the inspection gallery corresponding to the contraction joints. These are assumed to be traces of the scrapings between the contraction joint faces caused by the different behavior of each block of the dam body during the main shock. The displacement response of the dam was larger for the lower-order mode and relative vibration displacement between blocks of the dam body caused a fairly substantial energy loss. Therefore, the spectral amplification factors may be smaller around the lower natural frequency mode, as shown in Fig. 7. As a result of these phenomena, high damping caused by three-dimensional structural form may need to be considered in the case of conducting two-dimensional response analyses of concrete gravity dams with input of strong earthquake motions.

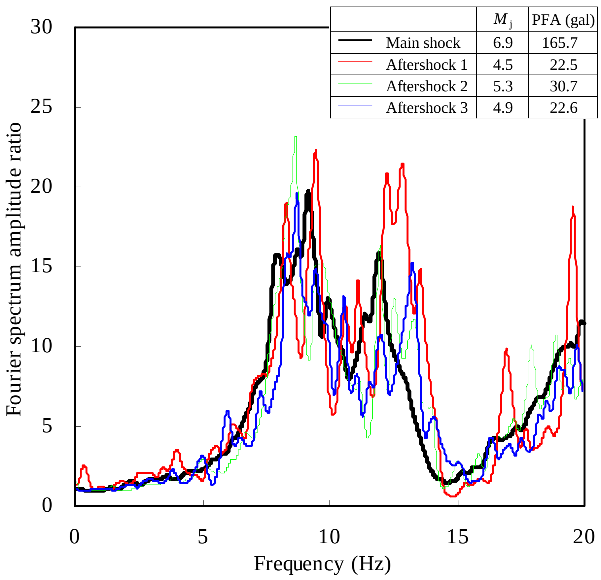


Fig. 7 Fourier spectrum amplitude ratio of crest to dam foundation during damped free vibrations after principal motions

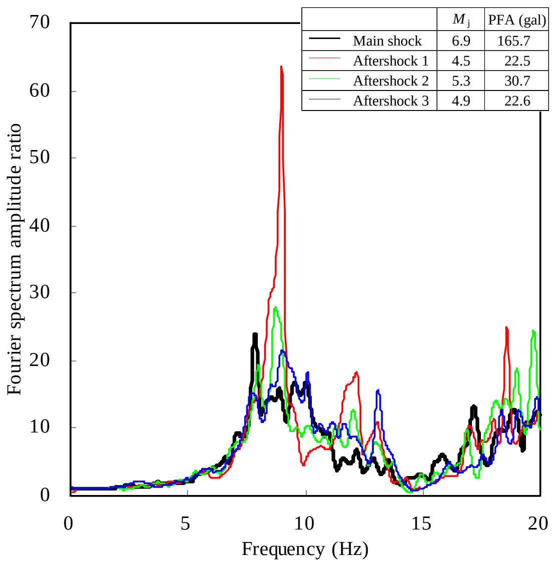


Fig. 8 Fourier spectrum amplitude ratio of crest to dam foundation during the main shock and aftershocks

Oya Dam

Oya Dam, which is a 56.6-m-high rockfill dam with a central core, is managed by the Public Works Department of the Ishikawa Prefectural Government. It was completed in 1993 and is located 48 km from the epicenter. Peak accelerations at the bottom of the inspection gallery were 81 gal in the stream direction, 156 gal in the dam axis direction and 77 gal in the vertical direction. At the crest, they were 316 gal in the stream direction, 473 gal in the dam axis direction and 202 gal in the vertical direction. The longitudinal section of Oya Dam is shown in Fig. 9.

Shortly after its completion, this dam was struck by the Noto Hanto-oki Earthquake (M_j 6.6) of February 7, 1993. The earthquake caused some minor damage to the dam such as hairline cracks in the crest pavement, which did not affect the dam's safety. The 2007 Noto Hanto Earthquake is the only large earthquake to have occurred since the 1993 earthquake. Two of us (Iwashita and Yasuda) surveyed Oya Dam immediately after the 1993 earthquake. The performance of Oya Dam during the earthquakes in 1993 and in 2007 is compared below.

Exterior survey

On the survey after the 1993 earthquake, about 10 hairline cracks were found in the crest pavement. Almost all of these cracks occurred in the upstream-downstream direction and along pavement joints. At the boundary of the dam crest pavement and spillway concrete, a slight opening of 3–4 mm had formed before the earthquake. After the 1993 earthquake, the opening was 5–6 mm.

The survey performed immediately after the 2007 earthquake did not find any new cracks in the dam crest pavement.

Observation data of dam body

– Seepage through the earth core

Seepage through the impervious earth core is measured at four separate zones (W-3 to W-6) as shown in Fig. 9. The change in seepage at the time of the 1993 earthquake was almost at the same level of the scattering of seepage amount before/after the earthquake, as shown in Fig. 10.

Figure 11 shows the change in seepage for Oya Dam before and after the 2007 earthquake. After the earthquake, the seepage amount rose to 5 liter/min at Zone W-5, and at the other

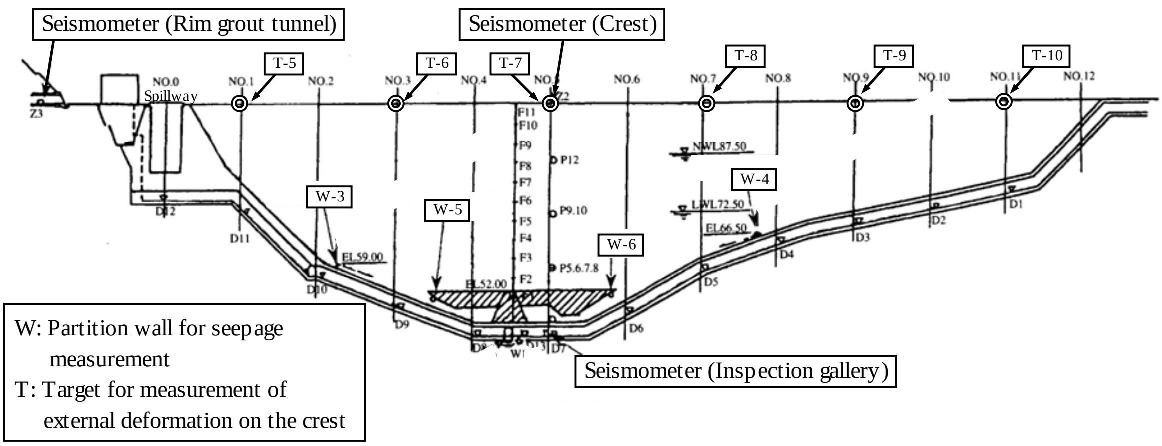


Fig. 9 Longitudinal section of Oya Dam

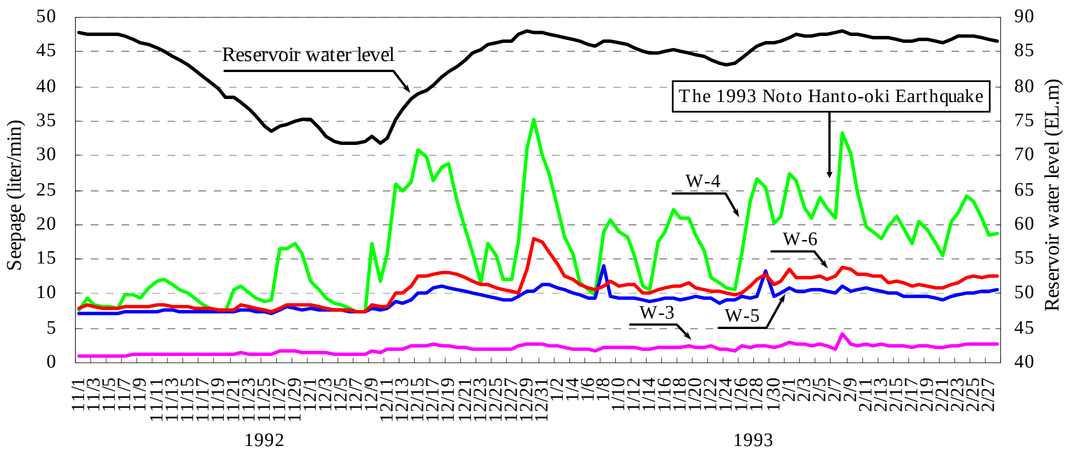


Fig. 10 Change in seepage amount through the earth core before and after the 1993 Noto Hanto-oki Earthquake

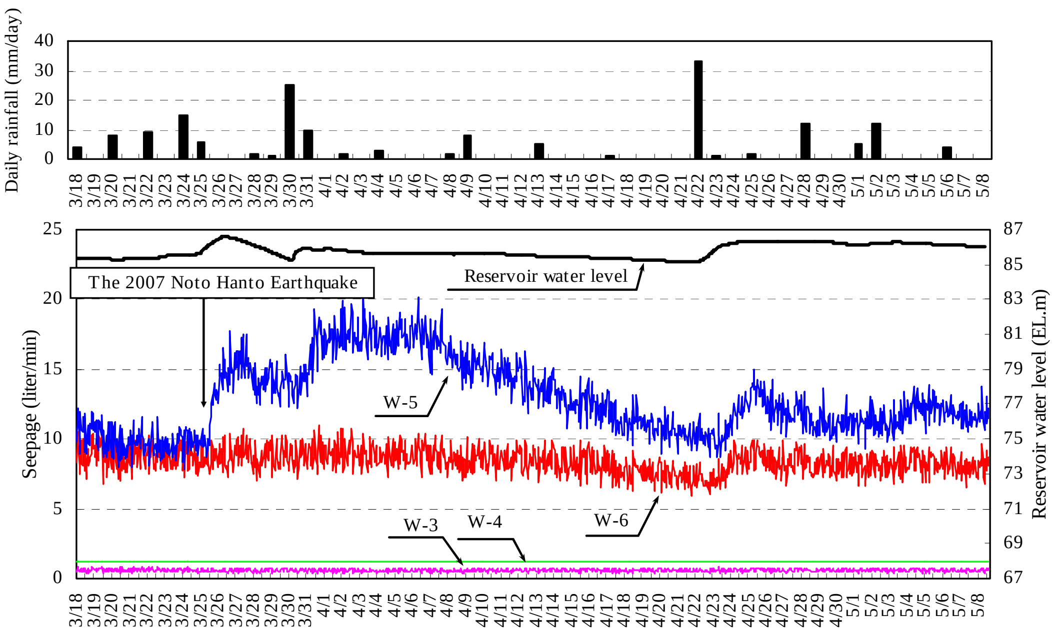


Fig. 11 Change in seepage amount through the earth core before and after the 2007 Noto Hanto Earthquake

zones there was almost no change. Figure 12 shows the relationship between the seepage amount at Zone W-5 and the reservoir water level before the earthquake (March 18–24, 2007) and after the earthquake (March 25 to April 30, 2007). This figure indicates that the seepage amount during the period of about twenty days after the earthquake (diamond symbols) is larger than the seepage measured before the earthquake. Rainfall of 15 mm occurred on the day before the earthquake. On the other hand, the seepage amount measured about twenty days after the earthquake (square symbols) agrees well with that measured before the earthquake. The slight increase in seepage at Zone W-5 may not have been caused directly by the excitation of the earthquake, but may instead have been caused by the rainfall and change in reservoir level rise before/after the earthquake.

Brownish turbidity of the seepage water at Zone W-3 was noted by the official observer at 20:28 on March 25, the day of the event, but turbidity was not observed at 6:18 a.m. on March 26, the day after the event.

– Exterior deformation

Targets for measuring exterior deformation are installed at a total of 13 locations on 3 longitudinal measurement lines on the dam crest as shown in Fig. 9, the upstream slope and the downstream slope at Oya Dam.

Earthquake-induced settlement of 9 mm due to the 1993 earthquake was measured at Target No. T-7 installed at the crest on the maximum cross section of the dam. The value measured agrees with the cumulative value of each-layer settlement by differential settlement gages installed within the maximum cross section of the dam.

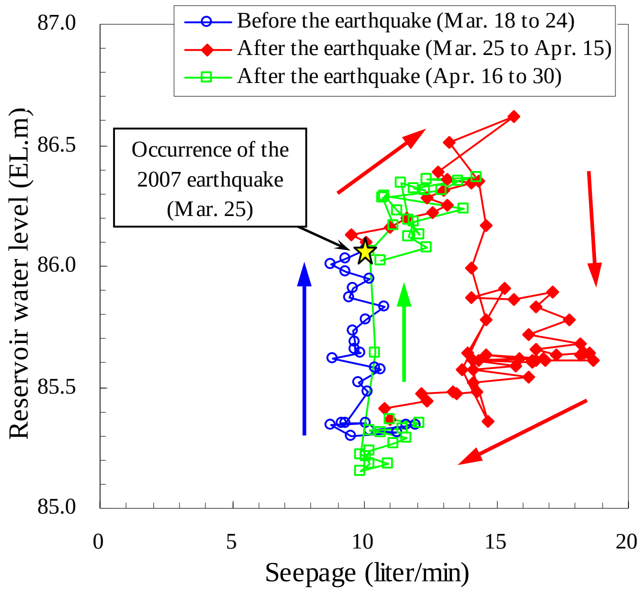


Fig. 12 Relationship between seepage and reservoir water level before and after the 2007 Noto Hanto Earthquake

Earthquake-induced settlement in the maximum cross section due to the 2007 earthquake was 25 mm on the dam crest, 19 mm on the upstream slope, and 11 mm on the downstream slope, obtained by comparing the measurements on March 26 with those on March 10 before the earthquake.

Figure 13 shows the change in cumulative settlement measured at the crest measurement line since the completion of dam banking in 1992.

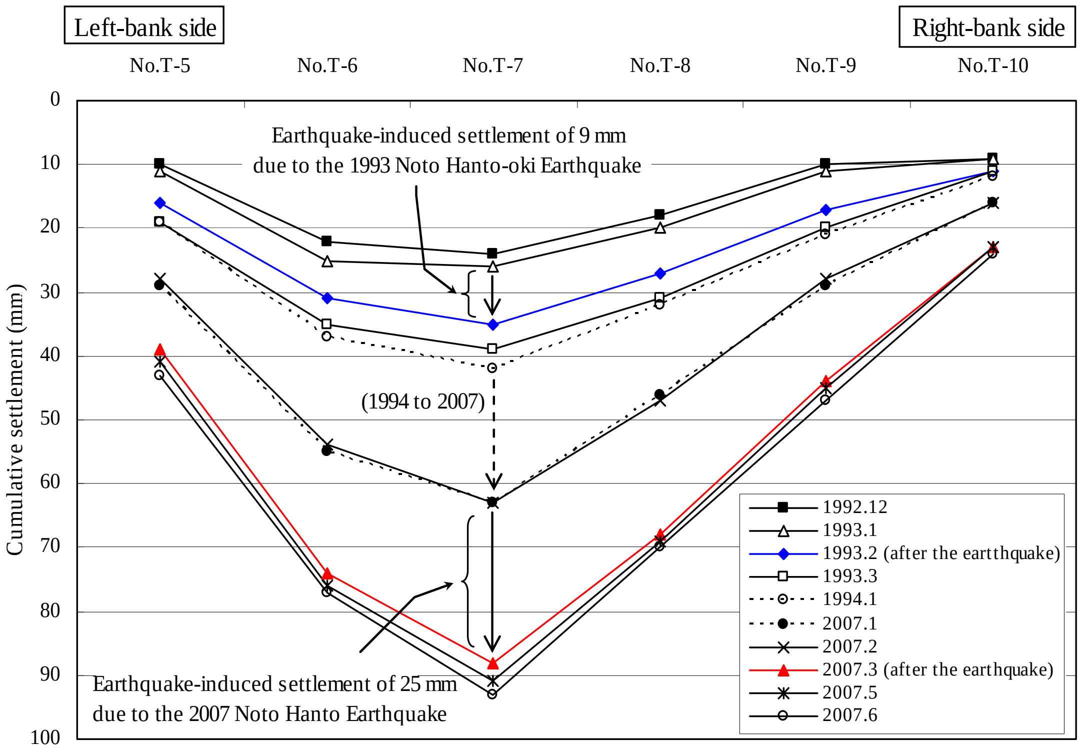


Fig. 13 Cumulative settlement at the crest of Oya Dam

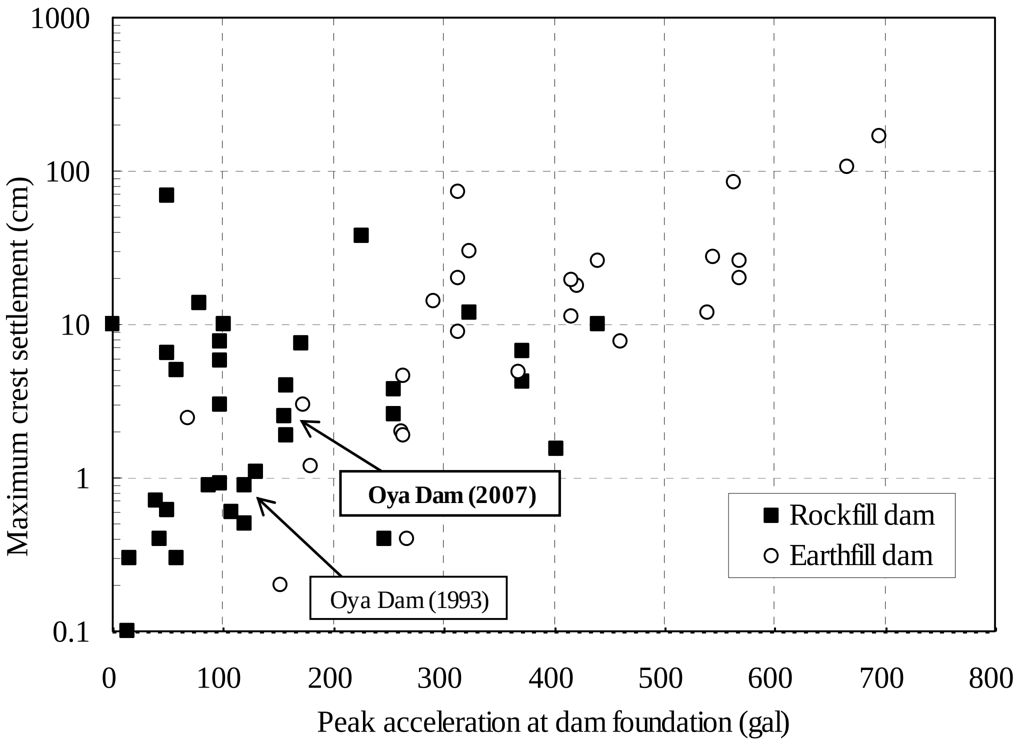


Fig. 14 Relationship between maximum crest settlement and peak acceleration at dam foundation for embankment dams in Japan and six other countries and one region (recent earthquake data added to the figure as per Iwashita (1999))

Figure 14 shows the relationship between maximum settlement at a dam crest and peak acceleration at the foundation of an embankment (including estimates based on the distance attenuation relationship) due to earthquakes that have occurred since the 1920s (After Iwashita, 1999). This figure consists of observation data from embankment dams in Japan and other countries and regions, including the U.S., Mexico, Chile, Peru, the Philippines, New Zealand and Taiwan. Embankment dams with a foundation layer of alluvial deposits are included in this figure. Cases of deformation induced by liquefaction of foundation and dam materials are omitted from this figure. The maximum settlement of 25 mm at the crest of Oya Dam induced by the 2007 earthquake and that of 9 mm by the 1993 earthquake are also dotted in Fig. 14. The dots of Oya Dam are located in a relatively lower portion of the distribution in this figure. The reason for this may be that Oya Dam is a rockfill dam constructed on foundation rock and well compacted using large mechanized works. The earth core of the dam was compacted using 21-ton tamping rollers under compaction control by a *D*-value of 95% or higher. The rock zone of the dam was compacted using 18-ton vibrating rollers.

The maximum horizontal displacement measured in the stream direction induced by the 2007 earthquake was 0.7 mm toward the upstream on the crest, 6.2 mm toward the upstream on the upstream slope and 3.4 mm toward the downstream on the downstream slope.

CONCLUSIONS

The 2007 Noto Hanto Earthquake in Japan registered a JMA magnitude (M_j) of 6.9. Two dams, Hakkagawa Dam and Oya Dam, are located within 50 km from the epicenter. We conducted a field survey to investigate the effects of the earthquake on these dams. Based on the field survey and analyses of observation data, it was confirmed that the performance of both dams during the earthquake was satisfactory and their safety was not threatened.

Hakkagawa Dam (concrete gravity) is located 14 km from the epicenter. Horizontal peak acceleration of over 200 gal was recorded at the bottom of the gallery, which is one of the largest peak accelerations ever recorded at a dam foundation in Japan. The different behavior between each concrete block of the dam body during the earthquake, as shown in the chipping of the joints of the crest parapet corresponding to the contraction joints, may have caused friction on the contraction joint faces. The phenomena of energy dissipation may have caused the low amplification and high damping against dam vibration mode shown in the spectral analysis results.

Earthquake-induced settlement at Oya Dam (rockfill) was evaluated through a comparison with cases of other embankment dams in Japan and other countries. The settlement at Oya Dam due to the earthquakes in 1993 and 2007 is located in a relatively lower portion of the distribution in the relationship between crest settlement and peak horizontal acceleration at the dam foundation.

ACKNOWLEDGMENTS

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