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Safety inspections and seismic behavior of embankment dams during the 2011 off the Pacific Coast of Tohoku earthquake

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Abstract

Immediately after the 2011 off the Pacific coast of Tohoku Earthquake, special safety inspections were carried out at over 300 dams in the affected area. Damage was identified at more than 10% of the inspected dams, with embankment dams showing a slightly higher ratio. Damage to embankment dams included relatively wide and/or long cracks mainly on the crest of earthfill dams, cracks in the impervious membrane of asphalt faced rockfill dams (AFRDs) and temporary increase in leakage. However, none of the dams under the jurisdiction of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) sustained damage severe enough to threaten the safety of the dam, although an old earthfill embankment dam for an irrigation pond located outside the area regulated by the River Law was breached due to the earthquake. In this paper, the results of special safety inspections are summarized, as well as those of subsequent detailed investigations of several embankment dams under the jurisdiction of MILT. The features of the earthquake motions observed at the dam foundations during the earthquake and their effects on the behavior of embankment dams are also discussed.

Keywords: The 2011 off the Pacific coast of Tohoku earthquake; Embankment dams; Special safety inspections; Detailed investigations; Earthquake motion

1. Introduction

On March 11, 2011, the Mw9.0 the 2011 off the Pacific coast of Tohoku Earthquake occurred near the northeast coast of Honshu, Japan. Special safety inspections based on the regulations developed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) were immediately carried out by the managers of dams located within the area regulated by the Japanese River Law, and where earthquake motions at or above a specified level were observed.

This report begins with an overview of the results of the special safety inspections. The next section introduces the results of detailed in situ investigations at several embankment dams under the jurisdiction of the MLIT and managed by the MLIT or prefectural governments. The investigations were carried out by the MLIT and the Public Works Research Institute (PWRI). Lastly, the features of earthquake motions observed at the dam foundations are discussed, as well as a fundamental analysis of their effects on the behavior of embankment dams.

2. Results of special safety inspections immediately after the earthquake (Yamaguchi et al., 2012)

At all dams located within the area regulated by the Japanese River Law, the dam managers are responsible for conducting special safety inspections immediately after an earthquake in the following cases:(Yamaguchi et al., 2012)

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(1) Earthquake motions of 25 gal (1 gal = 1 cm/sec^2) or higher are recorded at the dam foundation.
(2) Earthquake motions of seismic intensity 4 or higher (Japan Meteorological Agency, (JMA)) are observed at the nearest meteorological station.

The special safety inspections include a primary visual inspection immediately after an earthquake, followed later by a more detailed visual inspection and a safety inspection based on data that is recorded and measured by monitoring devices for safety management.

After the earthquake on March 11, 2011, special safety inspections were carried out at 363 dams in the affected area. The results revealed that among the flood-control dams and multi-purpose dams under the jurisdiction of the MLIT, none sustained severe enough damage to threaten the safety of the dam despite the huge scale of the earthquake. Outside the area regulated by the River Law, a 60-year-old earthfill embankment dam for an irrigation pond was breached due to the earthquake (Matsumoto et al., 2011).

Although not severe, damage was reported at more than 10% of the inspected dams, as shown in Fig. 1. The ratio rises to 18% for embankment dams, with more damage reported at dams managed by water users for irrigation or power generation (Yamaguchi et al., 2012). Fig. 2 indicates the breakdown of the damage reported at embankment dams. "Cracking on dam body" includes cracks on the dam crest and cracks with slippage on the upstream and/or downstream slope, which were mainly reported at earthfill dams, and cracks of the impervious membrane at AFRDs. The managers of the dams that had sustained some damage were required to carefully monitor various measured data such as the amount of leakage. At several dams, reservoir drawdown was necessary to ensure safety and enable investigations to identify the area and cause of the damage.

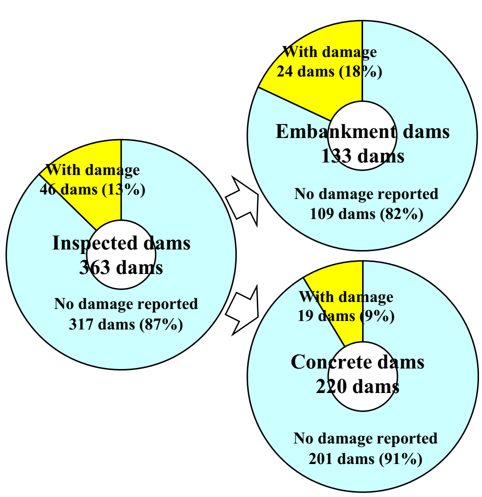


Fig. 1. Number of inspected dams with/without earthquake damage.

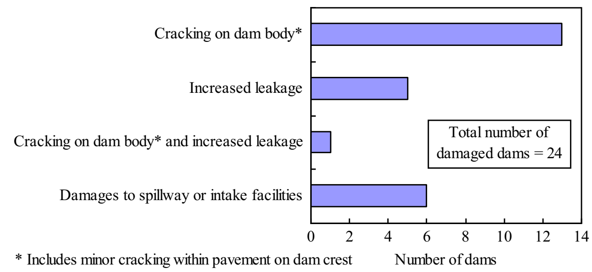


Fig. 2. Breakdown of reported damage at embankment dams.

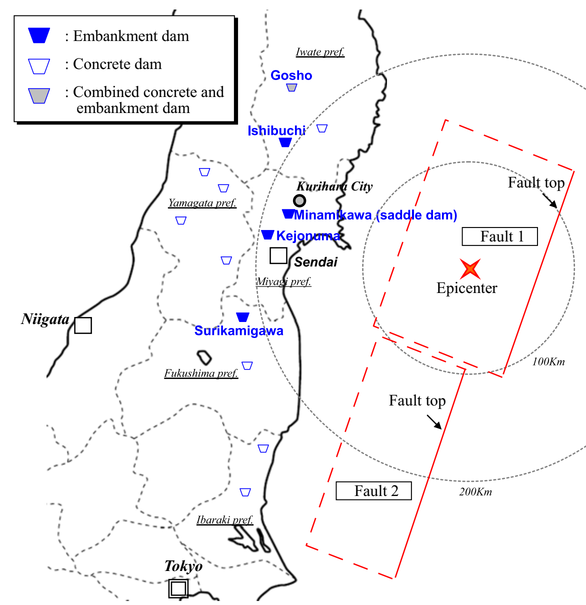


Fig. 3. Location of dams for detailed investigations.

3. Detailed investigations of damage to dams

3.1. *Outline of investigations (Yamaguchi et al., 2012)*

The PWRI conducted detailed investigations in collaboration with the MLIT at dams where damage had been reported, leakage had increased, or peak acceleration records were relatively severe. The major purposes of the investigations were as follows:

(a) To confirm the state of damage reported in the results of special safety inspections,
(b) To assess the safety of the dams and implement countermeasures as needed.

Detailed investigations were carried out in April and May 2011. Additional investigations by PWRI were also conducted in August and September 2011.

Fig. 3 shows the location of the investigated dams together with a source fault model estimated by the

Table 1
Summarized results of detailed investigations at embankment dams.

Dam (Year of completion)	Manager	Type[a]	Height (m)	Epicentral distance (km)	PGA[b] at foundation (gal)	PGA at crest (gal)	Results of special safety inspection	Results of detailed investigations
Surikamigawa (2006)	MLIT	ER	52.5	216	110	474	Dam crest cracking, Increased leakage	Max. EQ-induced settlement = approx. 17 cm, Cracked pavement on dam crest
Ishibuchi (1953)	MLIT	CFRD	53	204	(184)	607	Dam crest cracking	Max. EQ-induced settlement = approx. 1 cm, Cracked foundation of railing on dam crest
Gosho (1981)	MLIT	PG, ER	105	237	39	125	-	Increase of leakage from contraction joints of concrete dam
Kejonuma (1995)	Miyagi Pref.	TE	24	176	269	495	Increased leakage	Max. EQ-induced settlement = approx. 14 cm, Cracks on the crest
Minamikawa (Saddle dam)[c] (1976)	Miyagi Pref.	AFRD	19.6	182	258	1282	Increased leakage	Cracked asphalt facing on upstream slope Two relatively long cracks on the asphalt facing on upstream slope
Tarumizu (1976)	Miyagi Pref.	ER	43	177	272	1381	Increased leakage	No remarkable damage or abnormalities

[a]ER: Earth core rockfill dam, TE: Earthfill dam, CFRD: Concrete-faced rockfill dam, AFRD: Asphalt-faced rockfill dam.
[b]Peak value of horizontal component (stream or dam axis direction) recorded at the dam foundation except for Ishibuchi Dam, where the seismometer is installed at right bank terrace (not bedrock).
[c]Values for main dam.

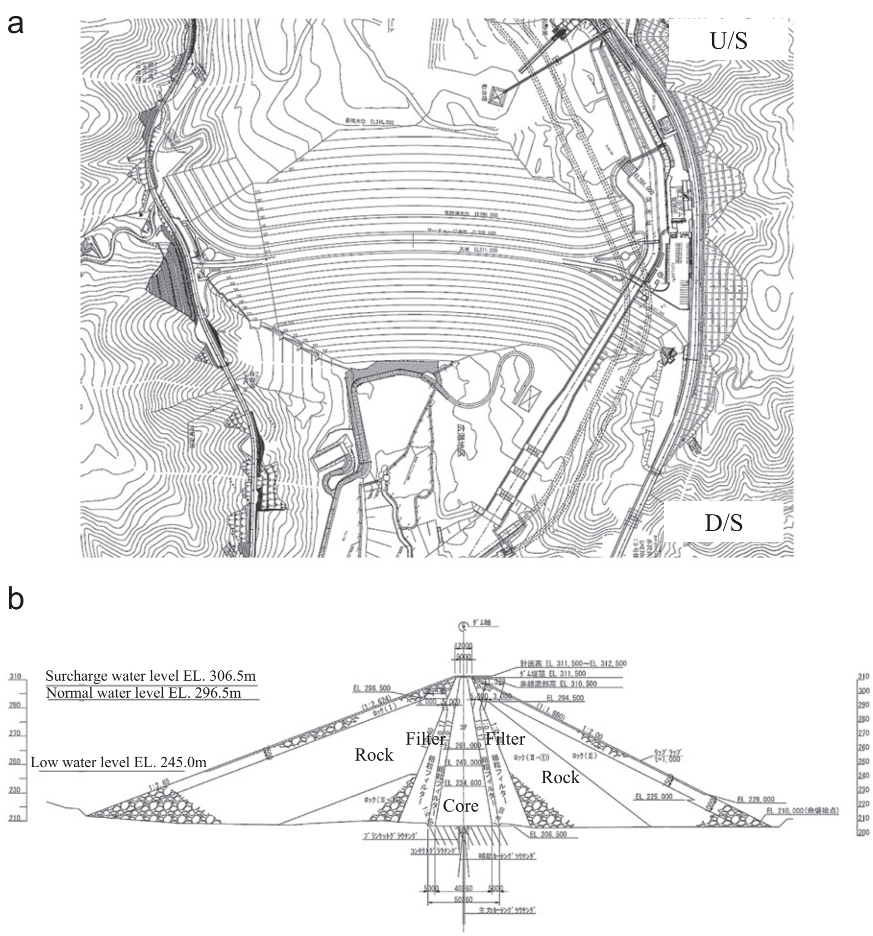


Fig. 4. Surikamigawa Dam.

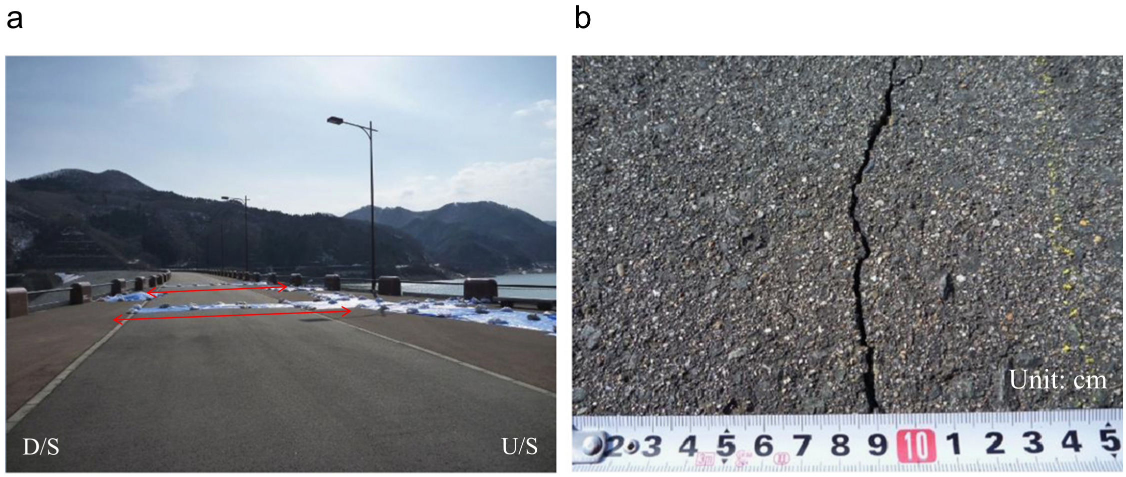


Photo 1. Cracking at the crest of Surikamigawa Dam. (a) Overview of the crest and (b) Close-up of a crack.

Photo 2. Crack depth analysis at Surikamigawa dam.

Geospatial Information Authority of Japan (GSI) (Geospatial Information Authority of Japan). The results of the investigation on embankment dams are summarized in Table 1.

3.2. *Results of detailed investigations*

(1) Surikamigawa dam

The Surikamigawa Dam, shown in Fig. 4, is a central earth-core type rockfill dam (ECRD) with a height of 105.0 m completed in 2006. The maximum horizontal acceleration observed at the rock foundation was 110 gal. Earthquake-induced damage and abnormalities at this dam were as follows:

(a) Cracking of the pavement on the dam crest near both abutments, primarily in the stream direction (Photo 1).
(b) Settlement of the dam body of approximately 170 mm at the crest near the maximum cross section.
(c) Increase in total leakage from approx. 70 L/min to 100 L/min.

As a result of the detailed investigation, it was concluded that there was no threat to the safety of the dam based on the following facts:

- The settlement caused by the earthquake was much smaller than the height of freeboard, and was not differential…
- The follow-up careful monitoring revealed that the increment of leakage was temporary.
- The cracks generated in the asphalt pavement on the dam crest were narrow in width.
- No damage was found on the upstream or downstream surfaces of the dam body.

However, to thoroughly ensure the safety of the dam, the depth of the cracks was investigated by the manager, as shown in Photo 2, with careful attention given to changes in the monitoring data. A close-up of a cross section around the dam crest is shown in Fig. 5. The investigation results confirmed that the cracks in the crest pavement terminated at 300 mm in depth within the protective layer just under the pavement, and did not reach the core zone.

(2) Ishibuchi dam

Fig. 6 shows the Ishibuchi Dam, a concrete faced rockfill dam (CFRD) with a height of 53.0 m completed in 1953. The maximum horizontal acceleration observed at the downstream right-bank terrace, which is not bedrock, was 184 gal. Earthquake-induced damage and abnormalities at this dam were as follows:

(a) Maximum settlement of dam body of approximately 12 mm at the crest around the maximum cross section,
(b) Cracks in the foundation of the crest railing.

As a result of the detailed investigation, it was confirmed that there was no threat to the safety of the dam, as the earthquake-induced settlement was small and no damage was found at the upstream concrete facing. The increase in measured leakage from approximately 2000 L/min to about 3000 L/min, reported in the results of the special safety inspection, was caused by algae blocking the water level inside the channel where the amount of leakage is measured. It was not clear why the algae had propagated inside the channel, but the importance of periodic inspection and maintenance of various facilities for monitoring of dams safety should be addressed. A seismograph installed at the dam crest recorded a peak acceleration of 1461 gal in the stream direction and 2070 gal in the vertical direction during the Mw7.0 Iwate-Miyagi Nairiku (Inland) Earthquake of 2008, which occurred near this dam. The 2008 earthquake caused rippling and cracking of the crest pavement and openings at the boundary between the crest pavement and railings (Photo 3(a)) (Yamaguchi et al., 2008), while damage due to the earthquake of 2011 (Photo 3(b)) was extremely minor.

In view of the relatively large settlement of over 500 mm caused by the 2008 earthquake, a new deformation measurement system using GPS to continuously monitor dam behavior was implemented at this dam (Yamaguchi et al., 2010). Fig. 7 shows the time series of

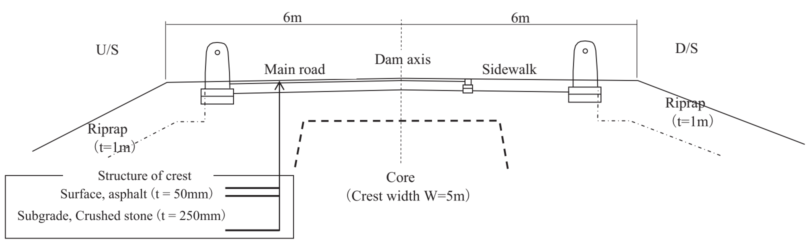


Fig. 5. Cross section around the crest of the Surikamigawa Dam.

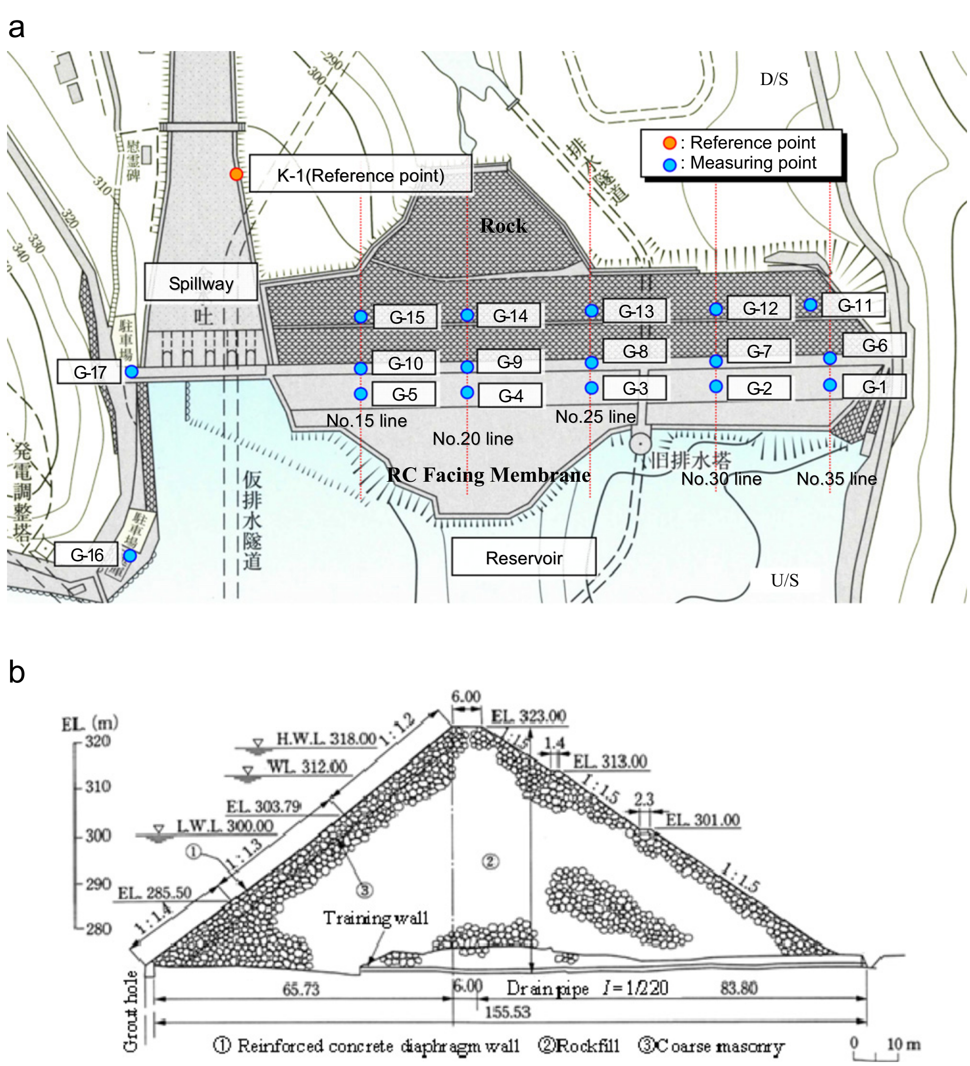


Fig. 6. Ishibuchi Dam.

a b

Photo 3. Crest of the Ishibuchi Dam. (a) After the 2008 earthquake (Yamaguchi et al., 2008) and (b) After the 2011 earthquake.

deformation at the measurement point at the center of the dam crest, namely No. G-9 indicated in Fig. 6(a). The results revealed that the main shock of the 2011 earthquake on March 11 caused 12 mm of settlement at the crest, and the largest aftershock, which occurred on April 7, resulted in a bit more settlement. Considering the GPS measurement data and the fact that no damage occurred at the concrete facing along the upstream slope, it was concluded that there was no threat to the safety of the dam.

(3) Kejonuma dam

The Kejonuma Dam, shown in Figs. 8 and 9, is a zoned earthfill dam with a height of 24.0 m completed in 1995. The maximum horizontal acceleration observed at the foundation was 269 gal. The earthquake-induced damage and abnormalities at this dam were as follows:

(a) Several small cracks in the stream direction on the dam crest including cracks of 25–30 mm in maximum width at the left bank side, as shown in Photo 4.
(b) A slight opening between the pavement and curb on the dam crest.
(c) A rapid but temporary increase in the total amount of leakage from 20 L/min to 430 L/min.
(d) A maximum settlement of 139 mm (much smaller than the height of freeboard) and deformation of 58 mm in the downstream direction at the center of dam crest.

Careful monitoring of measurement data with particular focus on the amount of leakage was continued. The results showed that the amount of total leakage rapidly decreased after the earthquake and remained stable at below 50 L/min, although it has increased just after rainfall within the range of past records. No other problems that threaten the safety of the dam have been found.

(4) Minamikawa saddle dam

The Minamikawa Saddle Dam, shown in Fig. 10, is an AFRD with a height of 19.6 m completed in 1987. It is located approximately 1 km from the upstream side of the main Minamikawa concrete gravity dam (height 46.0 m), which forms a reservoir with the saddle dam. Seismometers were installed at the main dam, but not at the saddle dam. The maximum horizontal acceleration observed at the rock foundation of the main dam was 271 gal. Earthquake-induced damage and abnormalities at the saddle dam were as follows:

(a) Two relatively long cracks in the asphalt facing forming the impervious membrane (Photo 5).
(b) Maximum earthquake-induced settlement of the dam body of approx. 90 mm at the dam crest around the maximum cross section.
(c) Temporary increase in leakage of 19 L/min–91 L/min.

As a result of investigation by the manager, the extent of cracks in the asphalt facing was identified. Remedial work consisting of partial reconstruction of the damaged facing is now being planned.

4. Earthquake motion observed at dam foundations and effects on embankment dams

4.1. Features of observed earthquake motions

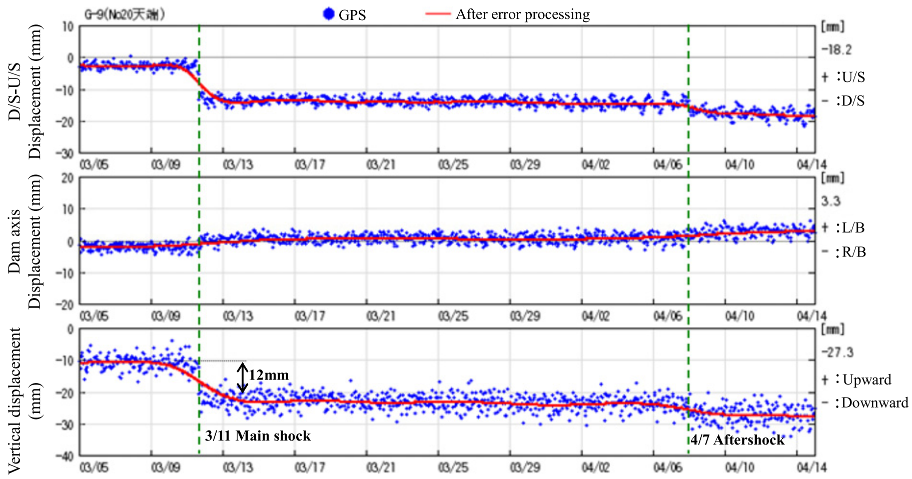
(1) Duration

At almost all of the dams under the jurisdiction of MLIT, seismometers are installed at or near the foundation and the crest. An example of an acceleration waveforms observed at the dam foundation and on the dam crest are shown in Fig. 11. As seen from this example, a major feature of the observed earthquake motion is its very long duration, while the peak acceleration value is not extremely large in comparison with earthquake motions observed during past inland active fault earthquakes in Japan. This feature becomes more distinct when comparing the duration of principal motion with various records observed during previous earthquakes, as shown in Fig. 12.

(2) Distance attenuation

Fig. 13 indicates a relationship between the distance from the source fault modeled as shown in Fig. 3 and the peak acceleration of the horizontal earthquake motion observed at the dam foundation, which is on bedrock at almost all the dams investigated.

Also shown in Fig. 13 is the empirical relationship calculated by using a distance attenuation formula (Mitsuishi et al., 2009) for estimating acceleration response spectra of earthquake motion at rock foundations for dams. The formula is used to set the earthquake motion for seismic performance evaluation of dams during large earthquakes (Shimamoto et al., 2007), and is now under trial implementation by the MLIT. The applicability of this formula for estimating the earthquake motion caused by Mw9 class interplate earthquakes should be carefully examined.



* Displacement was set to zero when the GPS was installed after the Iwate-Miyagi Nairiku Earthquake in 2008

Fig. 7. Earthquake-induced settlement of the Ishibuchi Dam measured using GPS monitoring system.

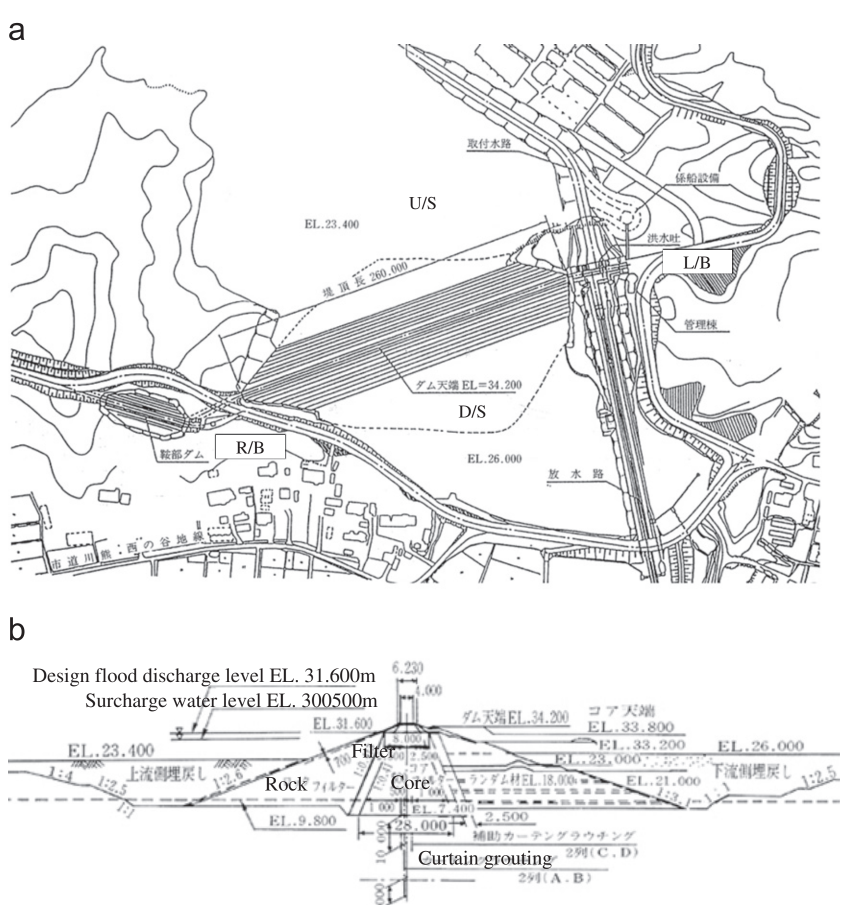


Fig. 8. Kejonuma Dam.

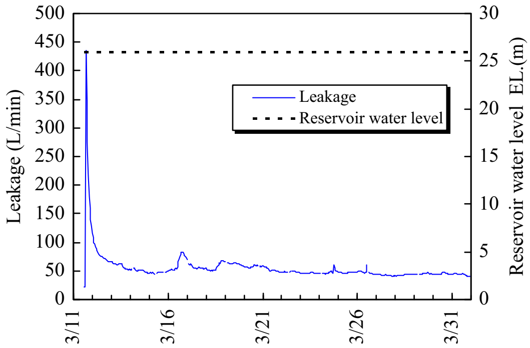


Fig. 9. Time series of total amount of leakage at Kejonuma Dam.

Photo 4. Cracking in the stream direction on the crest of Kejonuma Dam.

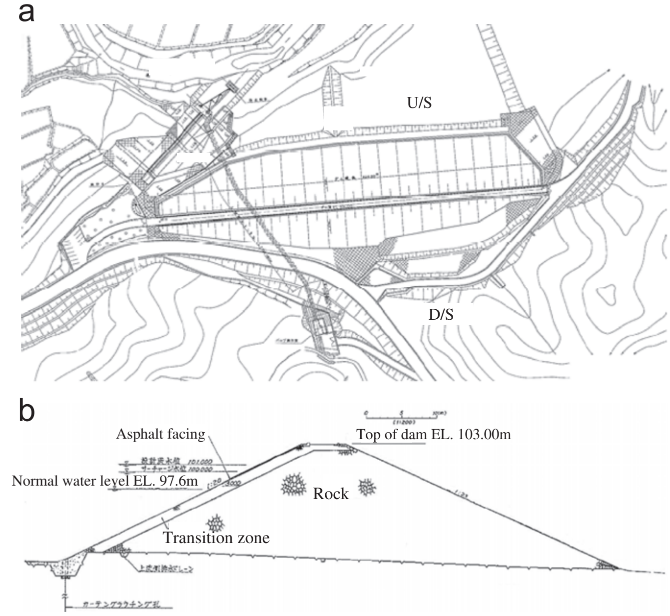


Fig. 10. Minamikawa Saddle Dam.

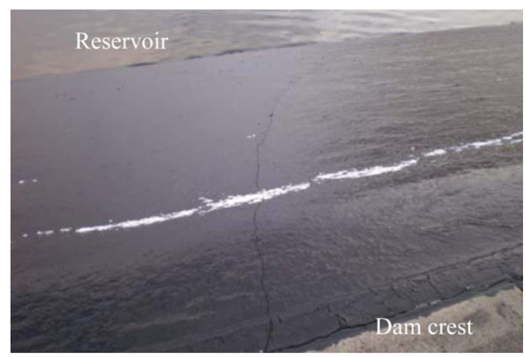


Photo 5. Cracking of the asphalt facing of the Minamikawa Saddle Dam.

(3) Response spectrum.

Fig. 14(a) shows examples of acceleration response spectra calculated from the horizontal component of earthquake motions observed at the dam foundations during the earthquake of March 2011 with those of several large earthquakes in recent years. Fig. 14(b) shows the spectra normalized by the value at 0.02 s in order to compare the spectrum shapes. A long-period component of the earthquake motions observed during the 2011 earthquake appears to be slightly larger than that of past inland active fault earthquakes, which generally have a strong short-period component. However, this type of trend is not so distinct in comparison to past large interplate earthquakes. There is a possibility that a shorter-period component of the earthquake motion was not well attenuated even at a certain distance from the source fault due to the huge scale of the earthquake. Further analyses on this point should be done.

4.2. Effects of earthquake motion on embankment dams

To roughly assess the effects of the 2011 earthquake on the embankment dams, the amount of settlement and change in amount of leakage, which are major indicators for monitoring the behavior of embankment dams, are analyzed.

(1) Amount of settlement

The relationship between the maximum amount of settlement measured at the crest of embankment dams after the earthquake, △H, and the horizontal peak acceleration observed at the foundation during the earthquake is shown in Fig. 15(a) for rockfill dams and in Fig. 15(b) for earthfill dams. In these figures, the amount of settlement is normalized by the height of each dam, H. Data on past earthquakes of various magnitudes that occurred around Japan and in other areas of the world (Swaisgood, 2003; Singh and Debasis, 2009) is also shown in these figures for comparison. Although the amount of settlement could change depending on the difference in material properties and internal structure of the dam body, geotechnical conditions and age of dams, these figures indicate that the settlement ratio for dams affected by the Mw9.0 earthquake of 2011 was not smaller in comparison with that for previous earthquakes with similar peak acceleration values, except in the case of the Ishibuchi Dam, which had previously settled by more than 500 mm after the 2008 Iwate-Miyagi Nairiku (Inland) Earthquake that occurred very close to the dam just two and a half years earlier.

(2) Amount of leakage

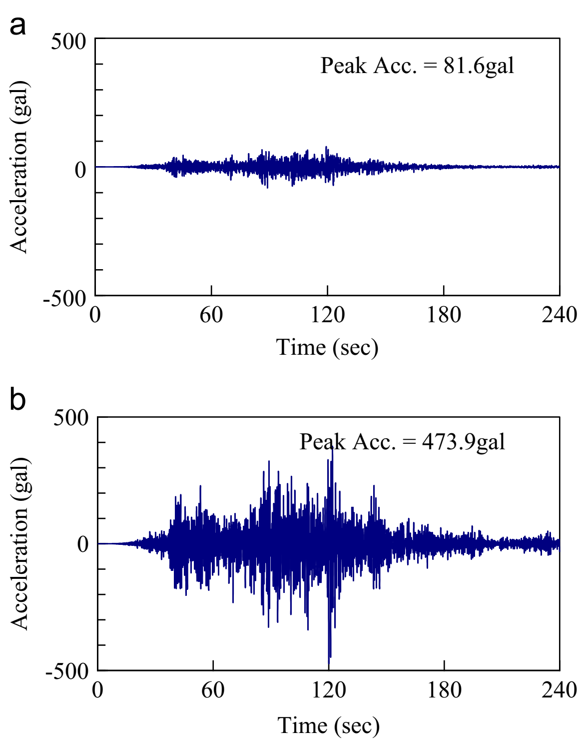


Fig. 11. Example of observed acceleration waveform (in the stream direction at the Surikamigawa Dam).

The relationship between the change in leakage measured at embankment dams before and just after the earthquake was studied. The results are shown in Fig. 16 together with data on past earthquakes in Japan. It should be difficult to find a simple relationship between a feature of the earthquake motion and the amount of leakage, because the amount of leakage at an embankment dam is affected by not only the soundness of the dam body but also the permeability of the foundation, change in groundwater level, rainfall and so on. However, looking at the rate of change in amount of leakage, it can be seen that some dams experienced a relatively large increase in leakage just after the 2011 earthquake in comparison to data on past earthquakes. Although we do not have any experimental or analytical findings on the relation between the amount of leakage and the characteristics of earthquake motion, when considering that the cyclic loading may cause the cumulative damage to embankment dams, the relatively large amount of leakage might be related to the long duration of the earthquake motion.

These rough studies are not enough to quantitatively assess the effects of earthquake motion as observed during the Great East Japan Earthquake. However, the long duration of the earthquake motion and frequency

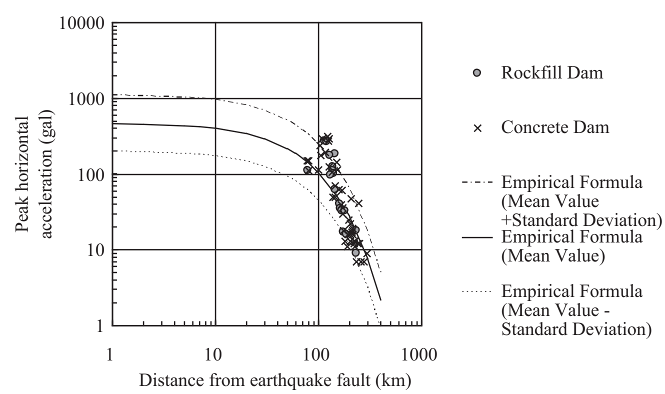
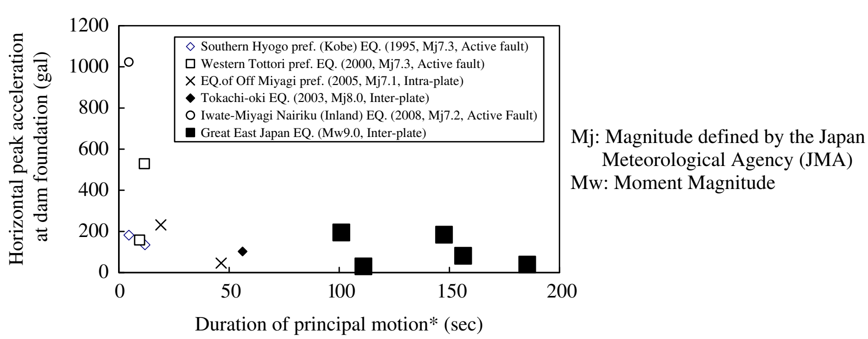


Fig. 13. Peak horizontal acceleration at dam foundation.



* Calculated as the time when acceleration equal to 10% or more of the peak value was first recorded to the time when finally recorded.

Fig. 12. Relationship between horizontal peak acceleration and duration of principal motion.

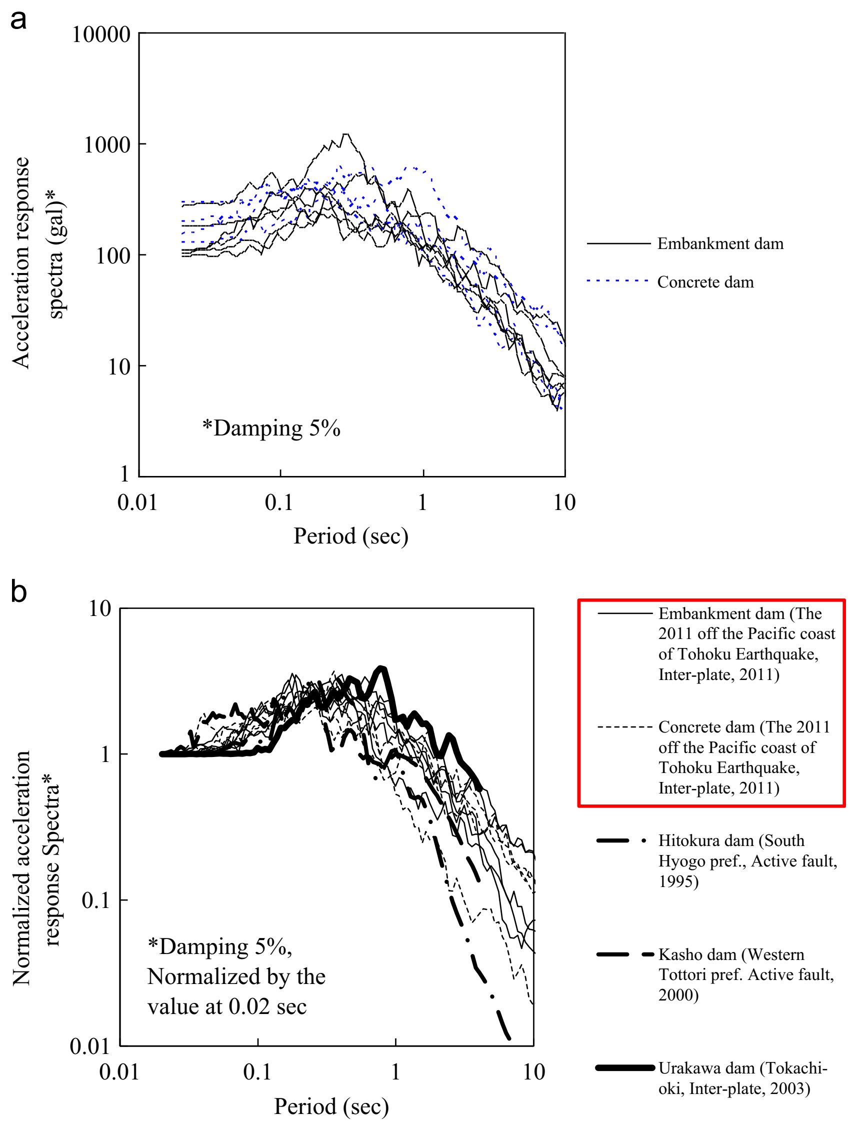


Fig. 14. Acceleration response spectra calculated from earthquake motion observed at dam foundation (Horizontal direction). (a) Acceleration response spectra and (b) Normalized acceleration response spectra.

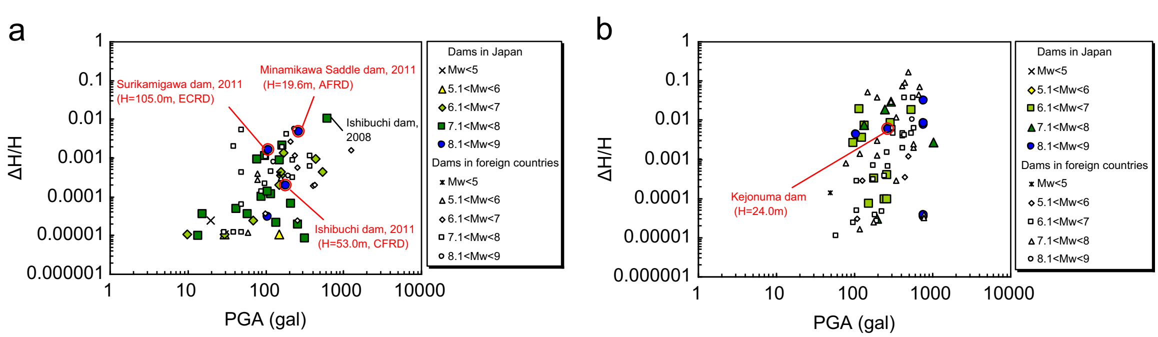


Fig. 15. Peak acceleration at dam foundation and settlement ratio of embankment dams. (a) Rockfill dams and (b)Earthfill dams.

characteristics mentioned above are possibly related to the behavior of embankment dams. More detailed studies such as a reproductive analysis of dynamic behaviors are required.

5. Conclusions

The effects of the 2011 Great East Japan Earthquake on dams, especially embankment dams, and the features of

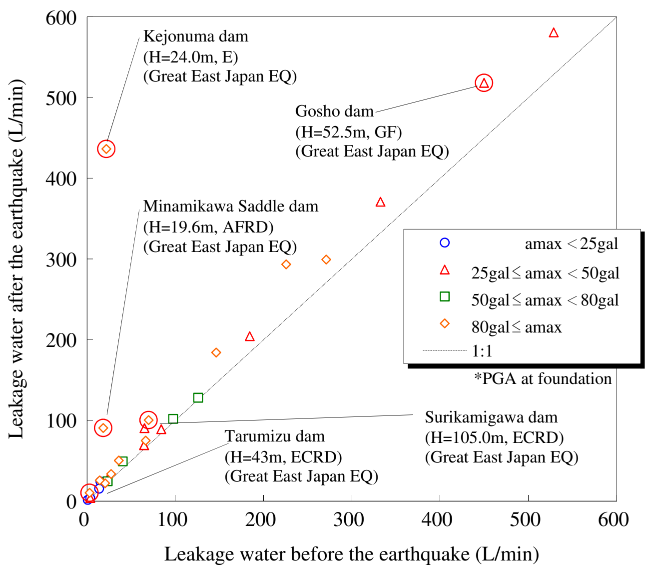


Fig. 16. Rate of change in amount of leakage at embankment dams before and after the earthquake.

earthquake motion observed at the dam foundations during the earthquake are summarized as follows:

a. As a result of special safety inspections conducted immediately after the earthquake, more than 10% of all inspected dams reported some damage. This ratio rose to 18% for embankment dams.
b. Major earthquake-induced damage to embankment dams included wide and long cracks on the crest and cracks at earthfill dams, cracks of the impervious facing at AFRDs and temporarily increased leakage.
c. Special safety inspections and subsequent detailed investigations confirmed that none of the dams under the jurisdiction of the MLIT sustained damage severe enough to threaten the safety of the dam, although careful monitoring and/or remedial work was required at certain dams.
d. A major feature of the earthquake motion observed at the dam foundations during the earthquake is the very long duration. Additionally, there is a possibility that a shorter-period component of earthquake motion was not well attenuated even at a certain distance from the source fault due to the huge scale of the earthquake. Further analyses should be done.
e. The rate of settlement and changes in leakage amount were reviewed in comparison to data on past earthquakes. The results revealed that the effect of the earthquake on embankment dams was not small at some dams, even though the peak acceleration of earthquake motions observed at the dam foundations during the earthquake was not stronger than that of past inland earthquakes that occurred nearby. Further studies are required to clarify the dynamic behavior of embankment dams for long-duration earthquake motion.

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References

Geospatial Information Authority of Japan: Crustal Deformation and Fault Model obtained from GEONET data analysis, 〈http://www.gsi.go.jp/cais/topic110422-index-e.html〉.
Japan Meteorological Agency 2004. The seismological and volcanological bulletin of Japan for January 2004.
Matsumoto, N., Sasaki, T., Amamiya, H., 2011. Effects of the 2011 Off the Pacific Coast of Tohoku earthquake on dams—Southern Region of Fukushima Prefecture. Engineering for Dams No. 296, 48–54 in Japanese.
Mitsuishi, S., Shimamoto, K., 2009. Seismic performance evaluation of dams during large earthquakes. Engineering for Dams, No. 274, pp. 6–35 (in Japanese).
Shimamoto, K., Sasaki, T., Kondo, M., 2007. Trial implementation of new Japanese guidelines for seismic performance evaluation of dams during large earthquakes, In: Proceedings of the 75th Annual Meeting of ICOLD.
Singh, R., Debasis, R. 2009. American Journal of Engineering and Applied Sciences, 2 (3), pp. 515–525.
Swaisgood, J.R., 2003. Embankment dam deformations caused by earthquakes, 2003 Pacific Conference on Earthquake Engineering, Paper no. 014.
Yamaguchi, Y., Iwashita, T., Mitsuishi, S., 2008. Preliminary investigation of dams stricken by the Iwate-Miyagi Nairiku Earthquake in 2008, In: Proceedings of the 5th EADC International Symposium on Co-existence of Environment and Dams.
Yamaguchi, Y., Kobori, T., Sakamoto, T., Kasai, T. (2010): Exterior deformation measurement for CFRD after a large-scale earthquake USING GPS, In: Proceedings of the the 78th Annual Meeting of ICOLD.
Yamaguchi, Y., Kondo, M., Kobori, T., Mitsuishi, S.,Okazumi, T., 2012.Safety inspections and seismic behavior of dams during the 2011 off the Pacific Coast of Tohoku Earthquake, Transactions of the 24th ICOLD Congress on Large Dams.