Effects on Dams due to the 2011 off the Pacific Coast of Tohoku Earthquake

by

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ABSTRACT

On March 11, 2011, The 2011 off the Pacific coast of Tohoku Earthquake occurred off the coast of the Tohoku Region of northeastern Japan. This report clarifies the impact on dams of this earthquake, which is the largest to occur in the history of Japan, outlines the results of special safety inspections performed immediately after the earthquake by dam managers, and summarizes the results of later detailed in-situ investigations by expert dam engineers. It also describes the characteristics of earthquake motion records observed at dams during this earthquake, and discusses future prospects for evaluating the seismic performance of dams during large earthquakes.

KEYWORDS: Dam, Detailed Investigation, Special Safety Inspection, Tohoku Earthquake

1. INTRODUCTION

At 2:46 p.m. (JST) on March 11, 2011, The 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as "The 2011 Tohoku Earthquake") occurred, striking mainly the Tohoku region of northeastern Japan and causing devastating damage. The number of dead or missing had exceeded 23,000 by the end of May 2011 [1]. At the many dams where earthquake motion at or above a specified level was observed, special safety inspections were immediately carried out by each dam manager and the results were reported to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Among the dams constructed on rock foundation under the regulation, “Cabinet Order Concerning Structural Standard for River Administration Facilities, etc.”, there were no dams with severe damages in spite of the massive scale of the earthquake. However, an old earthfill embankment of an irrigation pond, which was constructed more than 60 years ago and located outside of regulated areas under the River Law, breached due to the earthquake [2]. This report outlines the results of special safety inspections reported by the dam managers, detailed in-situ investigations of the dams in the jurisdiction of the MLIT carried out by the MLIT and the Public Works Research Institute (PWRI), and the characteristics of the earthquake motions recorded at these dams.

2. SPECIAL SAFETY INSPECTIONS OF DAMS IMMEDIATELY AFTER THE EARTHQUAKE

At dams in river areas managed under the River Law, dam managers must conduct special safety inspections immediately after an earthquake in cases where earthquake motion of 25 gal or higher was recorded at the dam foundation or cases where earthquake motion of JMA seismic intensity of 4 or higher was observed at the nearest meteorological station. The special safety inspections include a primary inspection and a secondary inspection. The former is a visual inspection immediately after the earthquake, while the latter includes a later, more detailed visual inspection and a safety inspection based on various data measured by monitoring devices.

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Special safety inspections were carried out after the earthquake of March 11 at 363 dams (Table 1). Earthquake motion with peak acceleration of 100 gal or more at the foundation was observed at over 20 dams. Except for several dams where inspections could not be performed because the area had been designated as restricted due to damages to the nuclear plants, the special safety inspections were completed. Damages severe enough to threaten the safety of the dams and need emergency measures were not reported. Reported damages were mainly minor cracking of the dam crest paving, temporarily increased leakage and so on (Table 2).

Although this report does not cite details, some damages were reported from dams managed by water users for irrigation or power generation. For example, relatively wide and long cracks on the crest and cracks or slippage on the upstream or downstream slope of earthfill dams and cracks of the facing membrane and increased leakage at asphalt face rockfill dams (AFRDs) were found. At dams where some damages were found, measured data are continuously being monitored and detailed investigations for repair works are being conducted, and temporary safety measures such as reservoir drawdown or waterproof covering over the cracks have been performed as needed.

3. DETAILED INVESTIGATIONS OF DAMAGE TO DAMS

3.1 Outline of Detailed Investigations

The MLIT and PWRI conducted in-situ detailed investigations focusing on those dams managed by the MLIT where some damages had been reported, leakage had increased, or peak acceleration records were relatively severe, in order to confirm the state of damages reported in the results of the special safety inspections, evaluate the safety of the dams, and to study countermeasures as needed. Several dams where leakage had increased in association with a rise of reservoir water level caused by later rainfall or snowmelt were added to the dams to be investigated, though it was not clear whether the increased leakage was related to the earthquake. Figure 1 shows the locations of dams investigated with a source fault model estimated by the Geospatial Information Authority of Japan (GSI) [3], while Table 3 outlines the investigation results. No damages severe enough to threaten the safety of dams were found at any of these dams.

3.2 Results of Detailed Investigations

3.2.1 Surikamigawa Dam

The Surikamigawa Dam, shown in Fig. 2, is a central earth core type rockfill dam with a height of 105 m completed in 2006. This earthquake increased the total leakage from approximately 70 L/min. to 100 L/min. and caused the following damages.

- Maximum earthquake-induced settlement of dam body of approximately 17 cm at the crest near the maximum cross section
- Cracking on pavement on the dam crest near both abutments, primarily in the stream direction (Photo 1).

As a result of the detailed investigation, it was concluded that there were no problems threatening the safety of the dam because of the following facts:

- The increased leakage and settlement caused by the earthquake were small relative to the scale of the dam.
- These values stabilized after the earthquake.
- The cracks in the crest pavement were narrow.
- No damages were found on the upstream and downstream surfaces.

In order to do everything possible to ensure safety, the manager is continuing to conduct careful monitoring, and has measured the depth of cracks. The results revealed that the cracks under the pavement terminated within the protective layer, and did not reach the dam section.

3.2.2 Ishibuchi Dam

The Ishibuchi Dam, shown in Fig. 3 is a concrete faced rockfill dam (CFRD) with a height of 53 m
completed in 1953. This earthquake caused the following damages.

- Maximum earthquake-induced settlement of the dam body of approximately 1 cm at the crest around the maximum cross section
- Cracking of the foundation of the crest railing

As a result of the detailed investigation, it was found that there were no problems threatening the safety of the dam, because the earthquake-induced settlement was small and no damages were found to the upstream concrete facing. The increase of measured leakage from approximately 2,000 L/min. to about 3,000 L/min. reported in the results of the special safety inspection were revealed to be due to blocking of the water level inside the channel where the amount of leakage is measured caused by adhering of algae. At this dam, a seismograph installed at the dam crest recorded a peak acceleration of 1,461 gal in the stream direction and 2,070 gal in the vertical direction during The Iwate-Miyagi Nairiku Earthquake in 2008 (Mj7.2, inland active fault earthquake). Damages due to the 2008 earthquake included rippled and cracked crest pavement and openings on the boundary between the crest paving and railings (Photo 2(a)) [4], while damages due to the 2011 Tohoku Earthquake (Photo 2(b)) were extremely minor.

3.2.3 Tase Dam

The Tase Dam, shown in Fig. 4, is a concrete gravity dam with a height of 81.5 m completed in 1954. This earthquake increased the total leakage from 14 L/min. to 69 L/min. and caused the following damages.

- Exfoliation of parapet concrete at the crest (Photo 3(a))
- Opening of cracks and level differences on crest paving (Photo 3(b))

As a result of the detailed investigation, it was decided that there were no problems threatening the safety of the dam considering the fact that leakage from each contraction joint was low at no more than about 10 L/min. and uplift pressure was not increased, though some leakage was generated from joint drain holes where it had been almost zero before the event. Therefore, in order to do everything possible to ensure dam safety, the manager is continuing to conduct careful monitoring, paying close attention to the correlation of reservoir water level with leakage.

3.2.4 Kamuro Dam

The Kamuro Dam, shown in Fig. 5, is a concrete gravity dam with a height of 60.6 m completed in 1993. Approximately one month after the earthquake, leakage at the dam increased remarkably (Fig. 6), at around the same time that the reservoir water level began to rise caused by melting snow and rainfall in the upstream area and a relatively large aftershock (Mj7.4) on April 7. However, the peak acceleration (horizontal component) of seismic motion observed at the foundation of this dam was 18 gal by the main shock, and 15 gal by the aftershock, neither particularly high values. A similar situation occurred at the Takasaka Dam located nearby.

The results of the detailed investigation revealed that the increased leakage was conspicuous primarily at the drainage hole from the contraction joint 2J3 (Photo 4), and its quantity exceeds the maximum value at the same reservoir water level in the past at this dam. Neither increased uplift pressure or leakage from the foundation drain holes, nor exterior damage to the dam body were found.

In response to the results of the detailed investigations, the manager has stepped up monitoring of leakage and opening of joints, particularly the contraction joints, and also began an investigation to identify the leakage channels for taking countermeasures. The leakage has tended to stabilize after the detailed investigation, as shown in Fig. 6. Further analyses of the impact of earthquake motion on leakage should be conducted.

4. OBSERVED EARTHQUAKE MOTIONS

The River Bureau and National Institute for Land and Infrastructure Management, MLIT is collecting earthquake motion records including
seismic wave records observed at dams. Although only limited records have been collected to date, the properties of earthquake motion triggered by this earthquake are described below.

4.1 Peak Acceleration

Figure 7 shows the relationship of the peak acceleration of the horizontal earthquake motion observed at each dam foundation with the distance from the source faults modeled as shown in Fig. 1. The peak acceleration observed at each dam relatively far from the source fault of the offshore earthquake is not extremely large compared with records observed at dams near the epicenter of past inland active fault earthquakes, as shown in Table 4. Although it is necessary to examine its application to an extremely large-scale earthquake such as this event, the empirical formula [5] for estimating the peak acceleration spectrum at dam rock foundations is also shown in Fig. 7. The formula is used in consideration of the variation of earthquake motion to set the earthquake motion for evaluating the seismic performance of dams during large earthquakes [6], which is now under trial implementation by the MLIT.

4.2 Acceleration Time History

As examples, seismic motions observed at the foundation and crest of the Miharu Dam and Surikamigawa Dam during the earthquake are shown in Fig. 8 and Fig. 9, respectively. In Fig. 10, the value of peak acceleration and duration of principal motion at these dams are compared to the records observed at dam foundations during major earthquakes in recent years. Obviously, the duration of the earthquake motion of 2011 is longer than that of other records.

4.3 Acceleration Response Spectra

Figure 11 shows examples of normalized acceleration response spectra of earthquake motions observed at dam foundations during the earthquake of 2011 and several earthquakes in recent years. Although waveform data collected during the 2011 earthquake is still limited, the long-period component is relatively somewhat larger than that of past inland active fault earthquakes, but this trend is not so strong in comparison with past interplate earthquakes. Further analyses using more waveform records are required to evaluate the impact of earthquake motion during the 2011 earthquake on the seismic behavior of dams.

5. CONCLUSIONS

Following The 2011 Tohoku Earthquake, which is the largest earthquake that has ever struck Japan, special safety inspections were carried out immediately, and the MLIT and PWRI conducted in-situ detailed investigations. As a result, among the dams in the jurisdiction of the MLIT, no damages severe enough to threaten safety were found at any of the dams. This appears to be because almost all Japanese dams, except earthfill dams, are constructed on rock foundation, and because the source fault of the earthquake was relatively far from the dams so the earthquake motion was not as strong as that observed at dams close to the epicenters of past inland active fault earthquakes.

On the other hand, the duration of earthquake motion was far longer than that of any past earthquake observed in Japan. The trial implementation to evaluate the seismic performance of dams considering maximum class earthquake motion is now continued in Japan. A characteristic of the earthquake motions observed in the 2011 earthquake suggests that it may be necessary to consider more severe damages to dams than previously assumed due to the cyclic action of earthquake motion which is not only extremely strong but also continues for a very long time.

Acknowledgments

The authors sincerely thank the managers of the dams for their cooperation with the detailed investigations and collection of seismic motion records.
6. REFERENCES


Table 1  Numbers of dams where special safety inspections were conducted

<table>
<thead>
<tr>
<th>Manager</th>
<th>Total</th>
<th>Concrete dams</th>
<th>Embankment dams</th>
<th>Combined dams</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLIT or Japan Water Agency</td>
<td>46 (11)</td>
<td>31 (6)</td>
<td>10 (3)</td>
<td>5 (2)</td>
</tr>
<tr>
<td>Prefectural Governments</td>
<td>104 (8)</td>
<td>81 (6)</td>
<td>22 (2)</td>
<td>1 (0)</td>
</tr>
<tr>
<td>Water users (Power generation-, Irrigation- and tap/industrial water supply- purpose)</td>
<td>213 (27)</td>
<td>107 (7)</td>
<td>101 (19)</td>
<td>5 (1)</td>
</tr>
<tr>
<td>Total</td>
<td>363 (46)</td>
<td>219 (19)</td>
<td>133 (24)</td>
<td>11 (3)</td>
</tr>
</tbody>
</table>

* The figure in (   ) represents number of dams where damages reported. Almost of them are minor except several cases at dams managed by water users.

Table 2  Typical damages reported in the results of special safety inspections

<table>
<thead>
<tr>
<th>Dam type</th>
<th>Damages in relation to dam body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete dams</td>
<td>- Minor cracks on dam crests</td>
</tr>
<tr>
<td></td>
<td>- Increased leakage</td>
</tr>
<tr>
<td>Embankment dams</td>
<td>- Cracks on dam crest of earthfill dams</td>
</tr>
<tr>
<td></td>
<td>- Cracks on upstream or downstream slopes of earthfill dams</td>
</tr>
<tr>
<td></td>
<td>- Cracks on waterproof facing of Asphalt Faced Rockfill Dams</td>
</tr>
</tbody>
</table>
Fig. 1   Locations of dams for detailed investigations
Table 3  Outline of results of detailed investigations

<table>
<thead>
<tr>
<th>Dam (Year of completion)</th>
<th>Manager</th>
<th>Type*</th>
<th>Height (m)</th>
<th>Epicentral distance (km)</th>
<th>PGA** (gal)</th>
<th>Results of special safety inspection</th>
<th>Results of detailed investigations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surikamigawa (2006)</td>
<td>MLIT</td>
<td>ER</td>
<td>52.5</td>
<td>216</td>
<td>110</td>
<td>Dam crest cracking, Increased leakage</td>
<td>Max. EQ-induced settlement ~approx. 17cm, Cracked pavement on dam crest (see 3.2.1.)</td>
</tr>
<tr>
<td>Ishibuchi (1953)</td>
<td>MLIT</td>
<td>CFRD</td>
<td>53</td>
<td>204</td>
<td>(184)</td>
<td>Dam crest cracking</td>
<td>Max. EQ-induced settlement ~ approx. 1cm, Cracked foundation of railing on dam crest (see 3.2.2.)</td>
</tr>
<tr>
<td>Tase (1954)</td>
<td>MLIT</td>
<td>PG</td>
<td>81.5</td>
<td>192</td>
<td>N.A.</td>
<td>Increased leakage</td>
<td>Exfoliation of parapet concrete on dam crest (see 3.2.3.)</td>
</tr>
<tr>
<td>Gosho (1981)</td>
<td>MLIT</td>
<td>PG, ER</td>
<td>105</td>
<td>237</td>
<td>39</td>
<td>Increased leakage</td>
<td>Increase of leakage from contraction joints of concrete dam</td>
</tr>
<tr>
<td>Gassan (2001)</td>
<td>MLIT</td>
<td>PG</td>
<td>123</td>
<td>265</td>
<td>11</td>
<td>Increased leakage</td>
<td>Increase of leakage from contraction joints</td>
</tr>
<tr>
<td>Kejoumura (1995)</td>
<td>Miyagi Pref.</td>
<td>TE</td>
<td>24</td>
<td>176</td>
<td>269</td>
<td>Increased leakage</td>
<td>(Max. EQ-induced settlement ~ approx. 14cm Cracks on the crest</td>
</tr>
<tr>
<td>Zao (1970)</td>
<td>Yamagata Pref.</td>
<td>Hollow Gravity</td>
<td>66</td>
<td>212</td>
<td>91</td>
<td>Increased leakage</td>
<td>Increase of leakage from drainage holes installed in the foundation</td>
</tr>
<tr>
<td>Fujiigawa (1976)</td>
<td>Ibaraki Pref.</td>
<td>PG</td>
<td>37.5</td>
<td>289</td>
<td>174</td>
<td>Increased leakage</td>
<td>Increase of leakage from drainage holes installed in the foundation</td>
</tr>
<tr>
<td>Koyama (2005)</td>
<td>Ibaraki Pref.</td>
<td>PG</td>
<td>65</td>
<td>244</td>
<td>334</td>
<td>Increased leakage</td>
<td>Increase of leakage from contraction joints</td>
</tr>
<tr>
<td>Kamuro (1993)</td>
<td>Yamagata Pref.</td>
<td>PG</td>
<td>60.6</td>
<td>231</td>
<td>18</td>
<td>Increased leakage</td>
<td>Studying countermeasures on leakage from contraction joints (see 3.2.4.)</td>
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<tr>
<td>Takasaka (1967)</td>
<td>Yamagata Pref.</td>
<td>PG</td>
<td>57.0</td>
<td>254</td>
<td>25</td>
<td>Increased leakage</td>
<td>Studying countermeasures on leakage from contraction joints</td>
</tr>
</tbody>
</table>

* PG: Concrete gravity dam, ER: Earth core rockfill dam, CFRD: Concrete faced rockfill dam, TE: Earthfill dam
** Peak value of the horizontal component (stream or dam axis directions) recorded at dam foundation except Ishibuchi dam, where its seismometer is installed at right bank terrace (not bedrock).
*** Additional investigations concerning increased leakage approximately one month after the earthquake.
Fig. 2  Surikamigawa dam

(a) Overview of the crest  
(b) Closeup of a crack

Photo 1  Cracking at crest of Surikamigawa dam

Fig. 3  Ishibuchi dam
(a) After the Event of 2008 [4]

(b) After the Event of 2011*

*Traces of repairs of paving followed the 2008 earthquake

Photo 2  Crest of Ishibuchi dam

(a) Longitudinal section                              (b) Cross section

Fig. 4  Tase dam

(a) Exfoliation of parapet concrete  (b) Level difference at joint

Photo 3  Damages at crest of Tase dam
Fig. 5  Longitudinal section of Kamro dam

(a) Contraction joint 2J3  
(b) Leakage from contraction joint 2J3

Photo 4  Leakage from contraction joint of Kamuro dam

Fig. 6  Time history of leakage at Kamuro Dam
Table 4  Large earthquake motion records at the dam foundation in recent years

<table>
<thead>
<tr>
<th>Year</th>
<th>Earthquake Location</th>
<th>Earthquake Scale*</th>
<th>Dam Type</th>
<th>Dam Name</th>
<th>Dam Type **</th>
<th>Distance* &quot;&quot; (km)</th>
<th>PGA**** (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>Southern Hyogo pref. (Kobe)</td>
<td>Mj7.3</td>
<td>Active fault</td>
<td>Hitokura</td>
<td>PG</td>
<td>48</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48</td>
<td>135</td>
</tr>
<tr>
<td>2000</td>
<td>Western Tottori pref.</td>
<td>Mj7.3</td>
<td>Active fault</td>
<td>Kasho</td>
<td>PG</td>
<td>12</td>
<td>569</td>
</tr>
<tr>
<td>2003</td>
<td>(Off Miyagi pref.)</td>
<td>Mj7.1</td>
<td>Intraplate</td>
<td>Tase</td>
<td>PG</td>
<td>73</td>
<td>232</td>
</tr>
<tr>
<td>2003</td>
<td>Tokachi-oki</td>
<td>Mj8.0</td>
<td>Interplate</td>
<td>Urakawa</td>
<td>PG</td>
<td>55</td>
<td>228</td>
</tr>
<tr>
<td>2004</td>
<td>Mid Niigata pref.</td>
<td>Mj6.8</td>
<td>Active fault</td>
<td>Shirokawa</td>
<td>PG</td>
<td>115</td>
<td>103</td>
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<tr>
<td>2007</td>
<td>Noto hanto</td>
<td>Mj6.9</td>
<td>Active fault</td>
<td>Hakkagawa</td>
<td>PG</td>
<td>14</td>
<td>162</td>
</tr>
<tr>
<td>2007</td>
<td>Niigataken chuetsu-oki</td>
<td>Mj6.8</td>
<td>Active fault</td>
<td>Kakizaki -gawa</td>
<td>ER</td>
<td>31</td>
<td>170</td>
</tr>
<tr>
<td>2008</td>
<td>Iwate-Miyagi Nairiku</td>
<td>Mj7.2</td>
<td>Active fault</td>
<td>Aratozawa</td>
<td>ER</td>
<td>16</td>
<td>(1024)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.5</td>
<td>(657)</td>
</tr>
<tr>
<td>2011</td>
<td>Off the Pacific Coast of Tohoku</td>
<td>Mj9.0</td>
<td>Interplate</td>
<td>Miharu</td>
<td>PG</td>
<td>230</td>
<td>195</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>216</td>
<td>110</td>
</tr>
</tbody>
</table>

* Mj: JMA magnitude, Mw: Moment magnitude ** PG: Concrete Gravity Dam, ER: Earth Core Rockfill Dam, CFRD: Concrete Faced Rockfill Dam, *** Epicentral distance **** Maximum value of horizontal component (stream direction or dam axis direction). PGA value for Aratozawa Dam (2008) may be the upper limit for measurement by seismometer. PGA value for Ishibuchi Dam (2008) is estimated value [7].

Fig. 7  Peak horizontal acceleration at dam foundation
Fig. 8  Seismic motion observed at Miharu dam in stream direction

(a) Dam foundation                              (b) Dam crest

Fig. 9  Seismic motion observed at Surikamigawa dam in stream direction

(a) Dam foundation                              (b) Dam crest
Fig. 10  Peak acceleration and duration of principal motion observed at dam foundations

Fig. 11  Acceleration response spectra of earthquake motions observed at dam foundations in stream direction