Possible earthen dam failure mechanisms of Fujinuma reservoir due to the Great East Japan Earthquake of 2011

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Abstract:
A gigantic earthquake, now known as the Great East Japan Earthquake, with a magnitude of 9.0 (the maximum ever recorded in Japan) struck the Tohoku region of Japan on 11 March, 2011. As a result, as many as 745 reservoirs in Fukushima prefecture were damaged. The failure of the earth-fill dam at the Fujinuma reservoir in Fukushima prefecture resulted in eight deaths in a village downstream. This was only the second such dam to fail completely in the recorded history of Japan, the first being Mannou Lake dam. The failure was caused by the Ansei Nankai earthquake in 1854. According to official records, of the 210,000 reservoirs in Japan, at least 20,000 dams are vulnerable to future earthquakes. Therefore, it is imperative that the failure mechanism of the Fujinuma reservoir be understood. As such, we developed several theories to explain what happened. Adherence to recommendations made in this report will reduce the potential for damage in future catastrophic events.

KEYWORDS The Great East Japan Earthquake; Fujinuma reservoir; Fukushima prefecture; earth-fill dam; inland tsunami

INTRODUCTION
A gigantic earthquake, now known as the Great East Japan Earthquake, with a magnitude of 9.0 (the maximum ever recorded in Japan) struck the Tohoku region of Japan at 2:46 PM Japan Standard Time on 11 March 2011. The epicenter of the earthquake was approximately 72 km east of the Oshika Peninsula of Miyagi prefecture, at a relatively shallow depth of 32 m (USGS, 2011) (Figure 1). The ground shook for nearly 6 minutes with a 0.2- to 1.0-second dominant period of the main earthquake (Mimura et al., 2011). Because the dominant period of the 2011 earthquake was considerably shorter than that of the 1995 Great Kobe Earthquake, there was less intensive damage, but four bridges and as many as 745 reservoirs in Fukushima prefecture were damaged (Agriculture, Forestry and Fisheries Department of Fukushima Prefecture, 2011). The most devastating damage occurred at the Fujinuma reservoir in Fukushima prefecture, where the complete failure of an earth-fill dam occurred. This is only the second complete dam failure in history, the first being the failure of the Mannou Lake dam due to the Ansei Nankai earthquake in 1854, known to have occurred entirely as the result of an earthquake in Japan (Ono et al., 2011b). Because of the failure, 8 deaths were reported in Taki-syuraku, downstream from the Fujinuma reservoir (Figure 1).

Of the 210,000 reservoirs in Japan, the design guidelines and construction methods of at least 20,000 of them are less than adequate at the present time (Okuno et al., 2003). Ironically, neither the people living downstream nor the responsible government officials have heretofore paid attention to this grave problem. Given the increased vulnerability of both damaged and undamaged earth-fill dams in future earthquakes, it is important to examine strategies for disaster mitigation and prevention. To address this need, this paper summarizes all available evidence from on-site investigations and interviews with eyewitnesses to develop a plausible failure mechanism for the Fujinuma dam. Because complete dam failure due to an earthquake is a rare incident, once the failure mechanism is clearly understood, a proper assessment can then be made for other dams to prevent such failures in the future.

SITE DESCRIPTIONS
Built in 1949, the Fujinuma dam was 17.5 m in height and 133.0 m in length and stored 1,504,000 m3 of water (Japan Dam Foundation, 2011). The general slopes of the dam in the upstream and downstream directions were approximately uniform and ranged between 1:2.5 and 1:2.8, with the exception of the upper slope in the upstream direction, which had a relatively steep 1:1.5 slope (Figure 2a).

The dam was built for irrigation purposes to supply water to approximately 700 farming households in the locality. At the time of the earthquake, the Fujinuma reservoir was running at full capacity, ready to meet the demands of the upcoming irrigation season. Following the earthquake and dam failure, several field visits were made, including interviews with the locals in Taki-syuraku, a village downstream from the Fujinuma reservoir. An extensive inspection of the failure dam site and investigations of other earth-fill and concrete dams in Fukushima prefecture were also conducted.

DESCRIPTIONS OF THE INTERVIEWS AND FIELD SURVEYS
According to the eyewitnesses in Taki-syuraku, the
collapse of the dam was marked by a thudding sound just after the earthquake. Two flash flood waves ripped through the village. The first wave arrived just after the earthquake, and the second wave followed 10 minutes later. The resulting flash flood destroyed sections of forest and collected a large amount of sediment from the paddy fields. This resulted in significant damage in Taki-syuraku. After the first wave, some of the locals returned to their homes to collect their belongings and were victims of the second wave.

In the subsequent inspections, no large portions of the dam body were found downstream. The whole dam gave way and was flushed downstream, with the exception of a portion at the right side on the upstream section, where the dark brown earth fill remains almost uniformly flat at a level of approximately 6 m below the crest of the dam (Figure 2c). There is no recorded information available to detail the construction method or the type of embankment fill material. Based on visual observations of the remaining portion of the dam, different types of materials were used in the dam body. The black foundation material, with a thickness of approximately 1–2 m, consisted of organic residuals mixed with clay and silt (Figure 2d). On top of the foundation material, there was a dark brown sand and gravel fill up to 10–12 m above the foundation. The upper portion of the dam appears to have been filled with a layer of light brown volcanic ash and pumice. Inspections of four other earth-fill dams within a 27 km radius of the Fujinuma reservoir revealed serious longitudinal cracks varying in width from 2 to 10 centimeters on the crest and extending as much as 100 meters (Figure 2e). Several sand boiling spots were also noted around Nishigo dam (15 km southwest from the Fujinuma dam). It should be noted that none of the modern reinforced-concrete dams incurred much damage. Based on information collected during field visits, we developed several failure modes to explain the mechanisms of failure that occurred.

**POTENTIAL FAILURE MECHANISMS**

**Potential breach resulting from cracks and a slope failure**

According to the descriptions provided in the interviews, it is possible that the failure occurred in two steps. First, the observed severe longitudinal cracks in the other four earth-fill dams suggested that serious cracks may have developed on the crest of the Fujinuma dam as well, and they may have penetrated quite deeply. The uniformly flat nature of the remaining dark brown dam portion suggests that the crack propagation and failure may have started at the upper part of the dam, which was subject to strength losses during the long period of shaking. This evidence suggests that serious cracks caused by tensile stresses in the rarefaction between the earthquake shocks developed on the crest and extended to depths of up to 6 m. Because the reservoir was almost full, the force of the reservoir water acting from the upstream side caused propagation of the crack, structurally weakening the upper portion of the dam, which literally broke into pieces. If the degree of compaction was relatively small between embankment fill materials, then the interface between the upper and lower portions may have lost the strength required to hold back the force of the reservoir water acting from the upstream side, leading to the first failure, which likely occurred in the upper portion of the dam. The damage may have been exacerbated by upstream slope slides that frequently occur because of saturation in artificially reclaimed soft alluvial slopes (Kawagoe *et al.*, 2010; Ono *et al.*, 2011a) when reservoirs are at full capacity (Sherard *et al.*, 1963). The absence of transfer cracks in the other four dams investigated suggests that the major cause of failure was likely not deformation.

**Potential breach resulting from sliding of the lower portion of the dam**

In the second step, the appearance of the remaining portion of the dam indicates that the ultimate failure was very likely caused by sliding of the lower portion of the dam. Soil liquefaction tends to occur in dams with loose
and saturated soil when they are subjected to a series of cyclic loading. Because the dam was saturated because of the high water level, the pressure generated by the long-lasting earthquake with its many cycles of shaking may have severely reduced the shearing strength of the dam. In the Fujinuma reservoir area, several sand boiling points were observed, suggesting that the second failure occurred because of a loss of shear strength at the interface between the dark brown dam portion and the black foundation materials.

**Comparisons of the Fujinuma Dam Failure with Other Such Incidents at the National and International Levels**

Internationally, a similar event was recorded in California when the Sheffield Dam failed completely because of the magnitude 6.3 Santa Barbara Earthquake on 29 June 1925. According to the recorded history, a water leak had been observed at the downstream toe for several years (Sherard et al., 1963). At the time of failure, the water level was approximately 15 ft below the crest of the 35 ft dam. Unlike the Fujinuma dam, which had literally been shaken to pieces, the entire central portion of the Sheffield dam was found approximately 100 ft downstream. According to the inspection by a number of eminent dam engineers, it was concluded that the failure was caused by liquefaction of the lower portion of the embankment or the upper part of the foundation. Because the lower embankment was saturated, the shearing strength of the base was severely reduced during the subsequent vibration, and the force of the reservoir water acting on the upstream slope pushed the central portion of the dam body downstream. This failure phenomenon at the Sheffield Dam is quite similar to the proposed second-phase failure mechanism at the Fujinuma reservoir.

At the national level, small-scale embankments in Japan (less than 10 m high, in general) are frequently damaged by major earthquakes. For example, the magnitude 7.5 Nigata earthquake on 16 June 1964 caused severe damage to many hydraulic structures in the Tohoku region. Of the 8,700 total reservoirs in the area, 146 reservoir embankments were damaged, and 7 embankments totally failed (Electric Power Civil Engineering Association, 1972). Similar to the proposed first failure mechanism for the Fujinuma dam, the main cause of damage for at least 80% of the embankments was determined to be the major cracks that developed on the embankment crest and the upstream slope. The reports stated that considerable leakages gradually developed through the cracks, which led to piping failure in 7 embankments several hours to one day after the earthquake.

**Concluding Remarks**

The Great East Japan Earthquake caused a severe inland tsunami situation when the Fujinuma dam completely failed. The resulting flash flood destroyed sections of forest and picked up a large amount of sediment from the paddy fields. This resulted in significant damage in Taki-syuraku. Given
the increased vulnerability of both damaged and undamaged earth-filled dams in future earthquakes, we need to examine strategies for disaster mitigation and prevention. To date, the people who live downstream from the more than 20,000 dams have not paid enough attention to the risk of dam failure. The damage potential could be reduced substantially by proper and regular investigations and maintenance. In the mean time, soft measures must be taken, such as preparing risk maps of vulnerable reservoirs and associated downstream areas. In addition, to improve preparedness for future major earthquakes, better plans for land-use need to be drawn up and the relocation vulnerable populations in high-risk areas must be considered.

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