THE BREACHED EARTH-FILL DAM FOLLOWING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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ABSTRACT: Fujinuma dam, an earth-fill dam for irrigation located in Sukagawa City, Fukushima prefecture, was breached in the 2011 Off the Pacific Coast of East Japan earthquake. The water from the breached dam scoured its downstream valley floor and walls, and developed into a debris flow. The debris mass flushed a village downstream leaving 8 dead and 1 missing. The authors made a survey along the stream channel of the debris flow. During their survey, the breached dam body was LiDAR surveyed for its entire 3D image. With the findings from the survey, this paper discusses a possible mechanism of the dam breaching.

Key Words: The 2011 Off the Pacific Coast of East Japan Earthquake, LiDAR, dam breaching, debris flow

INTRODUCTION

The Great East Japan Earthquake measuring Mw 9.0 (USGS, 2010) hit the east Japan at 2:46PM, March 11th, 2011. The intense shake was followed by tsunami, which engulfed the entire stretch of the Pacific coast of east Japan leaving about 20,000 dead or missing. The earthquake-induced liquefaction had caused severe damage to dwellings, underground facilities in Kanto region, especially, in the Tokyo bay area. One of the most serious problems was the disaster at the Fukushima Daiichi nuclear power plant. This event yielded a long lasting problem of radioactive contamination. With the wide spreads devastation mentioned above, less attention was paid to landslides including seven slope failures in Shirakawa region, upstream reaches of the Abukuma River, which slides were responsible for at least 13 deaths (Kiyota et al., 2011). Fig. 1 shows the distribution of earthquake-inflicted landslides in the upper stream of Abukuma river and its geological map. Early Pleistocene no-alkaline pyroclastic flow volcanic rocks spread in this region and more than 1000 slope failures occurred here due to a torrential rain back in Aug. 27, 1998 shown as blue plot in Fig. 1. Fujinuma reservoir, located in Sukagawa city, Fukushima prefecture (37.301944, 140.195278: See Fig. 1) was constructed for irrigation in this area with the similar geological setting back in 1949. The northeast earth-fill dam of this reservoir was breached in the Great East Japan Earthquake with the surface maximum ground acceleration of 309gal and the earthquake duration over 100 seconds recorded by the strong-motion seismograph at the nearest Kik-net Naganuma station (National Research Institute for Earth Science and Disaster Prevention), which is located about 2 km away from the Fujinuma reservoir (37.2792, 140.2178: See Fig. 1). The dam is 18.5m high, 133m long and 99,000m^3 in volume, and the full

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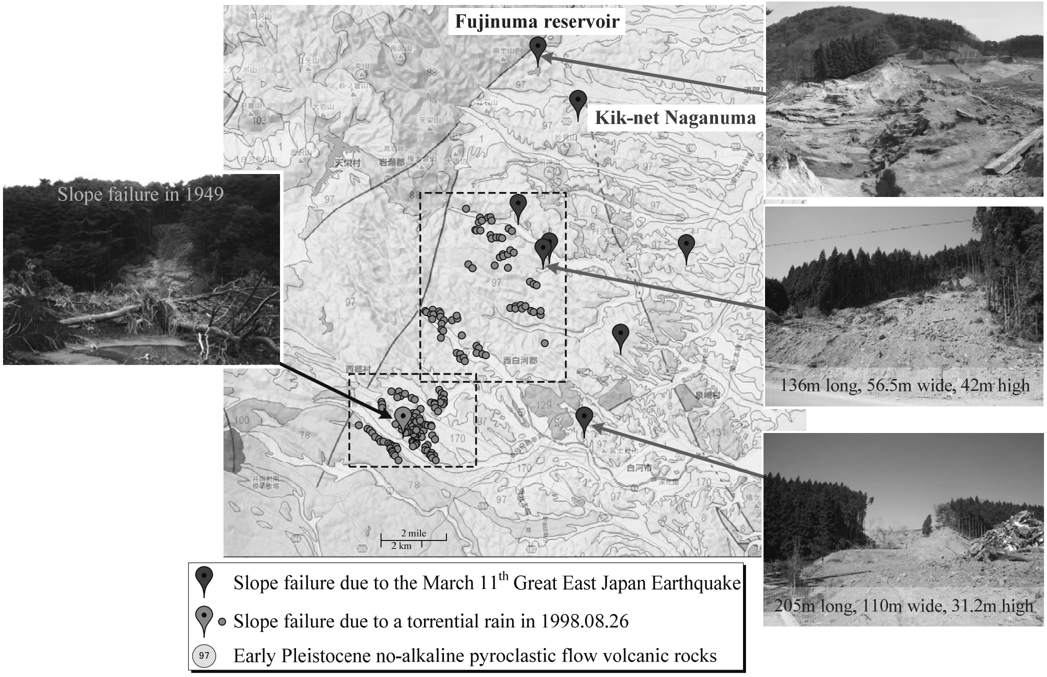

Fig. 1 the distribution of earthquake-inflicted landslides in the upper stream of Abukuma river, and geological map

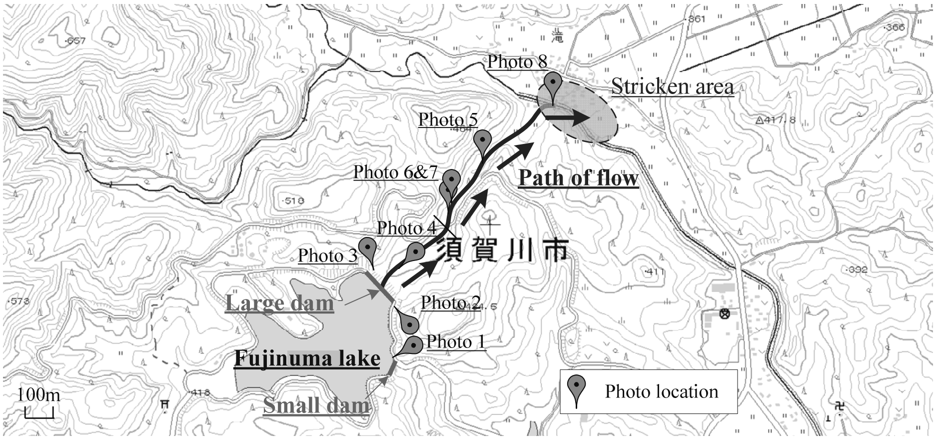

Fig. 2 Survey map (modified from Geospatial Information Authority of Japan, 2011)

capacity of its reservoir of 1,504,000m^3 (Dam Association of Japan, 2008) was reached at that time. The water from the breached dam scoured its downstream valley floor and walls, and uprooted trees. The debris flow rushed down the valley and flushed at least 5 houses leaving 8 dead and 1 missing. Approximately 750 earth-fill dams and reservoirs for irrigation in Fukushima prefecture have been also damaged in this earthquake.

Authors surveyed Fujinuma reservoir and the stream channel of the debris flow. The breached dam body was LiDAR surveyed for its entire 3D image. With the findings from the survey, this paper discusses the mechanism of the dam breaching.

DAMAGE OF FUJINUMA RESERVOIR AND ITS DOWNSTREAM

Fig 2 shows the route for the survey along the debris flow channel and photo-shooting locations. There were large and small earth-fill dams stopping the water of the Fujinuma reservoir as shown in Fig. 2.

Photo 1 Upstream slope failure of the small dam (April 15th at 37.299778, 140.195348)

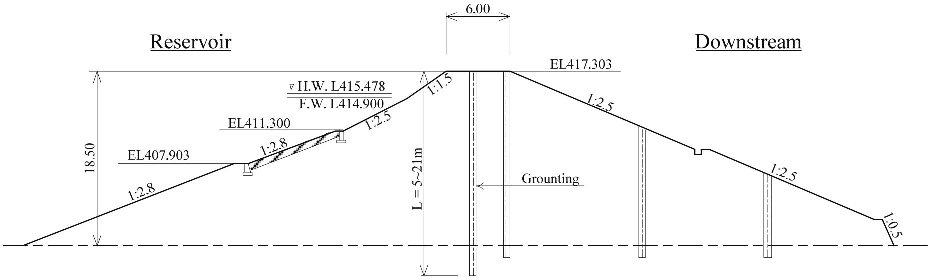

Fig. 3 Cross section of original large dam body

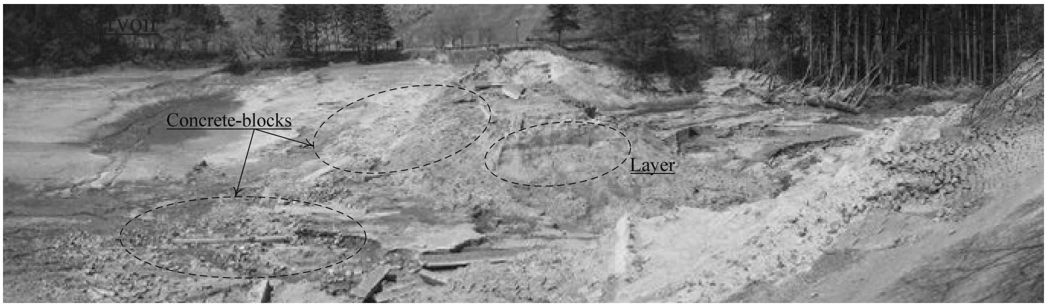

Photo 2 Breached large dam as seen from its right abutment
(April 15th at 37.301265, 140.195401)

Photo 3 Breached large dam as seen from its left abutment
(April 15th at 37.302465, 140.195223)

Photo 4 Breached dam body as seenfrom downstream (April 15th at 37.302661, 140.196055)

Photo 5 Mud marks on valley walls (April 15th at 37.306236, 140.199503)

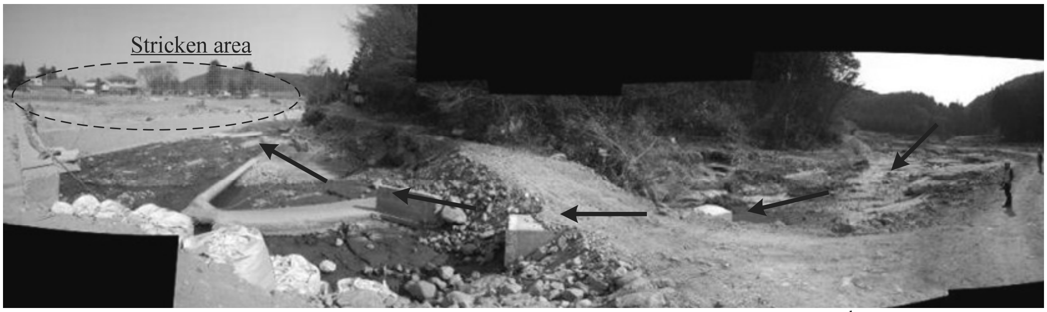

Photo 6 Debris flow channel and the village caught in the flash flood (April 15th at 37.308131, 140.202481)

Photo 1 shows the failure of the upstream slope of the small dam (13m high, 55m wide and 108m long). Almost the entire upstream slope slid down into the reservoir leaving its thin and fragile crest soil behind the dam body, which narrowly escaped from breaching probably because the larger dam breached first emptying the water of the reservoir. During the emptying process, the soil mass of the upstream slope of the small dam may have been carried further down toward the bottom of the reservoir.

Fig. 3 shows the original cross section of the large dam. The large dam is 6 meters wide at its crest, 133 meters long with upstream surface concrete-block-faced to make it impervious to prevent leakage. Photo 2 and 3 show the breached large dam body (Height 18.5m, Length 133m, Volume 99,000m^3) as seen from its right and left abutments, respectively. The middle to right part of the dam body was scoured deep by the overtopped water. A clear laminar structure was seen on the exposed interior of the dam body. Dark-colored mudstone was exposed on the scoured abutment. 20 to 30 cm-thick Ignimbrite sand layers were also found bedding horizontally in the exposed dam body (See Photo 2) indicating that the dam body was constructed by compacting ignimbrite sand. It is known that the dam body was constructed through 3 stages compaction process from 1938. According to a local resident, he witnessed that the crest of the entire dam body had subsided by about 1-2m approximately 20 minutes after the earthquake hit the area (Kokusho, 2011). From these evidences, it can be deduced that the upstream slopes of both the large and small dams slid fist toward the reservoir, and it was then followed by the subsidence of the large dam body leading to the water-overtopping.

The debris flow from the breached dam scoured its downstream valley floor and walls, and uprooted trees as shown in Photo 4. From mud marks remaining on valley walls, super-elevations were measured at several locations where the stream channel takes sharp turns, and the debris flow velocity was estimated to be around 10m/sec. The debris flow, when it reached the village, took a sharp 90 degrees clockwise turn along the existing river channel and flushed downstream village (See Photo 8).

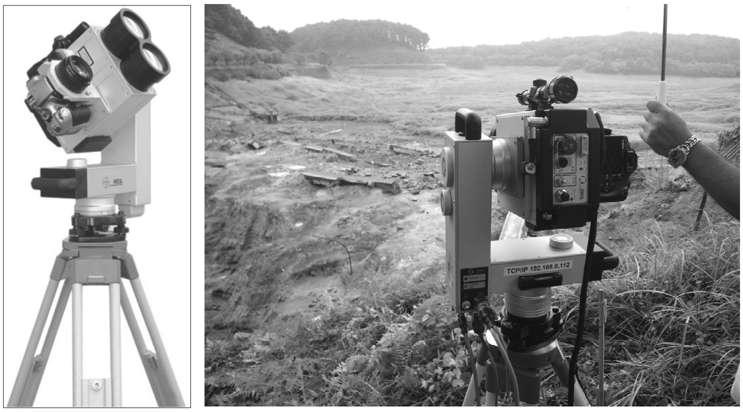

Photo 7 LPM-321 (left: LPM-321, right: laser-scanning scene)

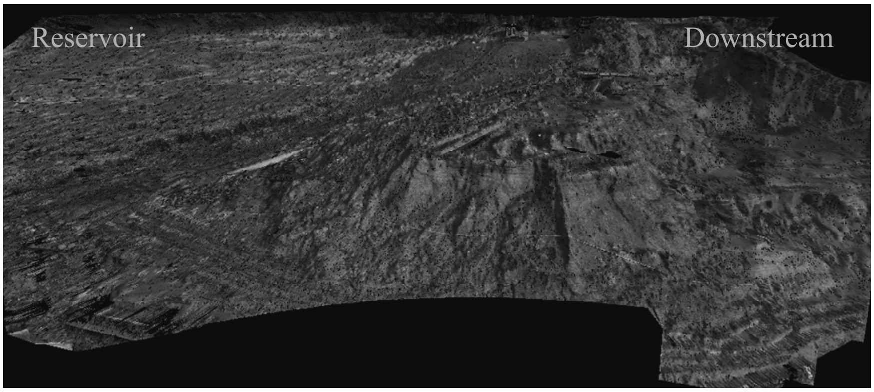

Fig. 4 3D image of the breached dam body using LPM-321

LIDAR SURVEY OF THE BREACHED EARTH-FILL DAM

Outline of LIDAR survey

The breached dam body was LiDAR surveyed for its entire 3D image using the laser profile measuring system LPM-321 (See Photo 7). LPM-321 is based on the time-of-flight measurement of short laser pulse. It covers 6000m distance without reflector (@ Laser class 1M), with a wide view filed of 150° x 360°, an expected maximum error of 25mm and measurement rate of maximum 1000 points / sec. Using a high resolution digital camera along with it, a RGB color image can be obtained for all laser-shot points. The dam body was laser-scanned on Aug. 21st from three different locations: two were on the right abutment and one on the left abutment. The measured 3D digital surface models were then combined to be the entire terrain model of the dam body(Fig.4).

Result of LIDAR survey

Fig. 5 shows a bird-eye view of the breached dam body. There yet remained some areas hidden from laser light, which appeared black in this figure. 5 months after the earthquake, the bottom of the emptied reservoir was covered thick with vegetation. Fig. 6 shows the contour map with the coordinate origin set at 1.5m above the original dam body crest. The right side of dam body was completely scoured.

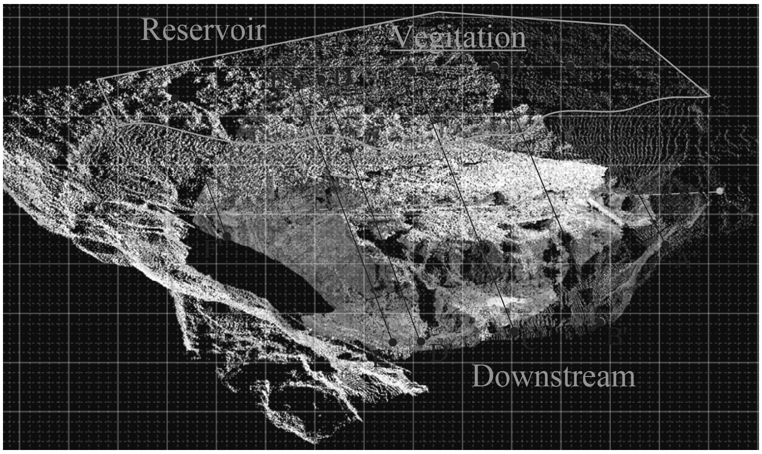

Fig. 5 Bird-eye view of the breached dam

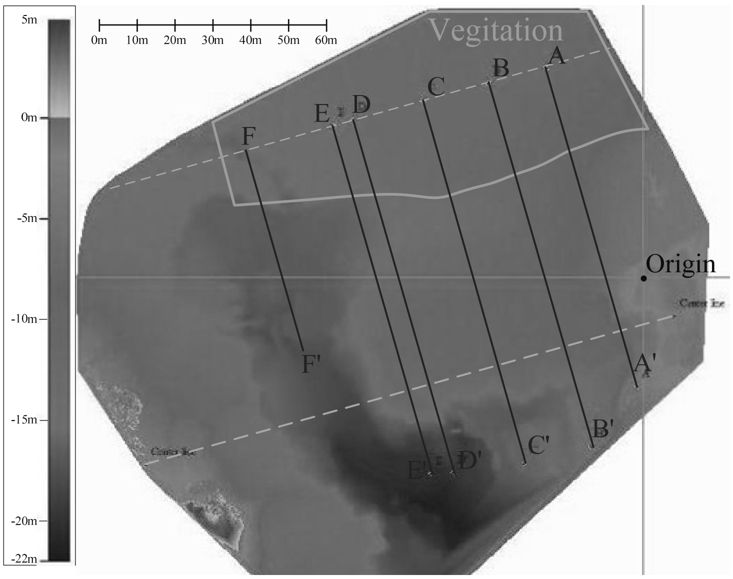

Fig. 6 Contour map of Z-value

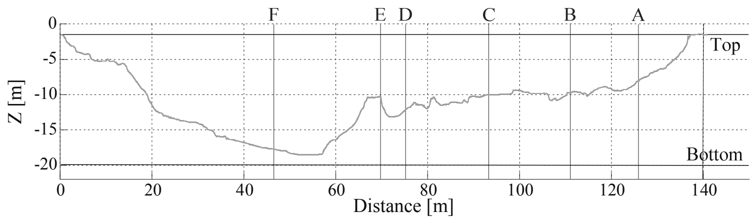

Fig. 7 Longitudinal section of breached dam

Fig. 7 shows the longitudinal cross-section of the damaged dam body, where two lines indicate the top and bottom levels of the original dam body. The top surface of the remaining left dam body is about 50m long, and about 8.5m below the original dam crest. Fig. 8 compares several cross-sections of the

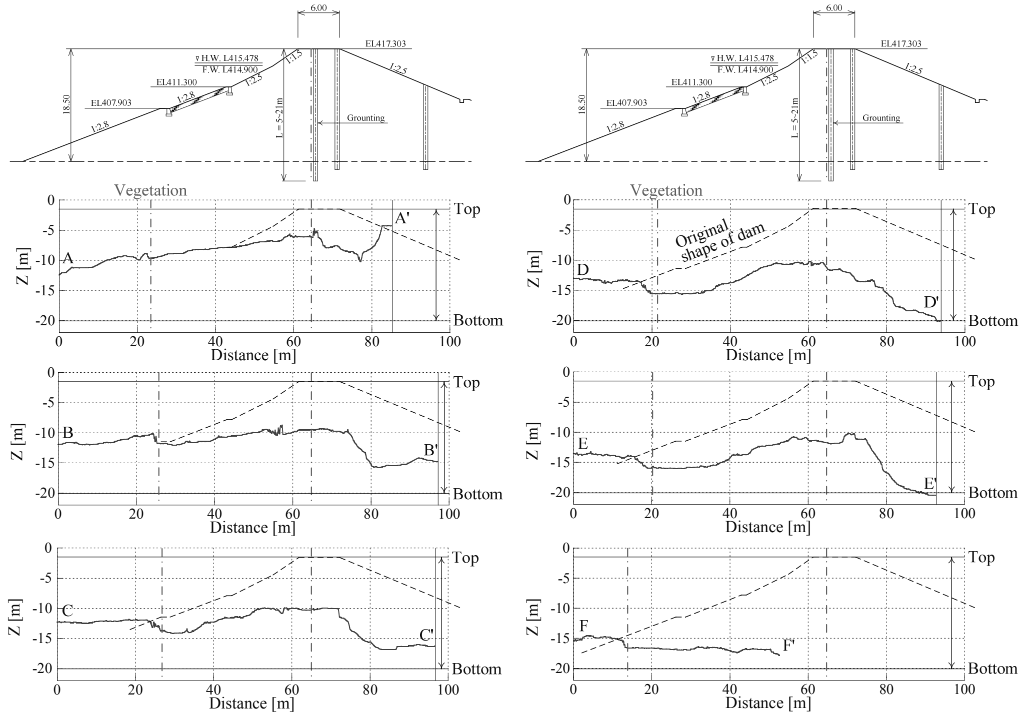

Fig. 8 Comparison of the obtained 3D image of the damaged dam with its original shape

damaged dam body with their original ones. These cross sections in Fig. 8 respectively correspond to lines A-A', B-B', C-C', D-D', E-E' and F-F' in Fig. 5, 6 and 7. With the presence of vegetation, every cross section after the earthquake shows an increase of the reservoir bottom by about 0 to 0.25m. It is clear from these cross-sections that scouring of the soil mass was seen over the entire stretch of the downstream slope. Particularly scouring was the most serious near the middle to right part of the dam body. Therefore, it can be deduced that the right dam body, which is the highest part of the entire dam body, slid first, causing either subsidence of the dam crest or razor-sharp earth wall to remain such that the water forced its way through this point. And then the overflowing water eroded both the upstream and downstream dam body.

SUMMARY

The northeastern earth-fill dam of Fujinuma reservoir, located in Sukagawa city, Fukushima prefecture, was breached in the March 11th Great East Japan Earthquake. Its entire dam body was eroded deep by overflowing water. Particularly soil mass of its right side was completely washed away. The debris flow, whose speed was estimated to be around 10m/sec from mad marks remaining on valley walls, rushed down the valley and flushed at least 5 houses leaving 8 dead and 1 missing. Comparing a 3D image of entire dam obtained from LiDAR survey with its original shape, the right dam body whose height is 18.5m was completely washed out from its bottom. From the authors' reconnaissance and the obtained LiDAR image, it was deduced that the right side of large dam body, which was the highest point of the dam body, slid toward the reservoir side causing either subsidence of the dam crest or razor-sharp earth wall to remain such that the water forced its way through this point. The numerical simulation will be carried out for a further discussion of the failure mechanism in later publications.

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