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# Earthquake Induced Failure of Fujinuma Dam

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**ABSTRACT:**
Fujinuma Dam failed due to The 2011 off the Pacific coast of Tohoku Earthquake and large mount of released water reached the downstream community causing a loss of seven lives and one missing. In order to identify the cause of the failure of Fujinuma Dam the geotechnical properties of embankment were grasped by investigations of the remnant embankment and the construction and repair works were evaluated. The stability of the embankment before the earthquake was also examined. Even though any abnormality had not been detected by regular inspection, the possibility of incurring failure still exists if and when it is exposed to strong and long duration earthquake motion such as that of The 2011 Tohoku Earthquake, depending upon its construction material and degree of compaction.

*Keywords: Earthquake, Earthfill Dam, Stability, Construction Material, Degree of Compaction*

## 1. INTRODUCTION

Fujinuma-ike (Location: Tamukaichi, Ebana, Sukagawa city) is an irrigation reservoir situated on the right branch of upper Sunoko River and it taps water from the main stream of Sunoko River by head race. There exists an auxiliary embankment dam on the right abutment saddle. The construction of Fujinuma Dam, auxiliary dam and head race were started April 1937, suspended during the war and completed in October, 1949. Fujinuma Dam is an earthfill dam with the height of 18.5 meter and the crest length of 133.2 meter, while the auxiliary dam is of earth embankment type with the height of 10.5 meter and the crest length of 72.5 meter.

From 1977 to 1979, the spillway and surface protection work of Fujinuma Dam were repaired and from 1984 to 1992, counter measures against leakage by grouting as well as upgrading of intakes were conducted.

The agricultural water taken from Fujinuma Dam irrigates the land of 837 ha and the dam is managed and operated by Ebanagawa Irrigation District.

Fujinuma Dam failed due to The 2011 Tohoku Region Pacific Coast Earthquake (14: 46hrs. M=9.0) and large mount of released water reached the downstream community causing a loss of seven lives and one missing. And due to the earthquake, some 750 of other small embankment dams and irrigation ponds were damaged in the Fukushima Prefecture.

Therefore, the prefectural government set up "the panel to evaluate the seismic stability of dams and small ponds for agricultural purpose" consisting of experts with relevant knowledge and experience on August 4, 2011. The panel also reviewed the cause of the failure of Fujinuma Dam which incurred especially severe damage.

The first panel meeting was held on August 4 and 5 and up until January 25 on which day the fifth meeting was held, the panel had continuously made its efforts to investigate and find what happened to the Fujinuma Dam and the auxiliary dam, seismic stability before the earthquake and mechanism of the failure due to earthquake shaking. This report describes findings of the panel on the cause of the failure.

## 2. OUTLINE OF FUJINUMA DAM

The dam has not been upgraded since it was embanked long before the enactment of design standards in 1956, and the structural design and construction specifications of the dam are those for a small earth dam and pond.

The water stored in the Fujinuma reservoir overflowed and breached the dam body because the reservoir, being full when the earthquake struck, was severely deformed by the earthquake (Fig.1). As a result of the breaching, the reservoir water severely damaged the community located downstream. At the auxiliary dam, the upstream slope flowed down into the reservoir from the dam crest. The front end of the sliding failure moved to 60m into the reservoir.

On the dam body of right abutment side, the water overflowing from the reservoir eroded the dam down to the foundation ground, while the left bank side body was also eroded by the flowing water, but the dam body remained to its middle height. During upgrading of the dam between 1983 and 1991, six exploration holes were bored, then after the disaster, five more exploration holes were bored. The excavation exploration of the dam body has clarified the following facts.

(1) The fill material can be classified into three embankment layers according to differences between the soil quality (top embanking, middle embanking, and bottom embanking), as shown in Fig.2.
(2) The top embankment layer is 6 to 8m thick, its material is generally homogeneous, with most consisting of gray coarse sand, and there are few clear traces of compaction layer or spreading.
(3) The middle embankment layer is between 7 and 9m thick, consists mainly of brownish gray sandy silt with alternating 20 to 30cm layers of sand containing yellowish-gray silt, loam-type clay, and humic silty sand ranging from black to dark gray, and shows clear traces of spreading.
(4) The bottom embankment layer between 4 and 6m thick, consists mainly of coarse to fine sand containing gravel including a silt fraction, with alternating 20 to 30cm layers of loam type clay and humic silty sand ranging from black to dark gray, and shows clear traces of spreading.
(5) The foundation ground is a late quaternary non-volcanic sedimentary layer and a quaternary early diluvium Shirakawa Stratum. The non-volcanic sedimentary layer is distributed under the dam body embankment, and its maximum thickness is about 7m.

An investigation conducted before the dam upgrading in 1983 indicates that, the average N-value of the top embankment was 3 (range of 2 to 6), the average N-value by standard penetration test of the middle and bottom embankment was 4 (range of 2 to 6), and no differences were found between the top and middle embankment. The investigation after the disaster found that the N-value of the top embankment was 2, as far as average values are considered, lower than those of the middle and bottom embankment.

Laboratory soil tests of the fill materials remaining after the disaster were performed. The particle size distribution, as revealed by Fig.3, shows abundant silt to clay in the middle embankment, and abundant sand in the top

**Figure 1.** Breaching state of Fujinuma Dam

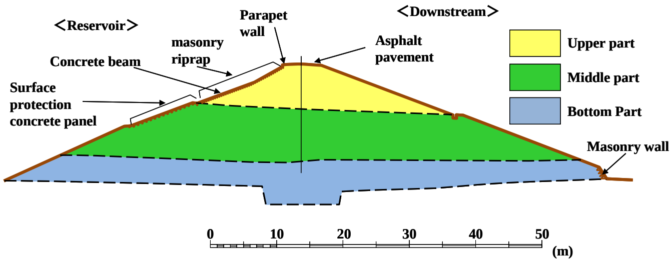


**Figure 2.** Cross section and classification of embankment layer

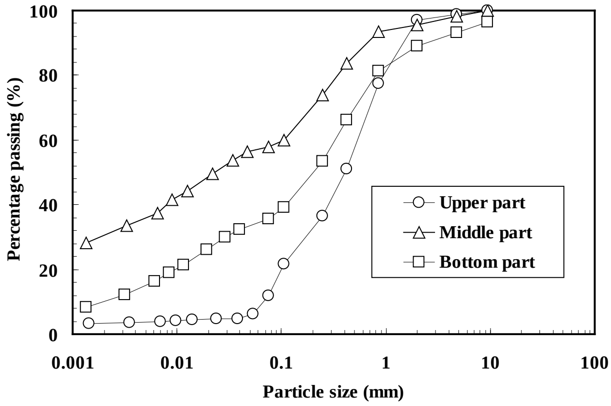


**Figure 3.** Particle size distribution of embankment materials

embankment and bottom embankment. The soil material in the top embankment in particular, was 17.2% fine grain material of 0.075mm and lower. Compared with normal uniform embankment dams constructed in the past, the top embankment consists of semi-impervious materials, and the middle embanking material is similar to impervious materials, while the bottom embanking is grain size material in an intermediate relationship to these materials. The degree of compaction value D of fill materials was, in the remaining part of the top embankment, 87.9% by the Standard Proctor test, but in the middle embankment, it was 81.6% and in the bottom embankment, it was 86.4% . In the middle embankment, a low value of 81.6% was obtained, confirming scattering in the degree of compaction of the fill material just as shown by the boring data. Most of the top embankment was washed out and lost, so test specimens were obtained from the end of the right bank of the dam body.

## 3. MAPPING THE DEBRIS OF FUJINUMA MAIN DAM AND AUXILIARY EMBANKMENT AFTER THE QUAKE

The mapping of debris of Fujinuma Dam and damaged auxiliary dam confirmed the following findings.

(1) Most of upper part of embankment was washed away and most of middle and lower part of downstream embankment was also washed away.

(2) From the movement of the structural elements, first masonry riprap of upper part of embankment fell to the reservoir and subsequently the surface protection work from the middle to the right abutment moved substantially to the reservoir (Fig.4).

(3) It was confirmed that slides occurred in the direction both of the reservoir and downstream judging from the distribution of main scarps, sliding surfaces and moved layers (Fig.5).

(4) In the auxiliary dam the main slide with the width of 55 meter, length of 25 meter and depth of more than 3 meter occurred and the secondary slide happened at its front (Fig.6).

## 4. INVESTIGATIONS, EVALUATION AND REVIEW OF THE STABILITY

The following investigations, evaluation and review of the stability were performed to identify the cause of the failure.

a. Field investigations and laboratory tests to recognize the zoning and properties of embankment materials
b. Investigations and evaluation of construction
c. Evaluation of the repair work
d. Evaluation of the safety of the dam by inspection before the earthquake
f. The stability evaluation based on the current design criteria

### 4.1 Field Investigation and Laboratory Tests to Recognize the Zoning and Properties of Embankment Materials

The results of field investigations including core boring revealed that Fujinuma Dam consisted of three different zones and in the middle and lower zones, construction on a layer-by-layer basis with the thickness of 20 to 30 cm was conducted. The upper zone consisted of sand rich

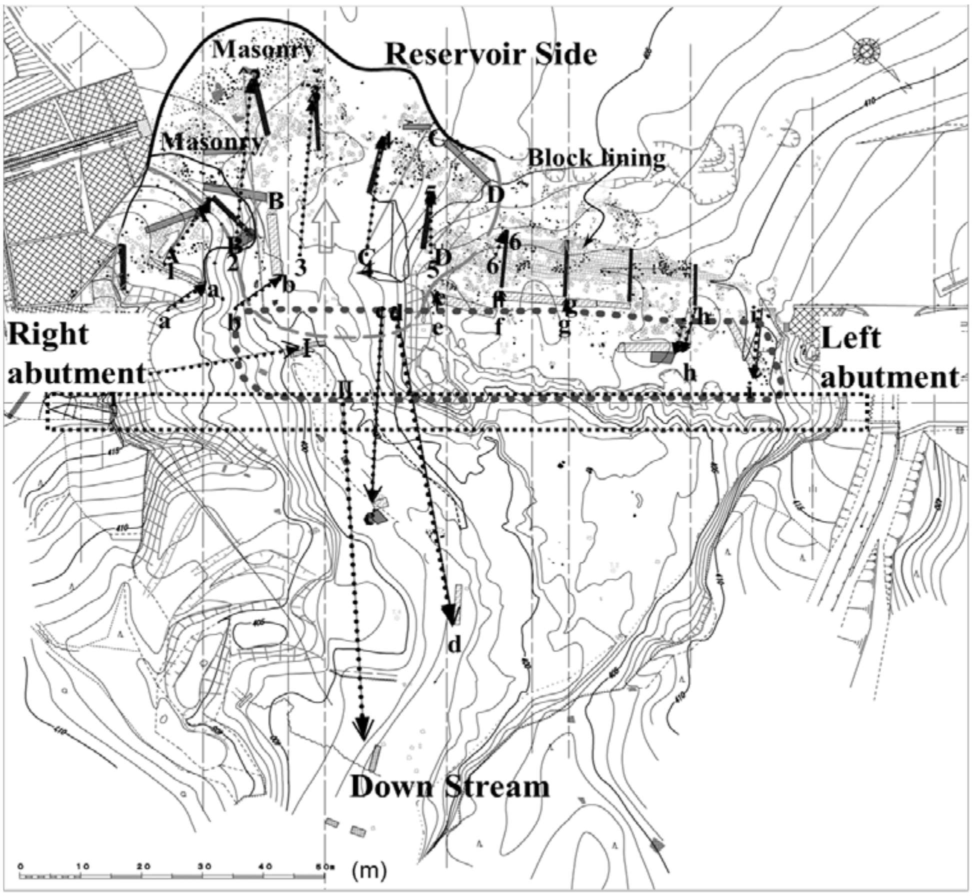


**Figure 4.** Mapping of structural elements after failure

Notes: The dot colored blue is the parapet wall. The dot colored green is masonry riprap. The small square colored purple is the surface protection work. The rectangular colored yellow is concrete beam on the upper upstream slope. Most structural elements moved to upstream.

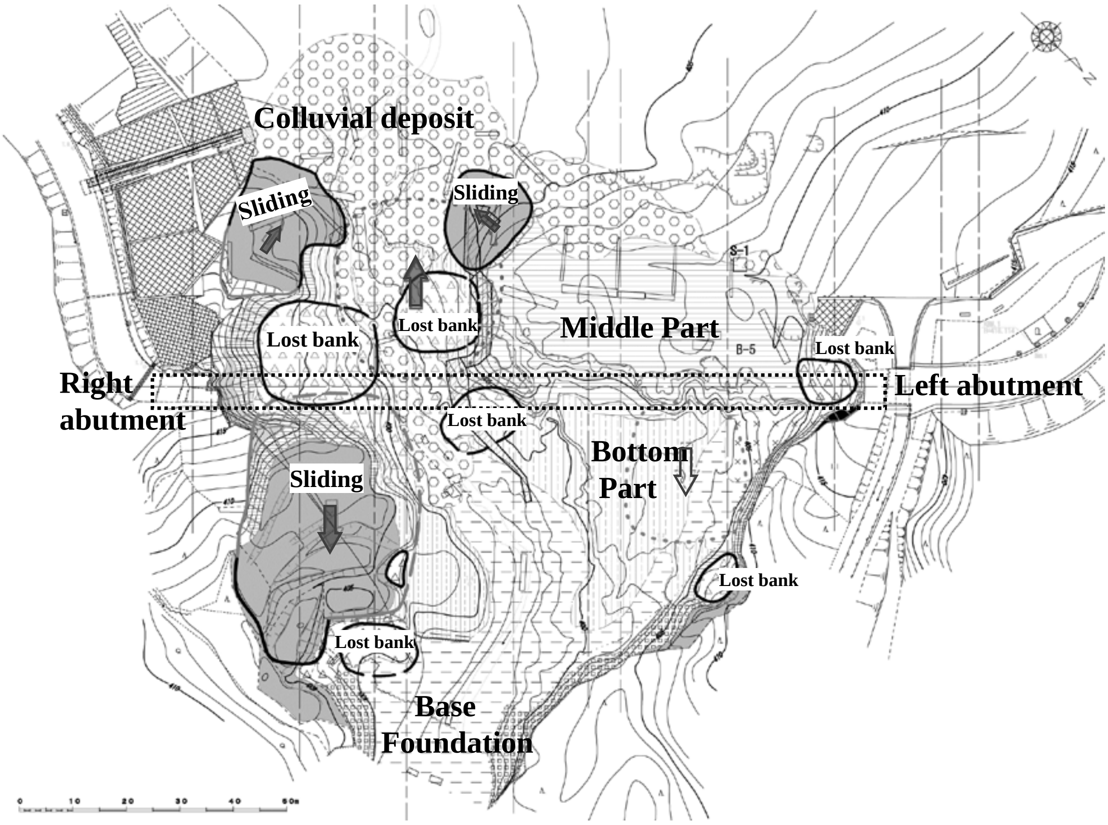


**Figure 5.** Possible slides estimated from geologic and topographic mapping

Notes: Circled lines indicate the slide block.

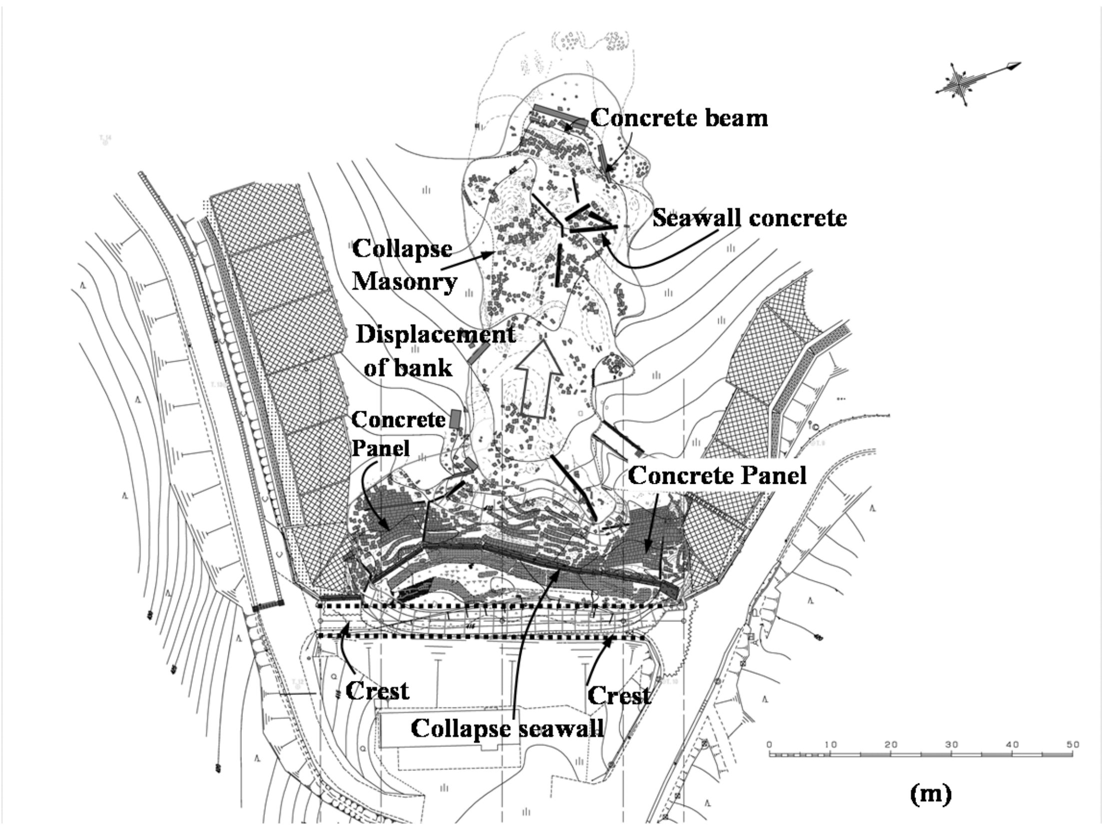


**Figure 6.** Damage of structure and slides of auxiliary dam

Notes: The area colored blue is concrete parapet wall. The small square colored purple is concrete block for surface protection work.

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materials as a whole and lacks clear compaction layer of placement.

### 4.2 Investigations and Evaluation of Construction

Hearings and evaluation of field investigations suggested that the dam was built by the normal construction method and the state-of-the-art at that time. However, it is considered that the upper zone was constructed at the period of immediately after the war when the construction environment was poor.

### 4.3 Evaluation of the Repair Work

It is considered that the repair work employed at Fujinuma Dam was selected from the normal methods of construction and was effective to reduce the amount of leakage judging from the measurement of leakage and phreatic surface.

### 4.4 Evaluation of the Safety of the Dam by Inspection before the Earthquake

Unusual behavior was not found by the ordinary and regular inspection of the owner of Fujinuma Dam. Therefore, within the scope of ordinary and regular inspection, it is considered that the dam was stable.

### 4.5 The Stability Evaluation Based on the Current Design Criteria

According to the criteria based method of stability analysis, the factor of safety is 1.15 which is less than the required value of 1.2 of the criteria when the seismic force is applied to the upstream direction. The panel regards that the dam was not in such condition as required special measures.

## 5. MECHANISM OF FAILURE OF THE DAM

Summing up the investigation results, slides are broadly classified to seven stages (Fig. 7). Among these slides, the upstream slide No.1 and No. 2 triggered the subsequent overflow and erosion and resulted in a failure of the dam. The slide No.1 occurred in the upper embankment and it was recognized from the remnant of the structural elements in the reservoir and sliding surface was lost by wash out. However, the earthquake deformation analysis (by modified Newmark procedure) considering the strength reduction due to cyclic loading indicated the existence of this slide.

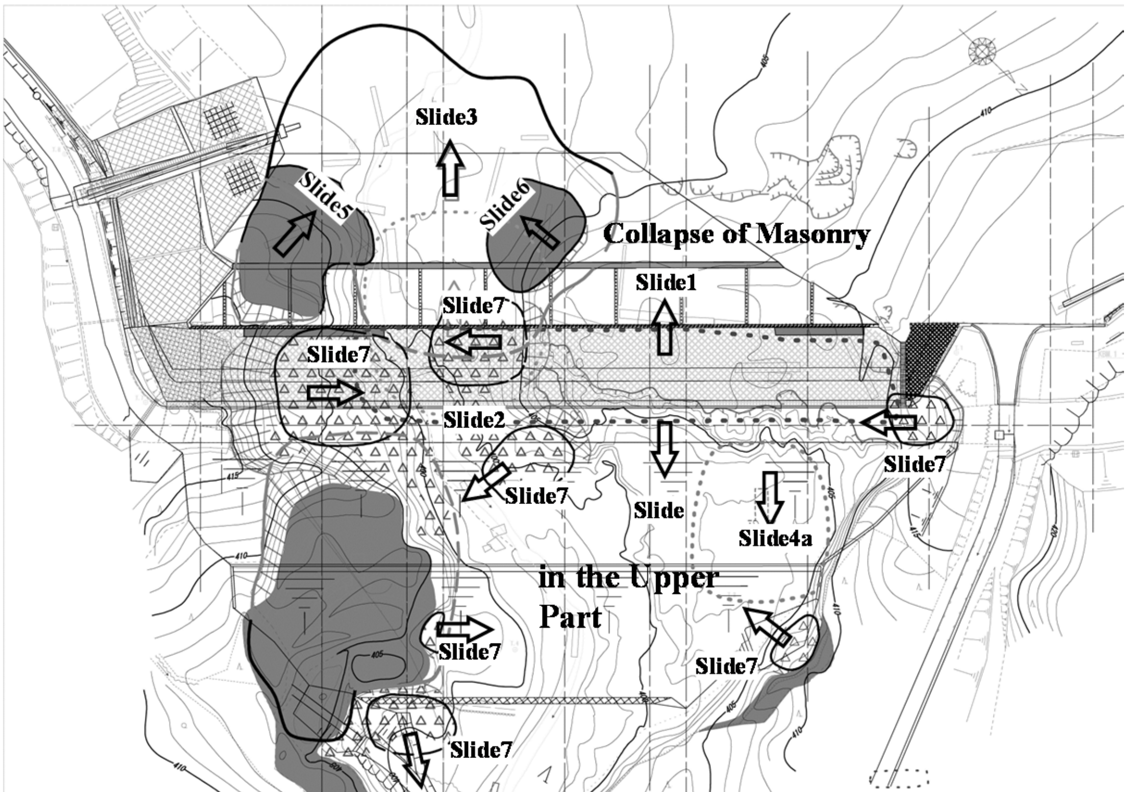


**Figure 7.** Integrated map of slides of Fujinuma main dam
Notes: The solid lines are existing slide bodies. The broken lines are estimated slide bodies which were lost by wash out.

There may be some possible processes of breach (initiation of overflow) such as the case of the slide No.1, No.2 combined with the secondary downstream slide and the case of the downstream slide caused by the reduction of water tightness in the upper embankment and others.

Considering the loss of upper embankment in the large areas in a short period, it was possible that these processes were combined resulting in a cause of overflow hence accelerated the developement of erosion of the dam.

## 5. Safety Evaluation of the Dam Embankment by the Modified Newmark Method

An analysis was performed based on the Newmark Method that considers the phenomenon, of which the embankment materials might reduce the strength by earthquake motion to estimate the possibilities of sliding failure due to large deformation or displacement of the embankment.

Because the shear force which acts during an earthquake is short term response and the embankment is in undrained condition, in order to evaluate the state of damage, it is important to perform analysis by the Modified Newmark method considering the condition that cyclic shear loading is received in saturated undrained condition.

So in order to obtain the physical property values used for analysis, a series of shear test accompanied by monotonic loading undrained triaxial compressive test after cyclic shear loading of the embankment soil was performed. For monotonic loading test after cyclic loading, soil properties used for stability analysis considering the deterioration related by earthquake motion (cumulative damage) are obtained.

The quantity of residual sliding failure was calculated by the Modified Newmark Method considering this process of deterioration of the soil. The result of the analysis show that the quantity of sliding failure towards the upstream side is about 0.81m in isotropic condition sliding failure, which sliding failure cause only in the inside of the upper embankment.

## 6. THE CAUSE OF THE FAILURE OF FUJNUMA DAM

We consider that the primary cause of the failure of Fujinuma Dam is the nature of its upper embankment and middle embankment and the triggering cause is the strong earthquake motion and its long duration. In addition, the following findings were obtained from integrating the results of field investigations, laboratory tests and analytical procedures.

(1) The earthquake response analysis suggests that the peak acceleration at the dam crest was 442 $cm/s^2$ and the duration of the motion over 50 $cm/s^2$ continued for 100 seconds which was an earthquake motion never had been experienced.

(2) The compaction of the embankment was low compared to the compaction of the modern construction method and the strength of the embankment is small in undrained condition during earthquakes. Especially in the upper embankment consisting of sand rich materials there was a saturated portion and it was proved the strength loss occurs when it is subjected to the earthquake motion such as that of The 2011 Tohoku Earthquake.

(3) The slide occurred in the auxiliary embankment consisting of similar material to upper embankment of main dam and one of its failure causes is the nature of the soil of embankment, rich with sandy materials.

(4) In the slide occurred in the auxiliary dam, sliding surface was restricted to the embankment boundary of the different construction periods. In the main dam, the difference of the degree of compaction depending on the different construction periods is possibly attributable to the occurrence of the sliding.

## 7. FINAL REMARKS

Through this verification, it has been proven that, among old earthfill dam and small irrigation ponds, even if the dam was constructed by the normal method and the-state-of-the-art in that period, further, any abnormality had not been detected by regular inspection, the possibility of incurring failure still exists if and when it is exposed to strong earthquake motion such as that of Tohoku Region Pacific Coast Earthquake, depending upon its construction material and degree of compaction.

We hope the findings obtained from reviewing the cause of the failure of Fujinuma Dam will contribute to upgrading the evaluation technology of seismic safety of dams and small irrigation ponds and is happy if they help to enhance the safe and secure society for the prefectural people.

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