Sediment Runoff Mechanism from a Landslide Dam: Case of Lake Ohatakedoro in Totsukawa Village, Nara Prefecture, JAPAN

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Lake Ohatakedoro is located in the southern part of Totsukawa Village in Nara Prefecture, and the only extant landslide dam from the 53 river course blockages was formed during the Great Flood in Totsukawa Village in Meiji (1889). During the massive flooding caused by the Great Floods on Kii Peninsula in September 2011, this dam was heavily eroded, and it collapsed generating a sediment discharge, and caused damage so great as to make the neighborhoods isolated. This paper discusses the results of the examination of the stability of the landslide dam based on the geological and hydraulic studies of the landslide dam, and future preventive measures, because a large portion of the landslide dam still remains as a risk.

Key words: landslide dam, piping erosion, overflow erosion, landslide

1. INTRODUCTION

A landslide dam lake was created by river course blockage from sediment caused by a large-scale landslide on the slope (of Mt. Kubotani) to the left of the left side tributary (Kubota-tani) in the southern part of Totsukawa Village in Yoshino County, Nara Prefecture, during the Great Flood in Totsukawa Village in Meiji (1889).

During the massive flooding caused by the Great Floods on Kii Peninsula in 2011, the dam of Lake Ohatakedoro was heavily eroded, and it collapsed, generating a sediment discharge. The sediment caused damage so great as to make the neighborhoods isolated, blocking Route 425 in the downstream area. It can be thought that since the inflow rate from upper drainage area to landslide dam lake was relatively small and the subsurface flow through landslide dam lake was relatively large, the landslide dam can remain around 120 years. The landslide dam erosion during the Great Floods in 2011 may affect on a stability condition of landslide dam of Ohatakedoro, but it was unclear.

This paper discusses the results of the examination of the stability of the landslide dam based on geological and hydrological studies, and future preventive measures.

2. STUDY SITE

2.1 Circumstances of the Great Flood in Totsukawa Village in Meiji (1889)

In the Great Flood in Totsukawa Village in Meiji (1889), a large-scale landslide occurred on the slope (of Mt. Kubotani) to the left of the left side tributary (Kubota-tani) of the Nishikawa River of the Shingu River Catchment Area.

According to the record at that time [*Totsukawa Village*, 1981], sediment carrying big trees flowed into the torrent, rolling like waves, blocking Nishikawa River, which is a tributary of Totsukawa River, and flowing down about 700 m[1)].

The water level in Nishikawa River increased to about 73 m as time passed, causing muddy stream waves to run up the river about 1.7 km, and creating a new lake with a 3.3 km periphery. This new lake breached several days later, but Lake Ohatakedoro (lake created by sediment) remained, due to a large-scale river course blockage upstream on the Kubotani. It still remains to this day.

Fig. 1 is an aerial photograph of Lake Ohatakedoro about 87 years after its formation. It is accompanied by a mountain stream with a catchment area of 102 km^2. Its landslide dam measures 70 m in height and 450 m in length, with

0.02 km^2 of watershed area. River course blockage is seen where flatland and moderate slope lots (barren area to the left in the photo) are located below the shifted clumps of earth. There were no clearly formed valleys in the flatland or on the west side of the slope, and no scars from overflows in the past were found. The scarp has been used for planted forest, etc. and no geographical deformation has been found, in particular.

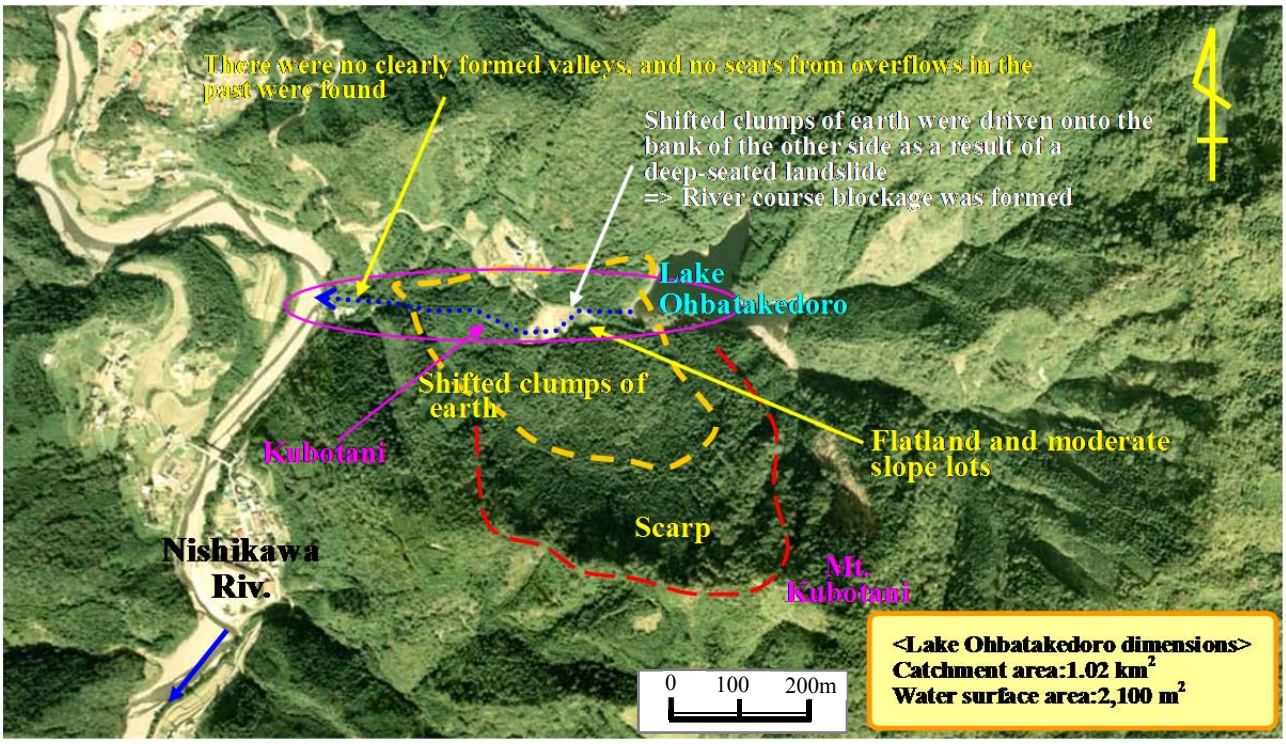

Fig. 1 Aerial photograph of Lake Ohatakedoro after the Great Flood in Totsukawa Village in Meiji (1976)

2.2 Circumstances of the Great Floods on Kii Peninsula (2011)

In the Great Floods on Kii Peninsula brought by Typhoon Talas in September 2011, the landslide dam was eroded, and it collapsed, over an extended area of about 450 m in length, 30 m in maximum height and 75 m in maximum width.

A cutbank was clearly formed downstream of Nishikawa River (**Fig. 2**). The total volume of runoff sediment, calculated by comparing the topographic base map and the post-disaster LiDAR (Laser Imaging Direction and Ranging) data, is estimated at about 300,000 m^3. The record shows 1,183 mm of total rainfall, 774 mm of maximum 24-hour rainfall and 63 mm of maximum hourly rainfall in the area (**Fig. 3**)[2].

According to the interviews conducted in the field, about a 1.5 m overflow at the landslide dam was observed about an hour and half before sediment runoff was seen going downstream.

Fig. 4 is a diagram showing geographical changes of Lake Ohatakedoro from the Great Flood in Totsukawa Village in Meiji (1889) to the Great Floods on Kii Peninsula (2011).

Fig. 2 Lake Ohatakedoro (after the Great Floods on Kii Peninsula)

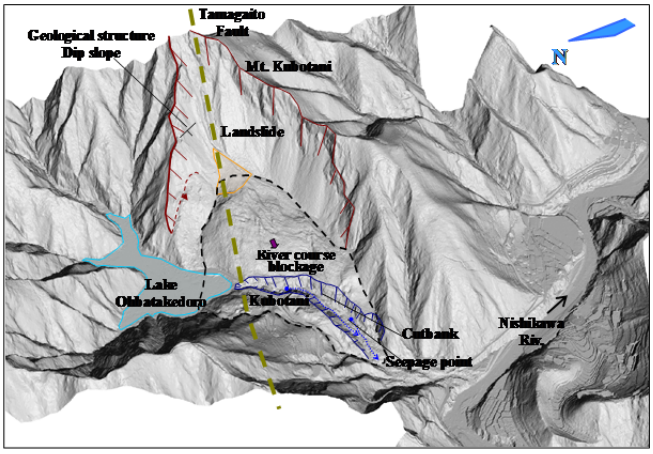

Fig. 3 Lake Ohatakedoro and area characteristics (after the Great Floods on Kii Peninsula)

The volume of inflow into Lake Ohatakedoro and the volume of outflow became unbalanced due to a decrease in height by about 8 m of the landslide dam caused by a large erosion of the dam, causing change in the stability of the dam. Discussion should be about future countermeasures from now.

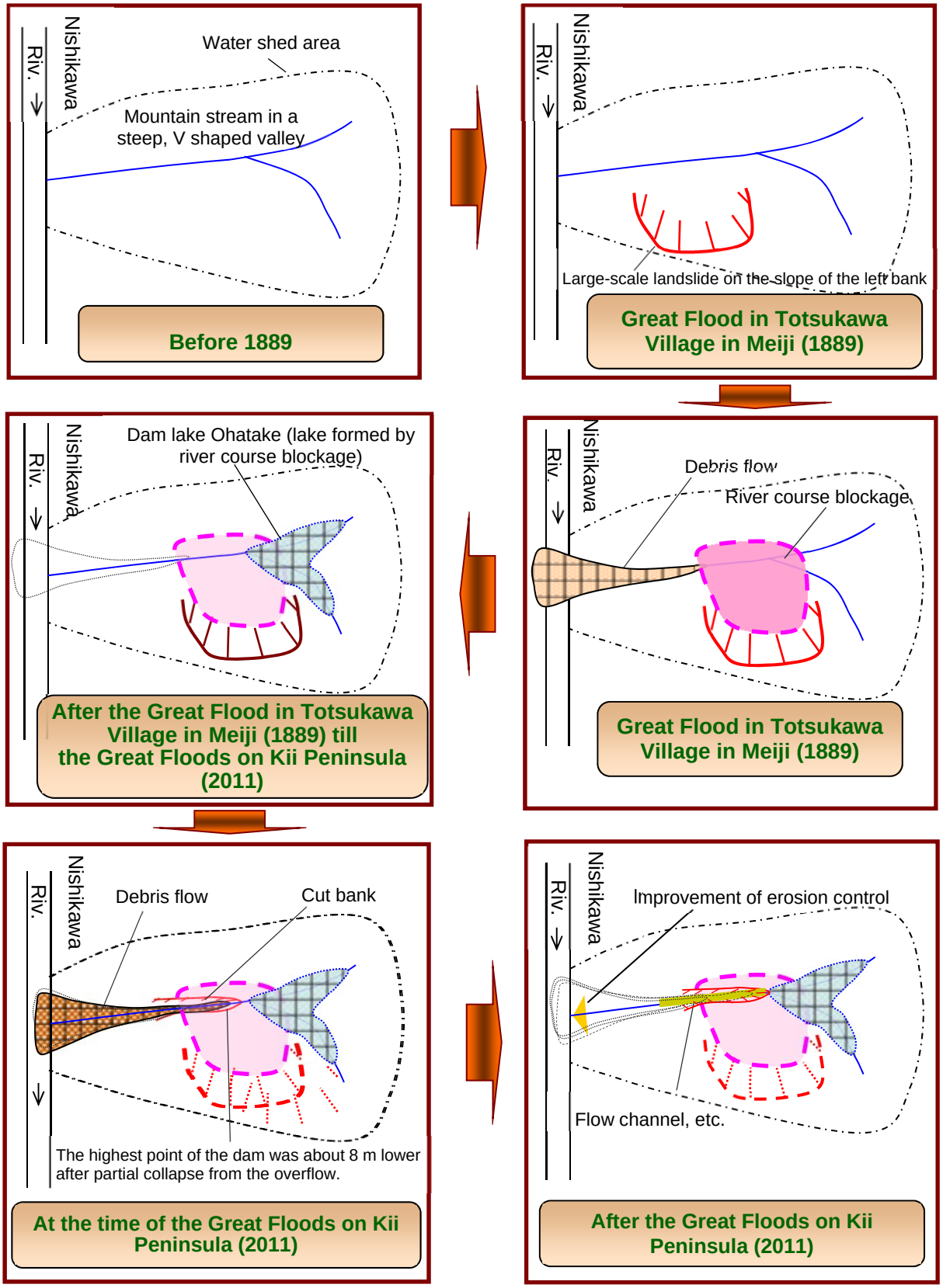

Fig. 4 Diagram of Lake Ohbatakedoro after the Great Flood in Totsukawa Village in Meiji (1889) till the Great Floods on Kii Peninsula (2011)

3. Field SURVEY

3.1 Geological survey

The area is consistent with the distribution of shale-dominant sandstone and shale alternation of the Hidakagawa Group in the Cretaceous (the Mesozoic) Shimanto Belt. Large-scale landslides appear to be triggered by dip slopes, while most of the slopes are remarkably striking from NE to SW, and facing NW.

Results from the boring survey revealed that the landslide dam has new blocks which are distributed randomly with relatively few gaps created in the strata by the shift during the large-scale landslide, and the dam consists of rocks that had been weathered by moderate to strong wind, and sand and gravel mixed in amongst the clumps, which contained a few granules, all in a layer of maximum thickness of 65 to 70 m (**Fig. 7 and Fig. 8**).

Old dents and gullies were formed in the shifted clumps of earth, whereas no clear tree root bends or micro topography showing fluctuations of steps, etc. are seen. No fluctuations in shifted clumps of earth have been detected by survey using borehole inclinometer or pipe strain meter, thereby no sign of clump shifting activities was found.

It is reported that a fault, called Tamagaito Fault, runs across the denuded land in the middle[3)]. Groundwater in the shifted clumps of earth and the landslide dam tends to be blocked by this fault, so that the rain water flows into the ground, presumably increasing the groundwater when there is a heavy rain.

In the Great Floods on Kii Peninsula, the landslide dam was eroded, and it collapsed, over an extended area of 450 m in length, 30 m in maximum height and 75 m in maximum width. A stream bank was clearly formed. A clear chain of stream banks is seen along the downstream of Nishikawa Riv. at this point.

3.2 Hydrological survey

Investigations of change in water level and seepage point quality of Lake Ohatakedoro, field tests during boring survey, and observation of groundwater level in the lake, etc., were conducted, and the results discovered the following: the landslide dam has a high water permeability of 1.0×10^{-4} to 1.0×10^{-5} (m/sec), and the water level of Lake Ohatakedoro and that of the landslide dam are linked together.

Several seepage points exist in the dam, forming gullies from erosion by the surface water flowing out from those points.

A water path with an average 2.0×10^{-4} (m/sec) of relatively high water permeability was formed in the dam. After the Great Floods on Kii Peninsula, a large quantity of seepage ith this high water permeability has been constantly flowing out (500 to 1000L/min) from this water path exit. (**Fig. 5**)

Fig. 5 A large quantity of seepage

The number of constant seepage points increases when the water level of the lake increases during typhoons, etc. At the same time, seepage points develop in many spots above the river course blockages, which causes gully erosion development at the landslide dam (**Fig. 6**), resulting in a gradual decrease of the stability of the dam.

Fig. 6 Gully development in the landslide dam (in local severe rain)

4. NUMERICAL SIMULATION

4.1 Outline of numerical simulation

Disaster factors possessed by Lake Ohatakedoro were examined from secular variation and current conditions of the lake to develop countermeasures for the future. In the Great Floods on Kii Peninsula, “overflow erosion” by surface-water flowing down the crest of the landslide dam is thought to be the biggest disaster factor possessed by the lake, from the results of the investigations in the past. However, the river basin is too small (1.03 km^2) to generate 300,000 m^3 of sediment. It is undeniable that other factors also have an impact on this disaster. Impact caused by “piping erosion” and “landslide” of the sediment dam was studied to reflect the results of the study in countermeasure development.

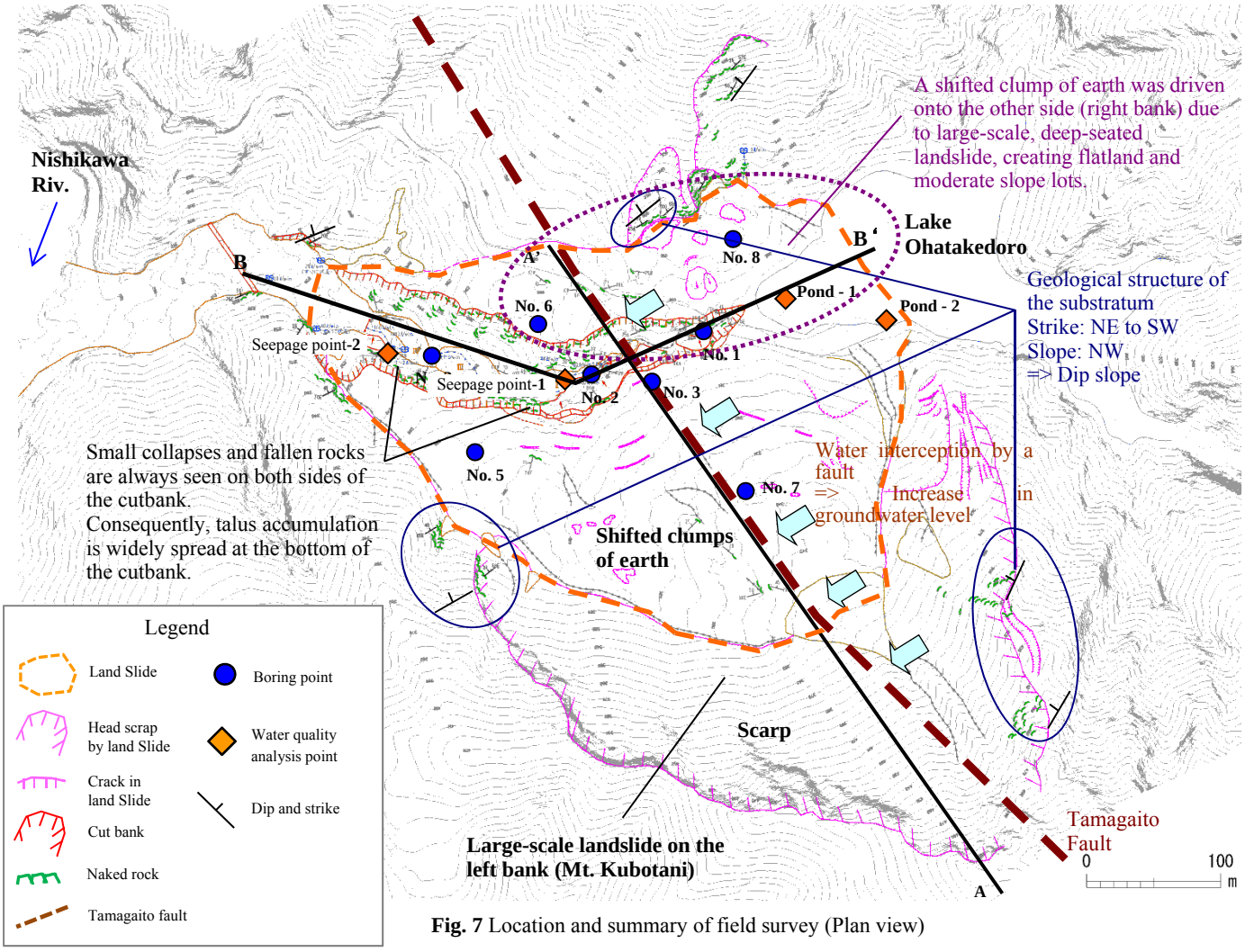

Fig. 7 Location and summary of field survey (Plan view)

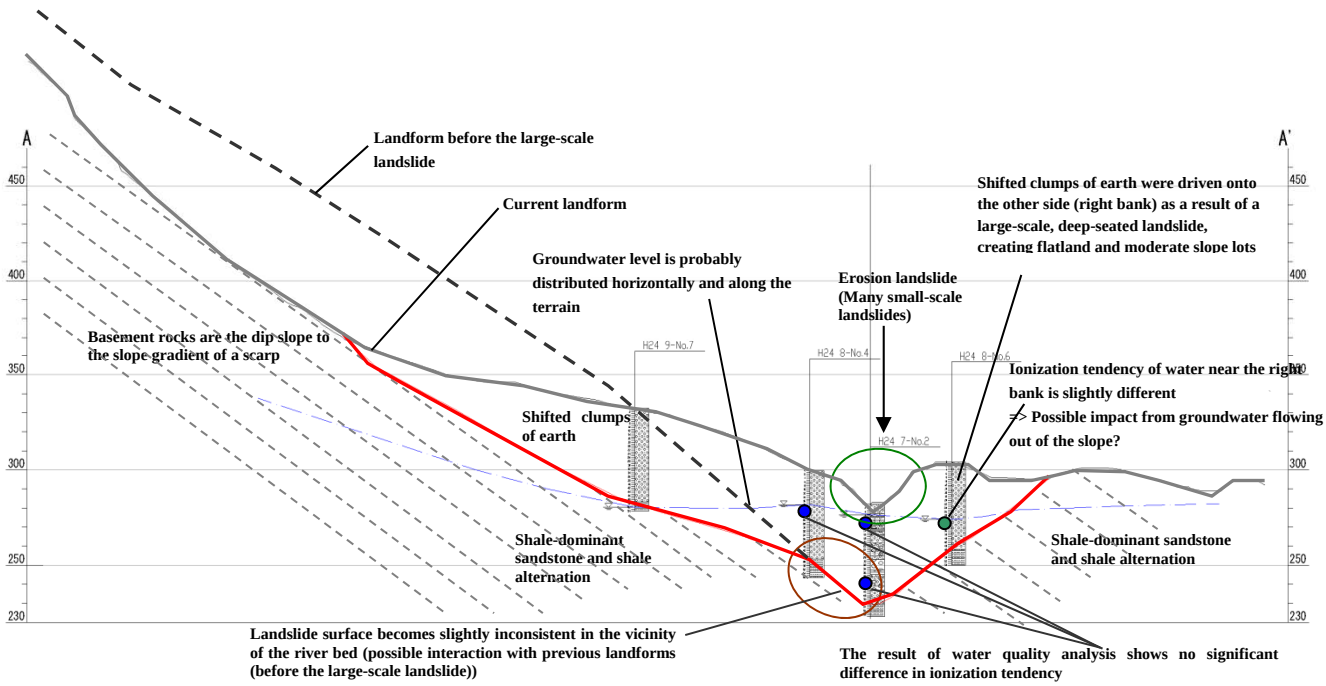

Fig. 8 Location and summary of field survey (Cross section of B-B' line in **Fig. 7**)

4.2 Study methods

In order to evaluate the impact on "piping erosion" and "landslide", geological and hydraulic models were built based on the results from the various geological surveys. Flow of the study is shown in **Fig. 9**. And the locations of the study are shown as the cross section B-B in **Fig. 7**.

4.2.1 Piping erosion

Specific locations where pore-pressure increased at the time of heavy rain were identified by regular seepage analysis using a two-dimensional cross-sectional model. The critical hydraulic gradient of the landslide dam *ic* was calculated using the geological nature of the dam. based on the outcomes of the geological surveys. to make a comparison with the local hydraulic calculations by simulation of infiltration, in order to evaluate the resistance to "piping erosion" (**Fig.10**).

The critical hydraulic gradient of the landslide dam is obtained by the following formula using density of soil particles comprising landslide dam "*Gs* (knots /m^3)", porosity of the soil "*n*" and void ratio of the soil "*e*":

Critical hydraulic gradient $ic = \gamma'/\gamma w = (1-n)\,(Gs - 1)$

$= (Gs - 1) / (1+e)$ ... (1)

Void ratio of soil $e = n/(1 - n)$ ... (2)

e = 0.667 was obtained using Gs = 2.711(knots/m3), which was obtained from the outcomes of the soil test, and n = 0.4 (equivalent to gravelly soil) based on boring cores, etc. by the formula (2): These values are used in the formula (1) to obtain the hydraulic grade line at the landslide dam, ic = 1.026≒1.02.

Regular seepage flow analysis at the landslide dam was conducted under the following conditions:

- Modeling range: Range which includes landslide dam.
- Mesh: Approx. 5 m near the face area, and the deeper the substratum, the rougher the mesh (Max. 15 m).

In addition, four ranges of models have been created based on the differences in geological features obtained from the boring surveys and soil tests, in-situ permeability tests and spring water distribution at the time of heavy rain. The hydraulic head, which is the high water level, was fixed at the landslide dam as an upstream water-level when analysis was conducted. The hydraulic head was fixed at the ground surface level at the lower stream, and the slope of the lower stream was establsihed as the seepage surface.

The value referred to in "Guidance to river dike structure development, July 2002, Japan Institute of Country-ology and Engineering" was used for the characteristics of unsaturated flow.

4.2.2 Landslide

Ground factors of the landslide dam, estimated from the soil properties and the hydraulic distribution obtained by the simulation of infiltration, were used for two-dimensional stability analysis (modified Fellenius method[4)]) to evaluate the resistance to "landslide". Stability analysis was performed as shown in formula (3):

$$Fs = \frac{\Sigma\{Cl+(W-ub)\cdot\cos\alpha\cdot\tan\theta\}}{\Sigma W\cdot\sin\alpha} \quad \text{... (3)}$$

Fs:	Safety factor	
U:	pore water pressure on slip surface	(knots /m^2)
W:	slice weight	(knots /m)
C:	cohesion	(knots /m^2)
l:	length of slip surface	(m)
φ:	angle of internal friction	(°)
b:	width of slice	(m)

Analysis was conducted on the two layers of the landslide dam and the foundation, with conditions of cohesion as "C", and angle of internal friction as "*φ*" as shown in **Fig. 13** and **Fig. 14**, based on the geological properties obtained by drilling, etc.

4.3 Results

4.3.1 Piping erosion

Fig. 11 shows pore-water pressure distribution in a heavy rain (steady-state) obtained by the simulation of infiltration after the Great Floods on Kii Peninsula (2011). Local pressure grade line of where the pore-pressure is highest is, horizontally: approximately 0.2, vertically: approximately 0.1. The result is significantly lower than the critical hydraulic gradient of ic＝1.02 of the landslide dam. Therefore, a possible infiltration failure of the dam in the future is extremely small. On the other hand, the analysis was conducted under the same topographic conditions seen in the Great Floods on Kii Peninsula (2011). As seen in **Fig. 12**, the local pressure grade line in the vicinity of the foot of the slope that increased under the conditions is horizontally: approximately 0.5, vertically: approximately 0.3. The end result may be easy increase of pore-pressure being converged locally compared to the time after the Great Floods on Kii Peninsula (2011). There is a possibility that "piping erosion" had an impact on the destabilization of the dam at the time of the Great Floods on Kii Peninsula.

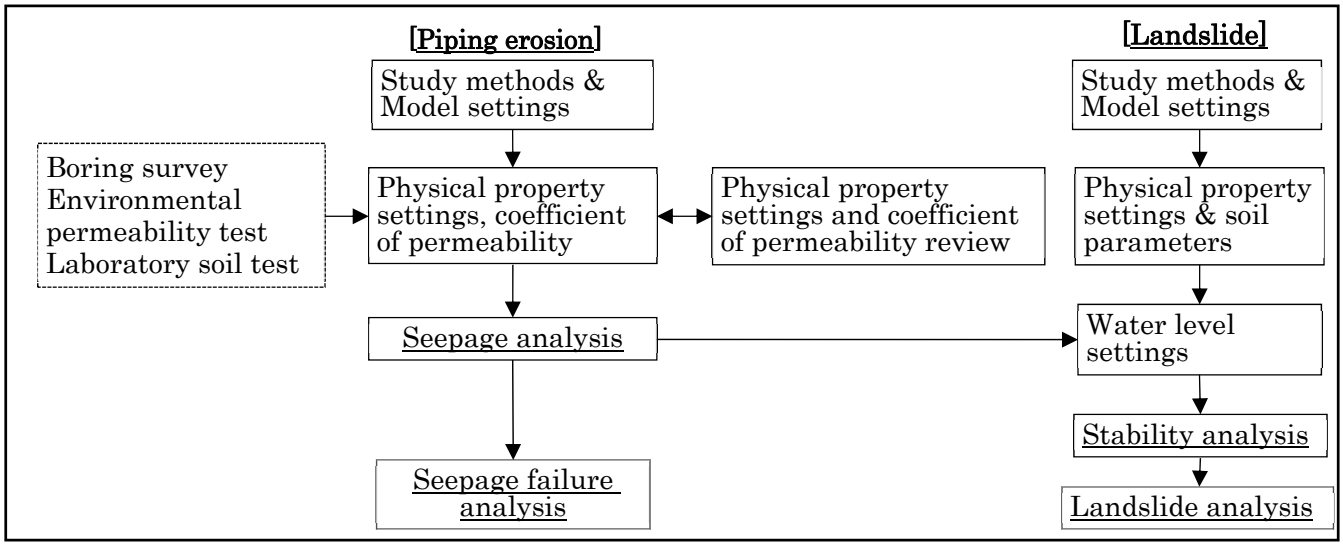

Fig. 9 Evaluation of disaster factors of the sediment dam

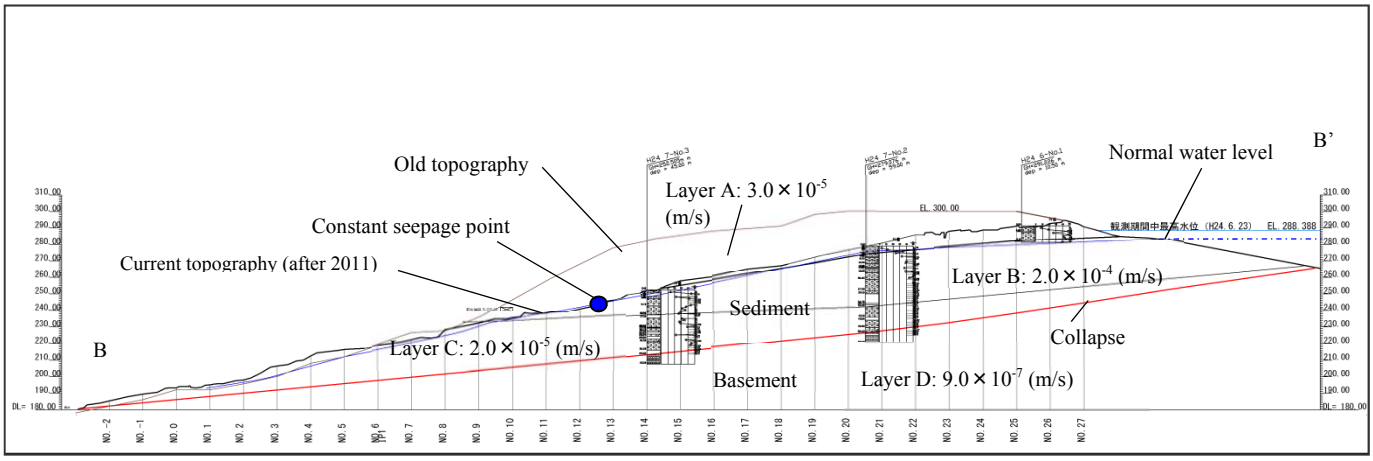

Fig. 10 Permeability cross diagram created from a simulation of infiltration

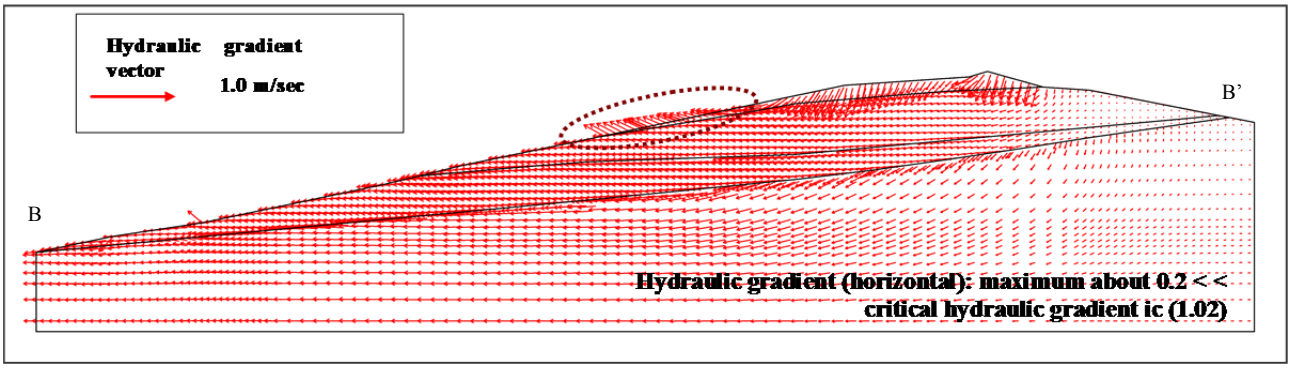

Fig. 11 Simulation of infiltration vector (after the Great Floods on Kii Peninsula, 2011)

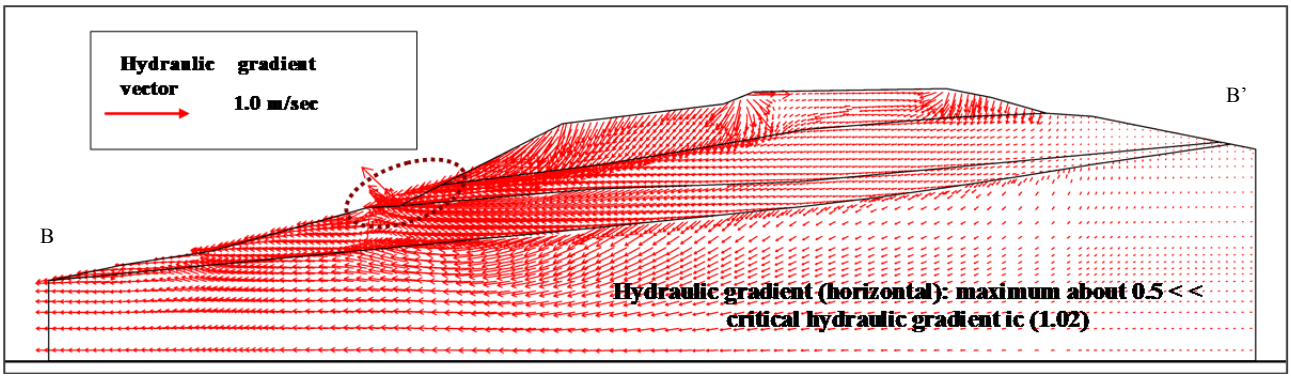

Fig. 12 Simulation of infiltration vector (before the Great Floods on Kii Peninsula, 2011)

4.3.2 Landslide

Fig. 13 shows the results from the stability analysis indicating the arc as the minimum safety factor of the landslide dam after the Great Floods on Kii Peninsula (2011).

As a result of the analysis, the slope gradient of the landslide dam became significantly gentle after the Great Floods on Kii Peninsula (after 2011) compared to before (before 2011). The resulting minimum safety factor was as high as Fs = 1.940 in order to act on the stable side of the slope. On the other hand, the part of the landslide dam where the gradient became steepest and the pressure grade line became largest in the simulation of infiltration above indicated that the safety factor was as low as Fs = 1.058 before the Great Floods on Kii Peninsula (before 2011). This means the stability decreased by about 45 % compared to the conditions before the the landslide dam improved its stability disaster (after 2011). (**Fig. 14**). From all the above, significantly against "landslide" regardless that the landslide dam holds a sufficient resistance to "landslide", as well as "piping erosion", after the Great Floods on Kii Peninsula (2011), compared to before the disaster (before 2011).

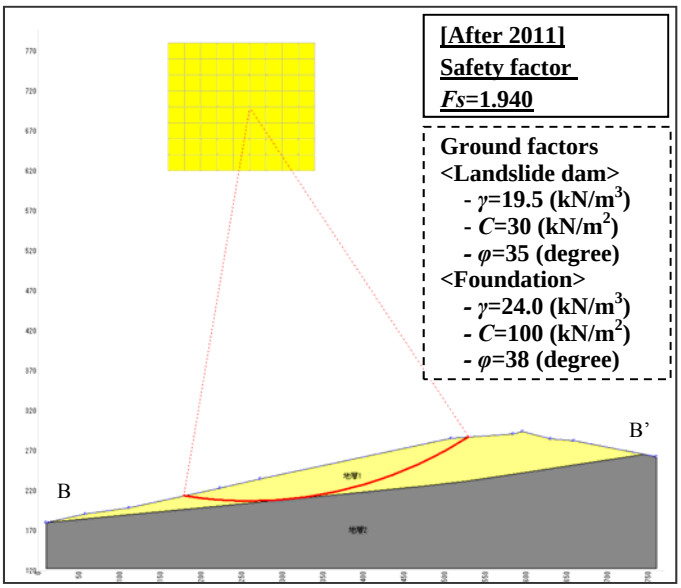

Fig. 13 Stability analysis results
(after the Great Floods on Kii Peninsula (2011))

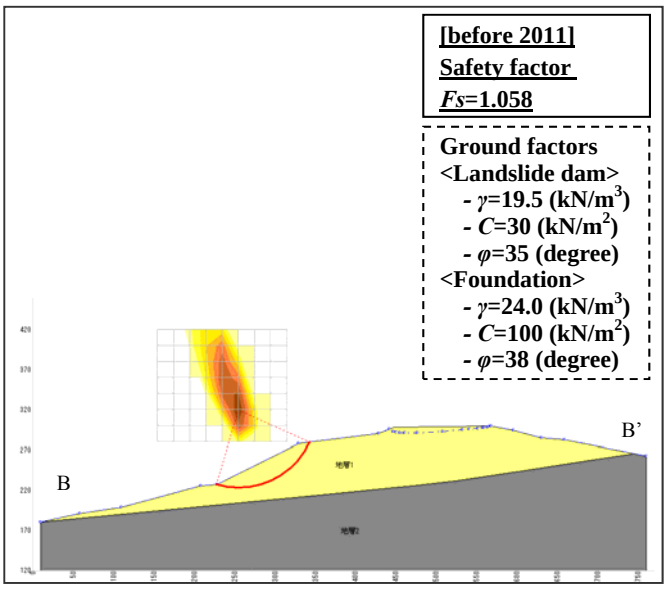

Fig. 14 Stability analysis results
(before the Great Floods on Kii Peninsula (2011))

5. PLANNING OF COUNTERMEASURES

According to the results of the stability study of the landslide dam with the current geological and water quality conditions of Lake Ohatakedoro, a possible great impact on the trigger of a disaster in the future caused by "piping erosion" or "landslide" is small. On the other hand, the height of the sediment bank decreased by about 8 m to the water level of Lake Ohatakedoro caused by large erosion of the dam, leaving the dam vulnerable to "overflow erosion" compared to before the disaster. Therefore, countermeasures should be on the table, focusing mainly on "overflow erosion".

Specifically, manual deposition by building new dykes for the landslide dam, drainage construction for the purpose of stable flow of surface water, and installing box culverts, may be effective. Seepage points need groundwater drainage.

Possible "piping erosion" or "landslide" is still on the table, because topographical features and stabilities can always change due to abrupt water level increases of Lake Ohatakedoro at the time of local severe rain which occurs several times a year from typhoons, etc., causing erosion at seepage points in the landslide dam. Therefore, it is necessary to continue to monitor the topographical change and water level at the landslide dam, to reflect the outcomes of the study for countermeasure development.

6. SUMMARY

(a) During the massive flooding caused by the Great Floods on Kii Peninsula in 2011, the landslide dam was heavily eroded, causing a decrease in the dam height by about 8 m. Therefore, the dam became vulnerable to "overflow erosion" compared to before the disaster (before 2011), when the water level of Lake Ohatakedoro increased in a heavy rain.

(b) The results obtained by simulation of infiltration and stability analysis show that the resistance of the dam against piping erosion and landslide improved compared to before the Great Floods on Kii Peninsula (before 2011), decreases the possibility of being destabilized by “piping erosion” or “landslide”.
(c) Thereby the future countermeasures for Lake Ohatakedoro must focus mainly on “overflow erosion”.
(d) However, the topographical features can always change due to erosion at seepage points in the landslide dam in a heavy rain several times a year brought by typhoons, etc. Therefore, it is necessary to continue to monitor the topographical change and water level at the landslide dam, because the possibility of “piping erosion” or “landslide” has always been changing, in order to reflect the outcomes of the study for countermeasure development.

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