Countermeasures for large-scale landslide dams caused by Typhoon No. 12 in September 2011

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The record-breaking heavy rains caused by Typhoon No. 12 in September 2011 caused deep seated landslides that blocked drainages at 17 points in Nara and Wakayama Prefectures. At five of these locations, the damage was so severe that the landslide dam reached 100 meters in height, and erosion-control countermeasures are currently being undertaken by the Kii Mountain District Sabo Office under the direct control of the Japanese Government. At present, all emergency work, including the installation of temporary overflow channels, has been completed so that construction of the sabo dams and other works can be implemented. However, these countermeasures are an attempt to remedy unprecedented large-scale landslide dams. Moreover, ongoing rainfall triggered by typhoons has caused numerous difficulties with construction. This paper reports on progress and policies regarding the abovementioned countermeasures.

Key words: landslide dam, countermeasures plan, Sabo facilities

1. Introduction

A great number of large-scale debris disasters such as deep-seated landslides were caused by the heavy rainfall triggered by Typhoon No. 12 mainly in Nara and Wakayama Prefectures of Kii Peninsula in September, with the result that these places were seriously damaged. Landslide dam occurred at 17 positions. In five of these points where the damage was particularly serious, countermeasures are currently being taken by the Kii Mountain District Sabo Office under the direct control of the Government (**Fig. 1**).

At present, the emergency work of installing temporary overflow channel for ensuring provisional safety has been terminated. Full-scale measures such as construction and improvement of the sabo dam and overflow channel are currently being taken. For the study of the full-scale measures against the unprecedented large-scale landslide dam, "Study Committee for Measures against Landslide Dam " (headed by Prof. Takahisa MIZUYAMA of the Postgraduate course, Graduate School of Kyoto University) was established. The policy of the countermeasures was worked out under the guidance and instruction of this Committee.

The following reports the progress in working out the measures.

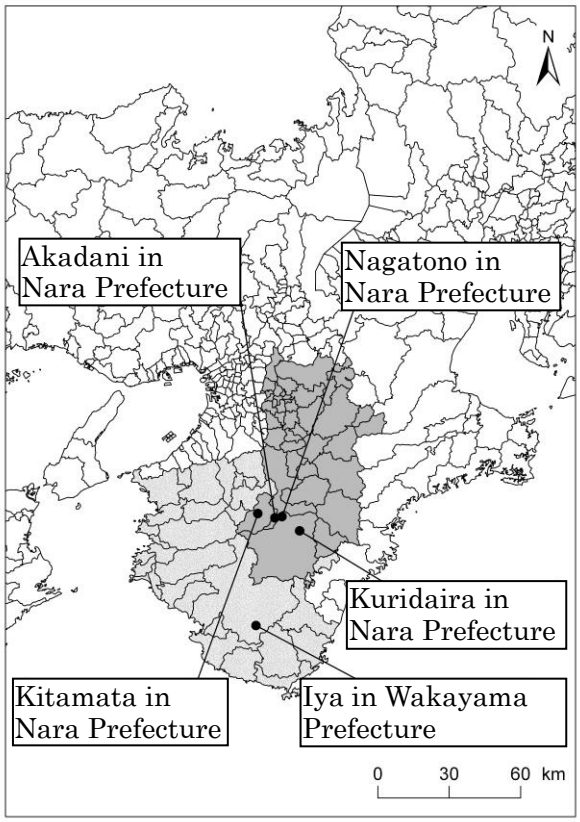

Fig.1 Scope of study area

2. Implementation of emergency work

Emergency work began on countermeasures at five locations: Akadani Area, Gojo City, Nara Prefecture (**Photo 1**) and Iya Area, Tanabe City, Wakayama Prefecture on September 16; Kitamata Area, Nosegawa Village, Nara Prefecture on September 30; and the Nagatono (**Photo 2**) and Kuridaira Areas (**Photo 3**), Totsukawa Village, Nara Prefecture on October 8, 2011.

The aim of the emergency work was to build temporary overflow channels to accommodate any flood on the level of 2-year probability of exceedance before the rainy season in the following year so as to prevent damage by overtopping and resulting erosion of the landslide dams. With the intent to complete the work by the time of the next year's deluge, the structure of the temporary overflow channels in each area was designed with consideration given to restrictions in the material locally available and delivery of equipment and material to the site. The latter included a mat for loading local boulders in a cage, soil cement to be formed by a mixture of debris and cement, and fabric-based formwork for filling with ready-mixed concrete if the latter could be delivered to the site (**Photo 4)**. Almost all measures were completed by mid-June 2012. At present, the emergency work has been supplanted by the implementation of full-scale countermeasures for building sabo dams and overflow channels.

3. Status of damages at the relevant positions during the period of deluge

On June 19 and September 30, 2012, the emergency overflow channels in each area were subjected to the disaster brought about by Typhoon No. 4 and 17, respectively. The following addresses in particular Akadani and Kuridaira Areas, which suffered heavy damage. In Akadani area, the upper portion of a deep-seated landslide that had occurred in September 2011 adjacent to the temporary overflow channel was remobilized by the rainfall of Typhoon No. 4 on June 19, 2012. This storm generated continuous precipitation of 127.5 mm and a maximum of 17.5 mm/h, according to the Akadani area rain gauge for of the Ministry of Land,

Photo 1 Akadani Landslide Dam

Photo 2 Nagatono Landslide Dam

Photo 3 Kuridaira Landslide Dam

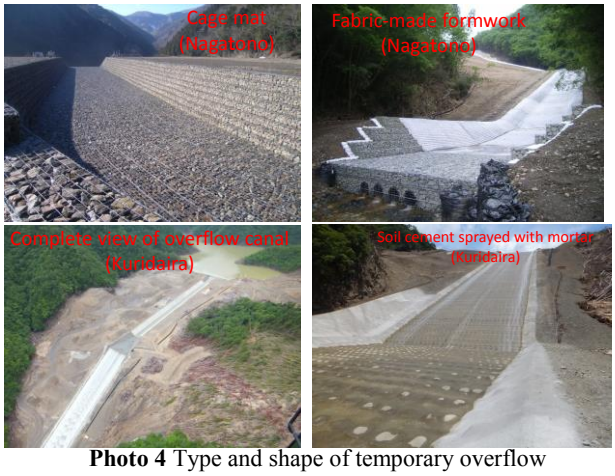

Photo 4 Type and shape of temporary overflow

Infrastructure, Transport and Tourism. Approximately 100,000 m^3 of debris flowed into the temporary overflow channel, resulting in the deposition of debris over the entire area of the channel, whose construction had almost been completed (**Photo 5**).

This was followed by continuing debris flows issuing from the collapsed slope. At present, a huge deposit of debris blankets the temporary overflow channel. This exemplifies the likelihood of disaster if facilities with an open water channel are built as countermeasures immediately below an unstable slope; the maintenance of such facilities will be made difficult by the inflow and deposition of debris. Meanwhile, water is discharged from the flood reservoir through an underground culvert below the temporary overflow channel bottom. There has been no increase in the water level of the flood reservoir. This suggests that the installation of a culvert may be effective for a landslide dam adjacent to an unstable slope when countermeasures are taken (**Photo 6**) [*SAKURAI et. al.,*2014(1)]. Furthermore, after Typhoon No. 18 in September 2013, a large-scale slide again occurred. On this occasion, the culvert again proved effective, and the water level of the flood reservoir did not increase.

Kuridaira Area suffered the greatest damage of all the sites where measures were taken, with a landslide dam about 100 m high. In this area, the rainfall from Typhoon No. 17 on September 30, 2012, caused large-scale erosion of the huge landslide dam.

This storm generated continuous precipitation of 231.5 mm and a maximum of 54 mm/h, according to the Kuridaira Area rain gauge of the Ministry of Land, Infrastructure, Transport and Tourism. Two-thirds of the temporary overflow channel with an overall length of 576 m was discharged (**Photo 7** and **Fig. 2**). The analysis of images from the closed-circuit television installed at the site suggests that scouring overwhelmed the temporary overflow channel due to running water with a head of 94 m, and this spread over the entire landslide dam [*SAKURAI et. al.,*2014 (2)]. The terminus of the temporary overflow channel had been subjected to scouring by the running water during Typhoon

Photo 5 Debris deposit in the temporary overflow channel of Akadani area

Photo 6 Discharge from the culvert drain pipe

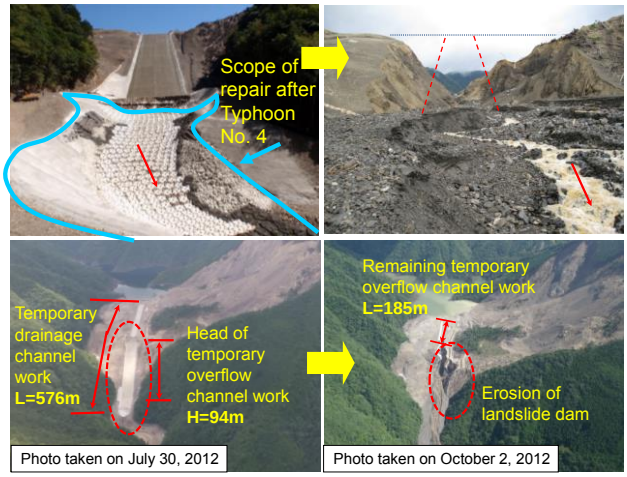

Photo 7 Comparison of temporary overflow channel before and after Typhoon No. 17 of September 2012

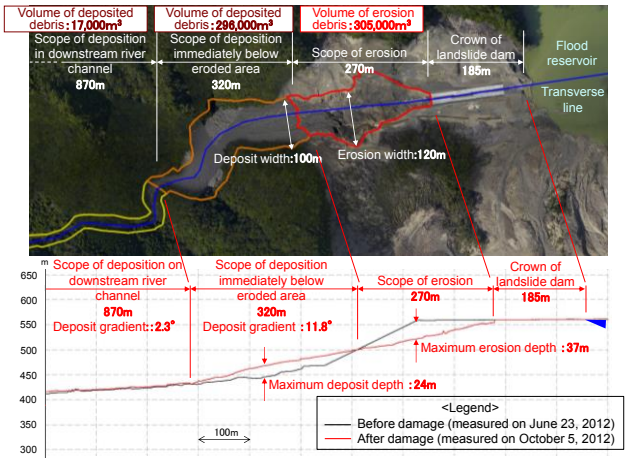

Fig. 2 Erosion of Kuridaira landslide dam

No. 4 on June 20, which may have weakened the structure. The riverbed 65 m downstream of the terminus was reinforced by a net filled with 2 t of concrete blocks and cobblestones (**Photo 7**). However, shortly after the start of flood overflow from the reservoir, the greater part of the temporary overflow channel was discharged, even though the channel bottom had been reinforced with soil cement to a maximum thickness of 4.6 m. This resulted in large-scale erosion of the landslide dam.

This example in Kuridaira Area shows that when an overflow channel is installed in a landslide dam with a great difference in hydrostatic head, it is important to build a sabo dam at the terminus of the overflow channel simultaneously with the overflow channel for the purpose of scour protection.

4. Working out the policy of the countermeasures for landslide dam sites

4.1 Discussions in the Committee

To implement full-scale countermeasures following the emergency work, we established the "Study Committee for Measures against Landslide Dams," headed by Prof. Takahisa MIZUYAMA of the Graduate School of Kyoto University (hereinafter referred to as "the Committee"), which includes academic experts in sediment control, geographic features, and rivers. The policy for the countermeasures was worked out under the guidance and instruction of the Committee. The Committee met four times between May 2012 and February 2013 before submitting their policy proposals. During the period when the Committee was active, successive storms (Typhoon No. 4 in June 2012 and Typhoon No. 17 in September 2012) generated more rainfall, each damaging the sites further. Every time a disaster occurred, the Committee recommended that quick action be taken on a contingency basis.

The following section discusses the policy recommendations for countermeasures regarding the landslide dams.

4.2 Policy for the countermeasures to be taken at the landslide dams

4.2.1 Target of the countermeasures

The target of the countermeasures at the landslide dams is to control the damage caused by seepage and overflow, erosion of the deposited soil in the river channel, and outflow of debris due to new landslides or erosion at previously collapsed sites. The purpose of these actions is avoiding debris flows and flooding downstream. To attain this target, a scale should be determined for the project and suitable facilities installed.

4.2.2 Scale of the project

The scale of the countermeasures project assumes a flow rate resulting from rainfall on the level of 100-year probability of exceedance. The facilities to be built as countermeasures against this flow rate include overflow channels and sabo dams.

4.2.3 Policy for installation of facilities

The basic policy for the countermeasures is to minimize the overflow elevation of the flood reservoir and to backfill the flood reservoir with excavated debris without sacrificing the stability of adjacent collapsed sites or soil deposition areas. This policy was determined for the following reasons. The facilities built during the emergency countermeasures were damaged by the overflow from the flood reservoir during the rains of 2012. This experience revealed the importance of minimizing the impact of water overflows from the reservoir, for example, by maintaining the reservoir at a lower level or by reducing its capacity.

Second, for the countermeasure structures, positive use of soil cement, which is a mixture of local debris and cement, was recommend as the material for construction of sabo dams. Surplus soil is often difficult to procure in the area surrounding the local site, and massive volumes of deposited debris can be incorporated to obtain soil cement of sufficient strength (3–6 N/mm^2) to meet the requirements for Sabo facilities. Thus, soil cement has advantages in terms of workability and cost. Based on this policy, soil cement is planned for use in construction of all the sabo dams at the specified sites.

Third, an overflow channel capable of ensuring safe discharge of water flow at the planned scale is to be built over the landslide dam. The overflow channel will have the following structure. When the slope downstream of the landslide dam is less steep or the height of landslide dam is low, a groundsel group is installed. However, when the slope downstream of the landslide dam is steep or the landslide dam is high, an overflow channel with chute structure is adopted to solve the difficulties of excavation and transport of a greater amount of excavated soil. Furthermore, to ensure that the overflow channel will not be affected by debris flows from collapsed slopes, a deposit dike and training levee will be constructed between the collapsed slope and the overflow channel. Even when there is an overflow of water from the overflow channel in excess of the planned level, the periphery of the overflow channel will be covered

with the sediment-control soil cement to prevent overflow erosion of the landslide dam.

Fourth, an sabo dam should be built at the earliest opportunity at the terminus of the slope downstream of the landslide dam for the purpose of preventing scour at the foot of the landslide dam and stabilizing the landslide dam. Particularly when a overflow channel is to be built on the landslide dam of significant height, scouring at the terminus of the overflow channel has a greater possibility of causing serious erosion of the landslide dam, as in Kuridaira Area at the time of Typhoon No. 17 in September 2012. To avoid this, an sabo dam must be constructed to protect the terminus of the overflow channel against scouring and to absorb energy of the running water issuing from the overflow channel. It is important to construct both the temporary overflow channel and the sabo dam simultaneously in the initial phase of emergency countermeasures.

Fifth, to counter seepage from the landslide dam, sufficient countermeasures must be taken to discharge water from the sabo dam by construction of drain works. **Fig. 3** shows the examples of the countermeasures in conformance with the abovementioned policies.

5. Examples of countermeasures for landslide dam

The following introduces representative examples of the countermeasures taken in Akadani, Kuridaira and Nagatono Areas, where the height of the landslide dams measured 100 m.

5.1 Example of countermeasures in Akadani area

We described the policy for installing overflow channel works as a countermeasure for landslide dam sites in Chapter 4. However, even if an overflow channel work were installed, it was expected that difficulties in the functioning of the countermeasure would occur due to deposition of sediment, because sediment discharge from the collapsed slope had occurred frequently. Therefore, two or more dam works were installed, without installing an overflow channel, as a countermeasure intended to stabilize the landslide dam.

5.2 Example of countermeasures in Kuridaira area

5.2.1 Installation of culvert by pipe-jacking method

In Kuridaira Area, most of the temporary overflow channels were damaged in Typhoon No. 17 of September 2012, but they were not able to be repaired before the deluge season in the following year. To alleviate the water discharged from the flood reservoir before the full-scale countermeasures are completed, it was decided to install culverts capable of discharging water starting from below the temporary overflow channel bottom elevation,

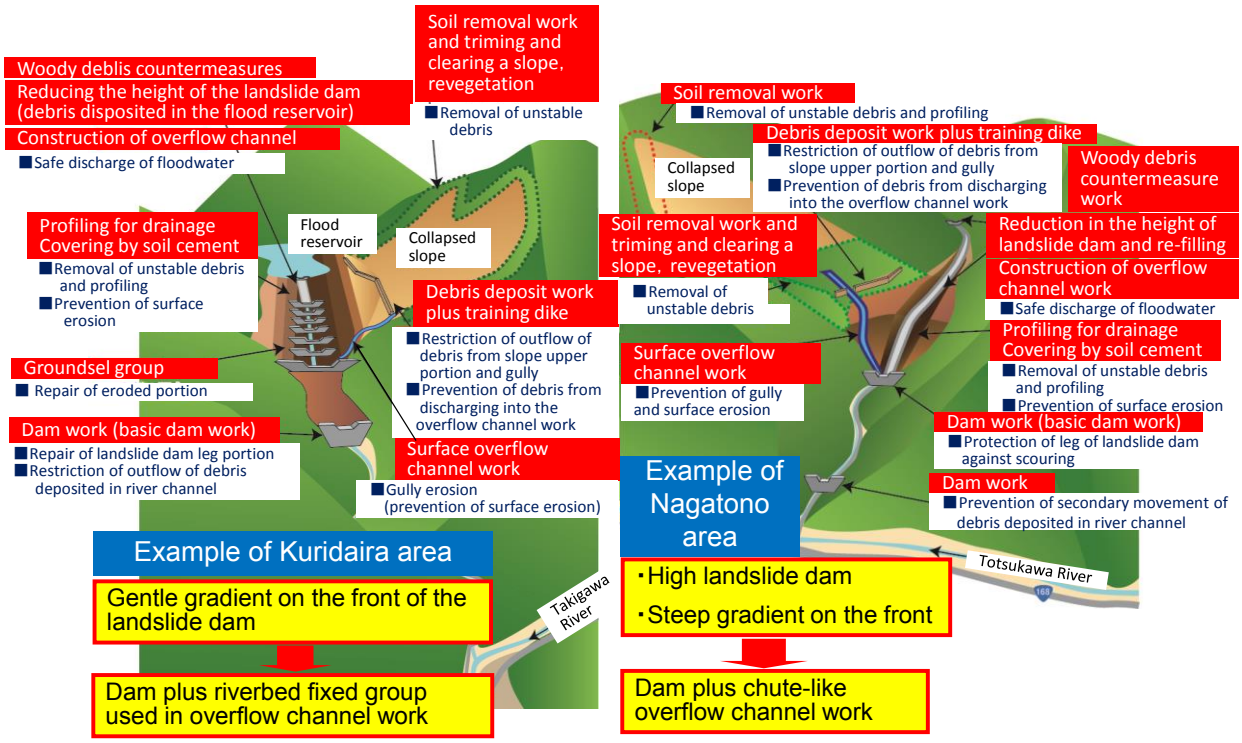

Fig. 3 Countermeasure example (Kuridaira and Nagatono area)

thereby reducing the water level of the reservoir.

To install the culvert, a selection had to be made between two methods: the cut-and-cover tunneling and backfilling method and the pipe-jacking method that permitted installation of piles without cut-and-cover tunneling. The pipe-jacking method was chosen because of the shorter construction period and reduced costs it affords. In the pipe-jacking method, a starting shaft and arrival shaft are installed on either end of the planned line where the culvert is to be installed. An excavator equipped with pick-jacking equipment is driven underground by a hydraulic jack from the starting shaft, and the pipes are sequentially connected via the excavator so that a row of pipes is formed that ultimately reaches the arrival shaft. In this way, a culvert is installed by so-called pipe-jacking [*Japan Microtunneling Association*, 2001] (**Photo 8**).

The culvert was designed to ensure that water would not flow out from the flood reservoir to the temporary overflow channel even when exposed to rainfall (56 mm/60 min) at the intensity of Typhoon No. 17 in September 2012, which damaged the temporary overflow channel. Furthermore, during the construction period, the water level could be

Photo 8 Pipe jacking method: forced-fitting of pipeline by tunneling machine and hydraulic jack

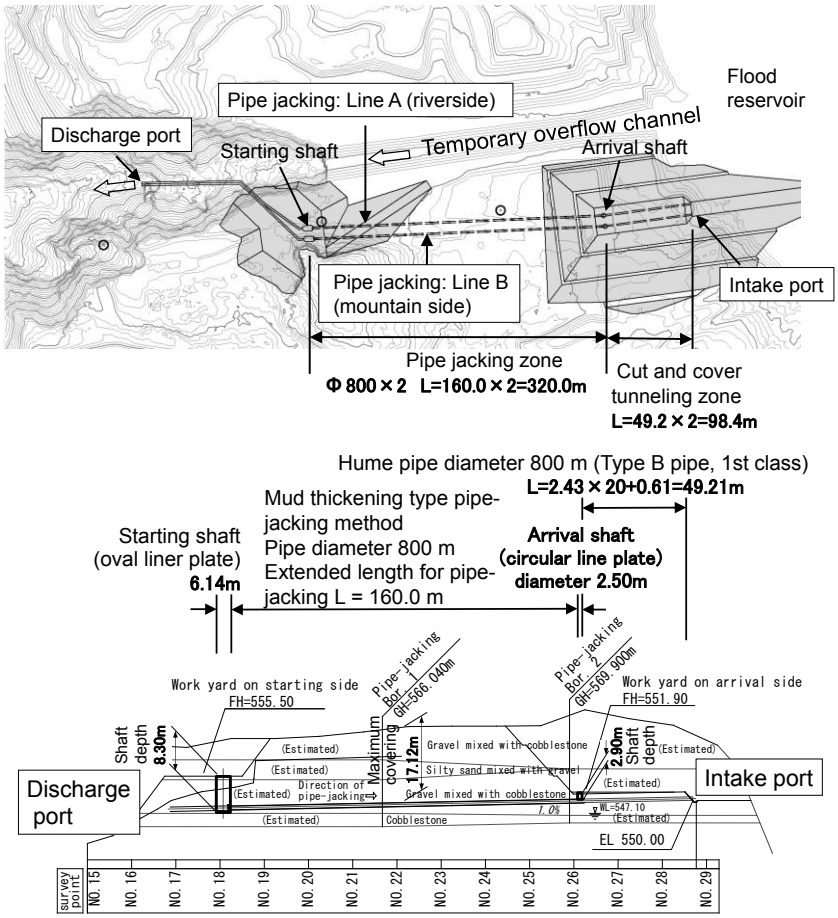

Fig. 4 Planned view, Planned profile in Kuridaira area

reduced through water discharge by pumping to a level of 550 m, 10 m lower than the temporary overflow channel bottom elevation of 560 m. Accordingly, this elevation was determined as the height of the culvert to be installed. In conformance to this plan, two culverts, each with a diameter of 800 mm and an extension of 265 m, were installed.

The pipe-jacking method was chosen to cover the length of 160 m, and the cut-and-cover tunneling method to cover the remaining 49.2 m (**Fig. 4**). Two 800-mm-diameter culverts were used because Kuridaira Area is located in a remote interior mountainous region, and pipes with greater diameter cannot be carried to the site. The use of two pipes allows the water discharge function to be maintained by one of the culvert drainpipes when the other has been clogged.

The landslide dam in Kuridaira Area is formed by a colluvial deposit with a depth of about 100 m. The pipe-jacking method had not been applied in the countermeasures for such a landslide dam in Japan, and there is concern about the following:

①Inflow of running water and ground water from the flood reservoir

②Presence of bedrock and breccia that cannot be identified in the soil survey

③High permeability coefficient of 4.8×10^{-2} cm/s at the site of tunneling

④Possibility of contact with driftwood during tunneling work

For①, during the construction work, the water level of the flood reservoir was reduced below the installation height of the culvert through water discharge by pumping. This eliminates the problem of inflow of running water or ground water from the flood reservoir.

For ②, the problem with unexpected bedrock was handled by an excavation machine capable of rigid-layer excavation with a secondary crushing mechanism. Furthermore, if a one-point concentration of collapsed rock impinged on the pipe, the resistance of the outer periphery of the pipe will increase with respect to pipe jacking. The pipe may be damaged if pushed forward by pipe jacking beyond the planned level while the contact between the pipe and gravel is maintained. To avoid this, plasticizer with a slipping property was injected immediately following the excavator. The outer periphery of the pipe was then coated with thrust-reducing agent.

For ③, performing tunneling in a waterless layer having a high permeability coefficient, as in Kuridaira Area, raises several concerns. The adopted method is a mud-thickening-type pipe-jacking method [*Japan Microtunneling Association*, 2006] in which excavation is performed by the excavator charged with highly concentrated slurry by pumping. The debris resulting from excavation is agitated with highly concentrated slurry and fluidized. While the cutting face is kept stabilized and the earth removal valve inside the excavator is adjusted, earth is removed, and sucked by a vacuum device to continue the pipe-jacking operation. As a result, if the permeability coefficient is high and if the slurry dissipates, the stability of the cutting face may be lost, and earth removal may be disabled. Furthermore, if the water content of the abovementioned plasticizer has been lost and the function deteriorates, there will be an increase in the resistance on the outer periphery of the pipe. The thrust will be increased beyond the planned level, with the result that the pipe may be damaged. Thus, to get the clogging effect of space intervals between soil particles, a clay- and mud-dissipation inhibitor, mainly comprising natural raw timbers, was used, and the volume of flowing muddy water was increased to solve this problem. Further means were taken by additional plasticizer, as discussed in ②.However, the possible impact of the driftwood in ④ was an unknown quantity. This required constant attention to possible driftwood during the tunneling operation.

To illustrate the actual construction work, **Table 1** shows the volume of excavation of Lines A (riverside) and B (mountainside). In both Lines A and B, the average daily progress volume was more than double the 2.5 m per day that was originally planned. The maximum daily progress volume was close to 10 m. As a result, the construction period of 79 days required to install the pipes with a length of

Table 1 Volume of tunneling per day

Volume of tunneling (m)	Line A	Line B
Average daily progress volume (m)	5.45	6.15
Maximum daily progress volume (m)	8.59	9.72
Minimum daily progress volume (m)	3.43	2.63

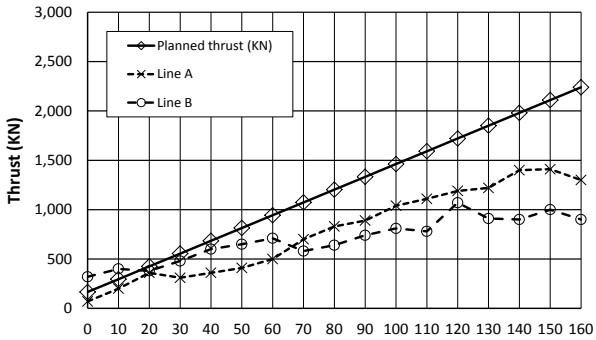

Fig. 5 Planned thrust and actual thrust for each line

160 m by the pipe-jacking method was reduced to 37 days.

There was no problem with driftwood, which had been a matter of concern. **Fig. 5** shows the thrust records achieved for each pipe-jacking distance in each pipeline. In each, there is a transition of about 40–80% of the planned thrust, without the planned level's being exceeded. This success is attributed to the following factors. Increased friction on the outer periphery of the pipe was reduced by the thrust-reducing material preliminarily coated on the outer periphery of the pipe as discussed earlier, and the water content of the plasticizer was not absorbed by the dry pipe. The plasticizer remained on the excavator for a longer period than anticipated, preventing gravel contact and increasing the thrust, with the result that increase in thrust beyond the planned level was minimized.

When the slurry dissipation is examined in terms of the percentage of flowing muddy water obtained by dividing the volume of water actually used by the planned volume, the percentage of flowing muddy water by the mud-thickening-type pipe-jacking method was approximately 120–140%. The average percentages of flowing muddy water of lines A and B in this construction work were 220 and 218%, respectively, throughout the construction period. The percentage of flowing muddy water show a remarkably high level of slurry dissipation. Thus, increasing the volume of flowing muddy water fully enabled the tunneling operation.

As described previously, the pipe-jacking method provided an effective way of constructing the countermeasures for a landslide dam comprising a thick layer of colluvium under complicated soil conditions.

In Kuridaira Area, large-scale erosion was caused by Typhoon No. 17 of September 30, 2012, with the result that the crown of the landslide dam was eroded to a maximum depth of 40 m. The discharged debris was re-deposited such that the slope downstream of the landslide dam became more gradual. The original gradient of 1/2 was converted to 1/5 to 1/6. On the other hand, the slope length was much increased from the original 180 to 600 m or more (**Fig. 2**). The slope gradient became gentle. However, due to a thick deposit of unstable debris vulnerable to erosion, it was necessary to take immediate action to achieve stabilization to prevent radical erosion of the entire landslide dam.

The following discusses the overview of the action taken. In Kuridaira Area, a large-scale flood reservoir remained after action was taken, and running water flowed out without sand being supplied. Accordingly, scouring of the foundation of the countermeasure facilities occurred. Concern arose that the landslide dam may experience large-scale erosion. The slope downstream of the landslide dam had to be converted into a longitudinal grade along which radical erosion should not occur even if the countermeasure facilities were damaged. Calculations using the one-dimensional riverbed fluctuation method showed that, if the longitudinal gradient became 1/12, erosion would decrease, with the gradient approaching the level of stability. Accordingly, this gradient was determined as the planned longitudinal gradient. The longitudinal gradient will be ensured by conformance to the following procedures (**Fig. 6**):

①The overflow elevation (temporary overflow channel bottom elevation) will be reduced by 20 m.

②A 35-m high sabo dam will be built at the terminus of the debris deposit. The sand deposit will be refilled at a 1/12 gradient. The foot of the landslide dam will be fixed as a loading berm.

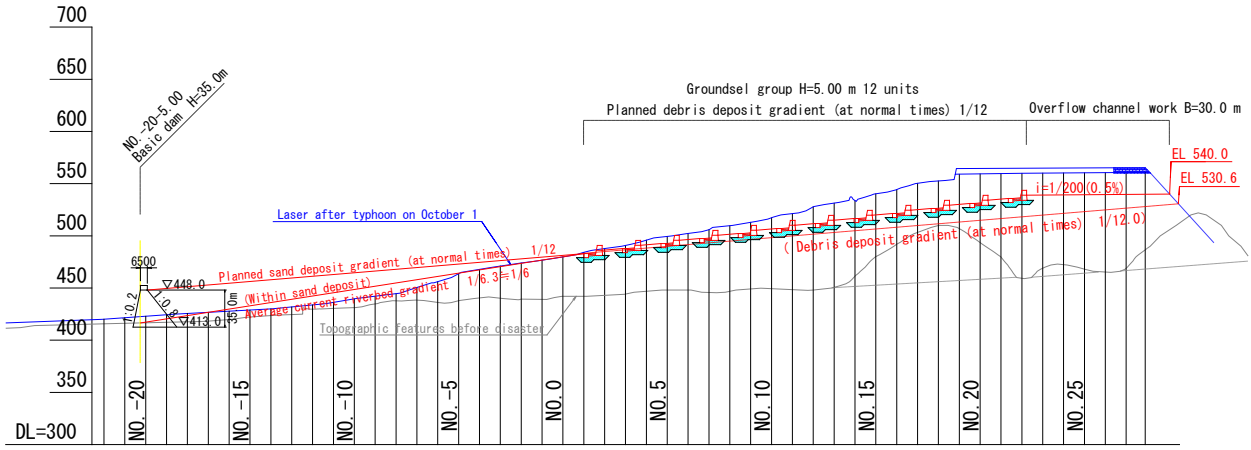

Fig. 6 Profile in Kuridaira area

③An overflow channel provided with a consolidation work group will be built in upper stream from sabo dam sand deposit.

Excavation work is currently under way for construction of the overflow channel.

5.3 Example of countermeasures in Nagatono Area

Through the countermeasures taken in Nagatono Area, the height of landslide dam will reduced by a maximum of 25 m, and the flood reservoir will be completely refilled with the excavation debris (approximately 500,000 m^3).

A new overflow channel (planned flow rate, 210 m^3/s) with the head of 80 m and an overall length of 880 m (gradient 1/11) will be constructed. An sabo dam for scour protection of the foot and dissipation of the energy of the water discharged from the overflow channel will be built on the foot of the landslide dam as a terminus of this overflow channel (**Fig. 7**).

The problem with Nagatono Area is that, even if the height of the landslide dam is reduced, the head of the overflow channel still measures 80 m, and the water channel has a three-sided covering structure with a gradient of 1/2.5, resulting in rapid design flow velocity of approximately 20 m/sec (Fr = 8.9). Furthermore, a normal line curving around the slope will be formed (**Fig. 7**). This makes it important to study a sabo dam structure to ensure the energy dissipation effect and an overflow channel structure

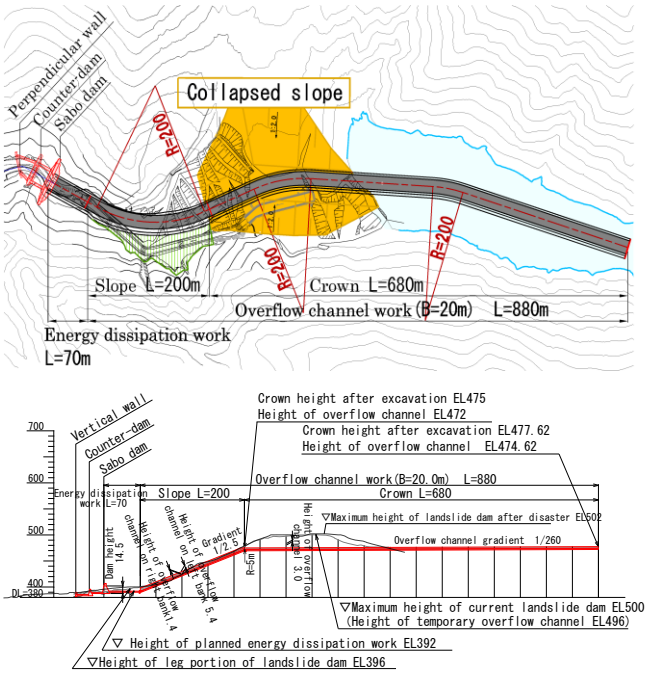

Fig. 7 Overflow channel plan and profile in Nagatono area

to ensure safe discharge of the running water. However, such Sabo facilities have never been constructed, and prediction of the hydrological phenomena in the overflow channel is difficult.

Thus, it is important to keep track of the phenomena anticipated at the time of deluge through testing using hydraulic experiment and to incorporate the experiment results in the subsequent design phase. The following describes the major study items required in the hydraulic experiment:

①Verification of the impact on the hydraulic regime of the curved normal line of the ramp discharged at high flow velocity

②Verification of the effects of the energy dissipater at the terminus of the landslide dam by drift

③Verification of the energy dissipation effect and hydraulic regime fluctuation caused by the differences in sand deposit conditions (fully loaded with sand or not) of the sabo dam

④Verification of the negative pressure on the crown of the water channel slope

For these verifications, we created a 1/60-scale model with an overall length of approximately 12 m and a level difference of 1.3 m (**Photo 9**) to check the hydrological conditions.

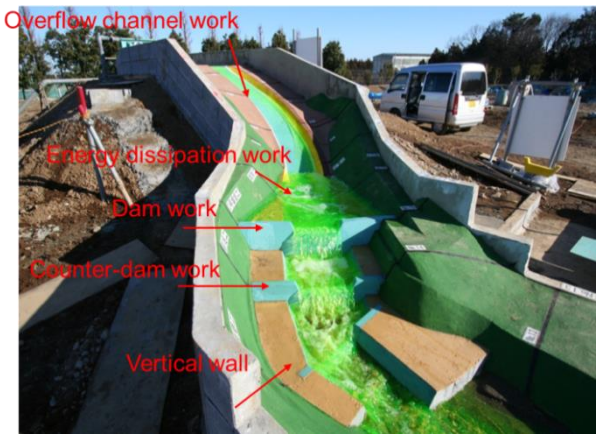

Photo 9 Complete view of model

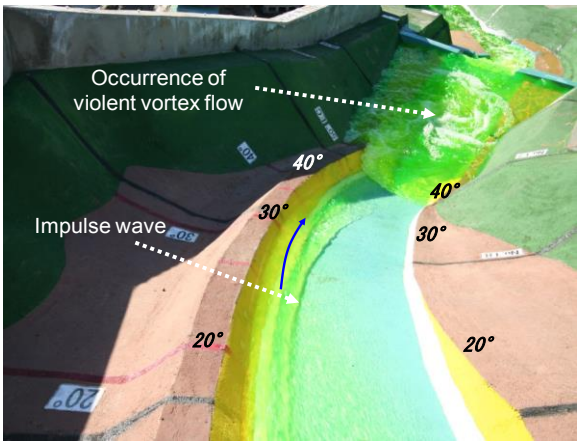

Photo 10 Drift at bend

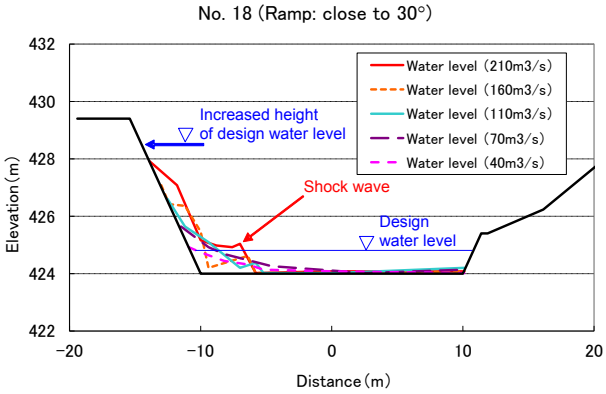

Fig.8 Profile of water level close to 30° bend

The result of these studies yielded the following. With respect to item ①, discharge at a flow velocity of approximately 20 m/sec occurred inside the overflow channel for the discharge at a planned flow rate of 210 m^3/sec. This gave rise to impulse waves, and the flow drifted outward toward the left bank of the bend due to centrifugal force (**Photo 10**). However, maintaining a free board of 0.8 m at the revetment extended height on the left bank, according to the original plan, avoided overflows (**Fig. 8**).

For ②, if the flow in the drifted state plunges into the energy dissipater (a portion of the sabo dam sand deposit), a strong vortex flow occurs inside the energy dissipater (**Photo 10**). When the length of the energy dissipater is kept at 70 m and the water depth is kept at 10 m, as in the original plan, stabilization of the flow at the sabo dam opening and other energy dissipation effects were obtained.

For③, the plan was to allow sand to be deposited on the sabo dam for scour protection of the foot of the landslide dam to serve as a sand cushion for energy dissipation. However, if the sand is fully loaded and the flow in the drifted state plunges into the energy dissipater, increased oscillation on the water surface and disturbance of the hydraulic regime may be caused by vortex flow, resulting in a conspicuous overflow from the wing. This was used as an impact basin (water cushion) to absorb the energy of the water discharged.

For ④, results showed that, if the crest portion were made into an circular arc with a radius of 5 m, the negative pressure would be resolved. These studies were used to determine the structure of the sabo dam and overflow channel.

6. Conclusion

We introduced the topics of urgent countermeasures, damage suffered during a flood season, policies pertaining to countermeasures, and permanent countermeasures for large-scale landslide dams.

Regarding institution of countermeasures for large-scale landslide dams, those not related to the concept of conventional erosion control are also needed. These may include application of the pipe-jacking method as a means of draining the flood reservoir or constructing a chute-type overflow channel, such as for high landslide dam in the Nagatono area. Thus, it is important to plan countermeasures suitable for a particular field condition, while also considering application of civil engineering technologies intended for purposes other than erosion control.

We will be satisfied if this paper proves to be useful for technical improvement of future countermeasures for large-scale landslide dams.

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