Hydrological Observation of Subsurface flow spouting from Pipe Exits in Torrent Bed Material and its Triggering Rainfall Condition of the Nishinokaito River in Mount Fujiwara, Mie Prefecture, Japan

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Several pipe exits were discovered in the torrent bed material in debris flow generation areas of the Nishinokaito River, Mount Fujiwara ,Mie prefecture, Japan. They were emplaced in a sand and gravel layer between 1.0 and 1.5 m below the surface of the torrent bed material. Gravel supported the internal walls of the pipe exits. Subsurface flows spouted when the rainfall intensity exceeded about 5 to 7 mm in 10 minutes and the soil water index exceeded about 110 mm. Hydrological processes such as subsurface flows spouting from pipe exits and its clogging, subsurface flows spouting at the new pipe exits during heavy rainfall may lead to debris flow generation. The critical rainfall thresholds for them were studied using radial basis function network (RBFN) method.

Key words: torrent bed material, subsurface flow spouting, hydrological observation, radial basis function network

1. Introduction

A debris flow occurred at Nishinokaito River on Mount Fujiwara, Inabe City, Mie Prefecture(hereafter referred as the "Nishinokaito River") from September 2 to 3. 2008 (hereafter referred as the "2008 Debris Flow." According to the photo analysis of the hydrological process leading up to the generation of the debris flow, the phenomena such as an increase in discharge and turbidity of the subsurface flows from the cross-section of torrent bed material (in this paper, this is defined as the same as the water spouting from pipe exits), the clogging of pipe exits, subsurface flows spouting from several places and the collapse of torrent bed material of the cross-section of torrent bed material (excavation cross-section area for the sabo dam construction) were observed by the generation time of debris flows

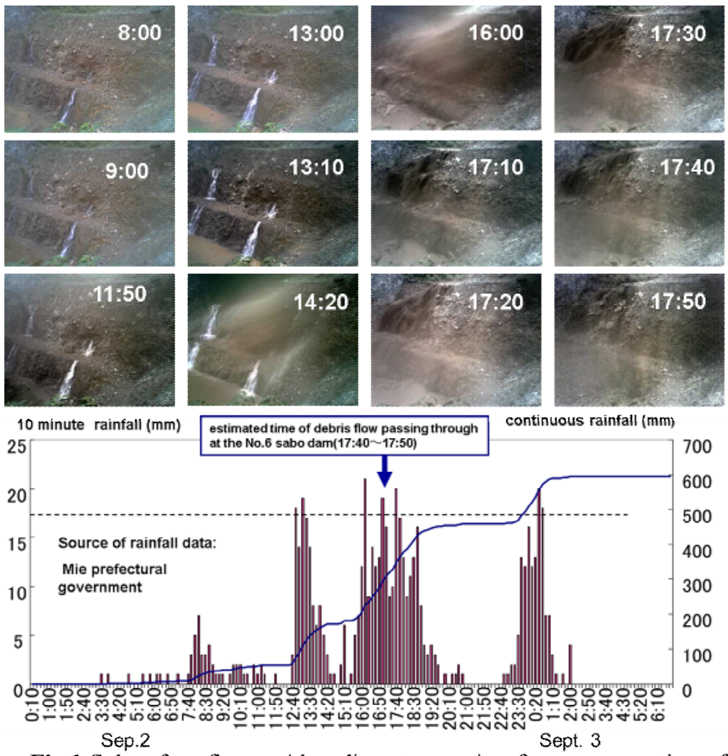

Fig.1 Subsurface flows with sediment spouting from cross section of torrent river bed material just before debris flow generation (taken on September 2, 2008)

[*Yamada et al.*, 2009] (Fig.1). From these facts it is known that when the subsurface flows spouted, pipe flows occurred within the torrent bed material. Therefore, these hydrological phenomena are considered to be important for the study on the generation process of the torrent bed scouring - induced debris flow at Nishinokaito River.

Several models of the generation of torrent bed scouring - induced debris flow have been proposed by the theoretical study[*Takahashi*,1977] which, due to the difficulty of onsite hydrological observation, are based mainly on hydraulic model experiments and numerical simulation. A few observations around debris flow generation areas have been made[*Berti et al.*,1999], however, the targets of these observations were mainly the flowing conditions and its hydraulic characteristics of sediment discharge after the generation of debris flow. In recent years, there has been study clarifying that saturated and unsaturated zones mixed within the torrent bed material during heavy rainfall, and that infiltration flows were flowing down through parts of the sediment deposit layers[*Mizutani et al.*,2008] through the observations of rainfall and pore water pressure. However, the process of hydrological phenomena leading to the generation of debris flow has yet to be clarified and no quantitative evaluation of the conditions for generation has been made.

It is extremely important to clarify the generation of pipe flow during heavy rainfall as well as the related hydrological phenomena that follow for the purpose of the prediction of debris flow generation.

The purpose of this study is to clarify an actual situation of pipe exits in the torrent bed material in Nishinokaito River and that of the subsurface flows spouting from these pipe exits during heavy rain and to consider the critical rainfall thresholds for pipe flow and debris flow generation .

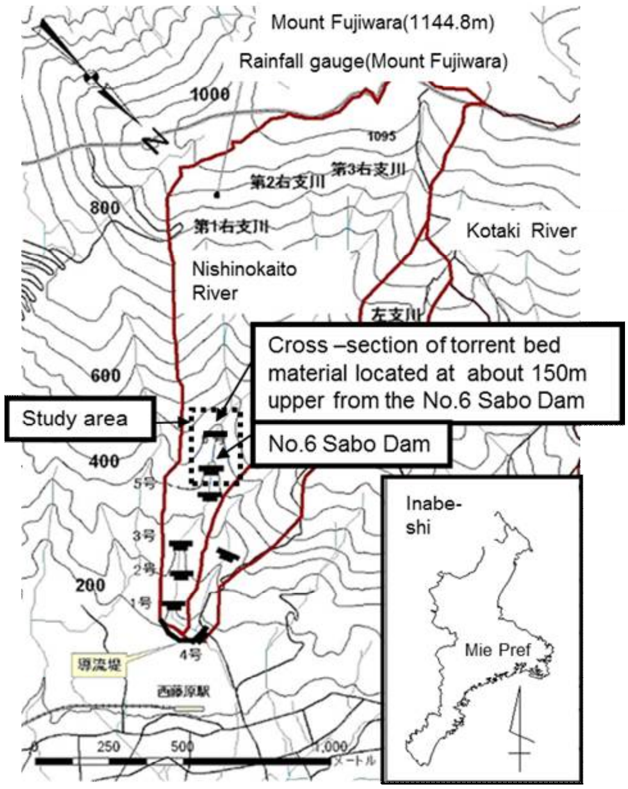

Fig.2 Study area

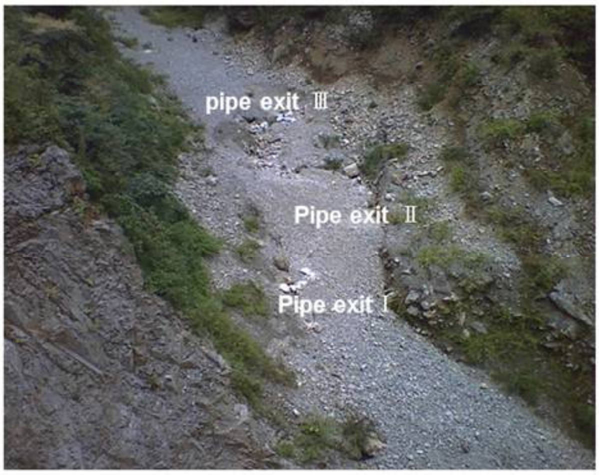

Fig.3 Exposed pipe exits(Ⅰ ～Ⅲ) at the torrent bed material due to its scouring on October 24, 2008

2. Study Method

Study area was the upstream of the No. 6 sabo dam of Nishinokaito River (Fig. 2). The basin area of study area was approximately 0.75 m^2, the average gradient was 24.3 degrees and the geology was limestone of Mesozoic-Paleozonic layer (refer to a previous report[1)] for more information). A part of torrent bed material (width: approximately 20 m, average gradient: 24 degrees) of the immediate upstream of No. 6 sabo dam collapsed about 10 m in length(no debris flow generated this time) due to the heavy rainfall on October 24, 2008 (maximum 10 minute rainfall: 6 mm, maximum hourly rainfall: 24 mm, and total amount of continuous rainfall: 174 mm), exposing the torrent bed material cross-section and allowing the confirmation of three pipe exits (“Pipe exit I”, “pipe exit II” and “pipe exit III” from downstream) (Fig.3). In 2009, the positions of the exits of these pipes were measured and the areas surrounding the pipe exits, as well as their internal structure were observed using a borehole camera (Mini Sea Snake (KDM200SLM), diameter of camera head: ϕ 35 mm). Using pipe exit I, the one furthest downstream, as a baseline, pipe exit II and pipe exit III showed the ratio of +2.2 m and +4.9 m, respectively. The slope distance between pipe exit I and pipe exit II was approximately 8 m, and that of between pipe exit I and pipe exit III was approximately 15 m. It could be confirmed from the photos that the depths of pipe exits I and III were approximately 1 m from the surface of torrent bed material while pipe exit II was approximately 1.3 m. According to the results of the boring investigation [7] at approximately 60m upstream from the locations where the above-mentioned pipe exits were exposed, the deposit depth of torrent bed material was approximately 9.6 m (the layer under it was a bed rock of limestone). There were mainly sub-angular breccias of ϕ 2-3 mm and coarse and medium coarse sands, partly mixed with cohesive soil from the surface to the depth of 3 m, under which there was a layer of approximately 1 m of sandstones mixed with cobbles. Although the deposit stratigraphy in the neighborhood of the above-mentioned pipe exits has not been investigated, the deposit stratigraphy where pipe exits existed can be considered to be mainly composed of sand gravels by the results of the boring investigation conducted at the immediate upstream area and from the observation of the cross section of deposits in the areas surrounding the surface exposed by the collapse of the torrent bed material.

In order to clarify the hydrograph of subsurface flows from these pipe exits, a stainless flume (width: 10 cm, height: 30 cm and length: 40 cm) was placed in the vicinity of each pipe exit in July 2010. From the observations using an interval camera, so far, granules and fine sands often spouted from the pipe exits together with the subsurface flows. Therefore, in order for the flow in a flume to flow in natural condition as much as possible, fast-dry instant cement (as rough as fine sand) was spread on the bottom plate of the flume. The gradients of the fumes placed in the areas surrounding pipe I, II and III were 12.1 degrees, 15 degrees and 12.9 degrees, respectively (the relationship between water level and discharge had been previously clarified by a hydraulic model test). In order to take the photos of water levels at the exits of flumes, an interval cameras (KADEC21-EYE II and Brinno Garden WatchCam) was set at approximately 2-3 m downstream of each flume (Fig.4). The serial shoot duration of these cameras is 10 minutes. In addition, two interval cameras (KADEC21-EYEII, Brinno Garden WatchCam) were placed at the wing crown of the No. 6 sabo dam to take the wide area photos of the conditions of subsurface flows sprouting from these pipe exits during heavy rainfall (the serial shoot duration is 10 minutes). These interval cameras are not designed to be used at night and they cannot be used about approximately from 18:00 to 06:00 of the following day in spring and autumn, and approximately from 19:00 to 05:00 of the following day in summer. Since July 2011, the immediate upstream region of the No. 6 sabo dam was filled with sediment to be used as construction machine carrying road for the groundsel, thus making it impossible to observe pipes I, II and III. Therefore, since then, both occurrence and the duration times of the subsurface flows have been observed from spouting from pipe exists recognized on the cross-section of torrent bed material (excavated for groundsel construction). Fig.5 shows the cross-section of torrent bed material. The pipe exits here exist at a depth of approximately 1.5 m from the surface of torrent bed material. According to the results of the boring investigation conducted by the Mie prefectural government, the depth of torrent bed material in the vicinity of the center of excavation site for groundsel construction was approximately 6.6 m (the layer under it was bed rock of limestone). There were mainly sub-angular breccias of ϕ 2-50 mm and coarse and medium coarse sands, partly mixed with cohesive soil from ground surface to the depth of 5.5 m, under which there was a layer of 0.6

Fig.4 Flume and interval camera installed in the lower of pipe II exit at the torrent bed material

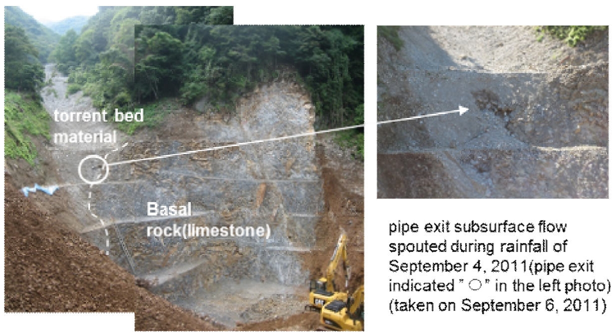

Fig.5 Cross section of excavated torrent bed material about 150 m upper from No.6 Sabo dam

m of sand and gravels of ϕ2-20 mm mixed with cohesive soil of. Further below, there was a layer of 0.6 m of sub-angular breccias of ϕ2-20 mm. The deposit stratigraphy where the pipe exits existed is considered to be similar to that of pipe exits confirmed at the immediate upstream part of the No. 6 sabo dam.

One rainfall event was defined as a single instance of rainfall during a period in which no other rainfall occurred 6 hours before or after the recorded instance. The accumulation of the rainfall within this period was determined to be continuous rainfall. The rainfall data of Mount Fujihara Observatory (Mie Prefectural Government) were used. We were able to determine the times of generation and settling using the photos of the discharge conditions taken by the interval cameras placed immediately below each pipe exit and the one placed at the wing crown of the No. 6 sabo dam. The point in time when the subsurface flow sprouting was confirmed was determined as "generation" and the point in time when the subsurface flow spouting could not be confirmed was determined as "settling."

From the above, the actual situations of the generation time, settling time and continuation period of pipe flow were revealed and the relationship between soil water index and the 10 minute rainfall intensity was studied. Furthermore, because there were only a few cases where the generation of pipe flows could be observed, the critical rainfall for pipe flow ,clogging of pipe exits and debris flow generation at Nishinokaito River was studied by using an RBFN method (Radial Basis Function Network).

In Japan, the method for establishing nonlinear Critical Line (CL) based on Radial Basis Function Network (RBFN) has been developed for the purpose of mitigating damages to local people caused by sediment-related disasters[*The Sabo (Erosion and Sediment Control) Department, River Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, the Forecast Department of the Japan Meteorological Agency and the National Institute for Land, and Infrastructure Management of the Ministry of Land, Infrastructure, Transport and Tourism, 2005*] . This method is to establish unique nonlinear CL for a target area by learning its past rainfall data statistically. It is characterized by detecting safe rainfall index by learning not only rainfall data that sediment disaster occurred (occurrence data) but also rainfall data that sediment disaster did not occur (non-occurrence data)[*Oishi et al*., 2011]. The rainfalls targeted for the analysis were 855 events from September 2002 to September 2012.

Fig.6 Exposed pipe exit Ⅱ at the torrent bed material due to its scouring on October 24, 2008 and its internal structure

3. Results and Discussion

3.1 Actual situation of pipe exits in the torrent bed material

Fig.6 shows the area surrounding pipe exit II as well as the deepest internal area that could be observed (measurable depth of the inside of pipe by borehole camera: 1.3 m). Either pipe exit I or II or III presented the structure that gravels of several decimeters in diameter with each other and supported the walls of pipe exits, and that sands and gravels of a few cm in diameter surrounded it. The internal diameters of pipe exits I, II and III were several decimeters. When the inside of the pipe exits were observed by a borehole camera, neither flowing water nor stagnant water was recognized in any pipe exit at the time of observation (Dec. 12, 2009). The inside of all pipe exits showed a cylindrical shape and it looked as though it was continuing upstream. The gradient of the bottom surface of the inside of the pipe exit measured only from the section the camera head could be inserted into was approximately 7 degrees in each pipe exit. It was revealed that, the inside of each pipe exit showed the condition that the nearly circular gravels of 10 cm-several decimeters in diameter with each other and that there were the gravels of several cm in diameter and fine article components, such as sand and granules, mixed with silt at the bottom surface of the pipe exits. By the analysis of photos obtained by the observations conducted on and after Sept. 2, 2009, it was revealed that the more the subsurface flow spouting from the cross-section of torrent bed material increased, the more the turbidity increased [*Yamada et al*., 2009]. This is considered to be caused by the sediment mixed with silt at the bottom surface of the pipe outflow when the subsurface water concentrate into a pipe and its discharge becomes large.

3.2 Actual situation of subsurface flow spouting from pipe exits

3.2.1 Immediate upstream area of the No. 6 sabo dam

Fig.7 shows the condition of the subsurface flow spouting from each pipe exit caused by the rainfall of Aug. 9, 2010 (hereafter referred to as “rainfall event I). These photos show subsurface flow spouting from each pipe exit observed during 8:00-12:20. Subsurface flows started spouting from pipe exits II and III in 8:00, followed by pipe exit I at 8:10. The amount of water spouting from each pipe exit appears to be increasing until 9:00. It was confirmed that the subsurface flows started spouting from each pipe exit almost simultaneously, and that the subsurface flow spouting from pipe exit I ceased at 11;10 while those from pipe II and III at 12;20. The torrent bed material immediately below pipe exit I collapsed downstream several meters in length and several meters in width when the discharge of subsurface flow increased during the period between 9;00 and 9;20.

Fig.7 Subsurface flow spouting from pipe exits of torrent bed material on August 8, 2010

Fig.8 shows the soil water index, continuous rainfall, amount of rainfall for ten minutes, times of generation and settling and spouting duration at each pipe exit during rainfall event I. Fig.9 shows the rainfall in Aug. 12, 2010 (hereinafter referred to as “rainfall event II”) and Fig.10 shows the case of rainfall in May 29, 2011 (hereinafter referred to as “rainfall event III”).

The continuous rainfalls when the subsurface flow spouted from pipe exits at the rainfall invents I, II and III were 97-101 mm、66-67 mm and 126-160 mm, respectively, and the soil water indexes (structure of tank model, values of each parameter and calculation method were the same as those previously reported by the Mie prefectural government) were 122.5 mm. 125.4 mm and 109-130 mm, respectively. Although the values of the continuous rainfall until subsurface flow began to spout from pipe exits at the rainfall events I, II and III varied, it is characteristic that subsurface flow spouting is generated at a soil water index about 110 mm-125 mm.

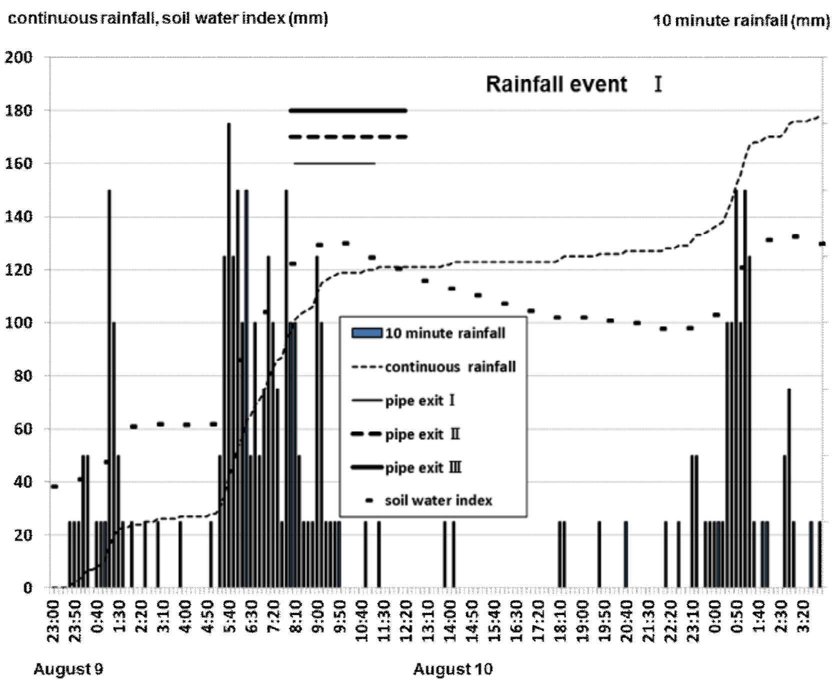

Fig.8 Actual situation of subsurface flow spouting from pipe exits of torrent bed material on August 9, 2010

The duration time of the subsurface flow spouting from pipe exit I at the rainfall event I was 3 hours. The subsurface flow spouting from both pipe exits II and III were 4 hours and 20 minutes; longer than the case of pipe exit I. During rainfall event II, the duration time of subsurface flow spouting from pipe exit I was 2 hours and 30 minutes and those from pipe exits II and III were 5 hours 18 minutes and 1 hour and 57 minutes, respectively. During rainfall event III, the duration time of subsurface flow spouting from pipe exit I was 3 hours, and those from pipe exits II and III were both 4 hours 10 minutes; longer than that from pipe exit I.

During the rainfall events I and II, several hours before the spouting from pipe exits, it was intermittently relatively heavily raining; 5-7 mm in 10 minutes. At the rainfall event III, immediately before the spouting from pipe exits, it continued to rain 1-3 mm in 10 minutes, after which it rained 5-7 mm in 10 minutes; equivalent to the approximate peak value in 10 minutes.

Fig.11 shows the the rainfall event II, where a hydrograph of the subsurface flow from pipe exit was obtained (as for rainfall events I and III, there were some observation problems such as that sediment were deposited in the flume and the subsurface flow flew out of the flume). The hydrograph of each pipe exit shows a relatively sharp shape. The peak discharge and total discharge of the subsurface flow spouting from each pipe exit were largest in pipe exit II (the depth from soil surface was deeper than those of other two pipe exits at 1.5 m level) and those of pipe exit III were a little larger than those of pipe exit I. The generation times of the peak discharge of subsurface flow spouting from pipe exits were 11:11 for pipe exit I and II and 10:47 for pipe exit III.

At this moment, there are only a few case examples of the observation of the subsurface flows from pipe exits and the developmental states of a pipe in the torrent bed material has not yet been made clear. Thus, the relationship between the generating location of a pipe exit and the generation time, settling time and duration time of the subsurface spouting from the pipe exit is not clear. Their influence on the peak flow rate and total flow are also unknown. Although the inner diameter of each pipe exit as well as the gravels structuring the pipe exits were similar, as shown in Fig. 5, the peak discharge and total discharge of pipe exits I, II and III were different. Factors contributing to the degree of water gathering in the pipe and its ability to flow down the subsurface flow within the pipe are considered to be the development length of pipe, cross sectional configuration, gradient variation, the flow in a circular pipe under the condition of a full water level and a pressure gradient in the case when a Hagen-Poiseuille flow is assumed.

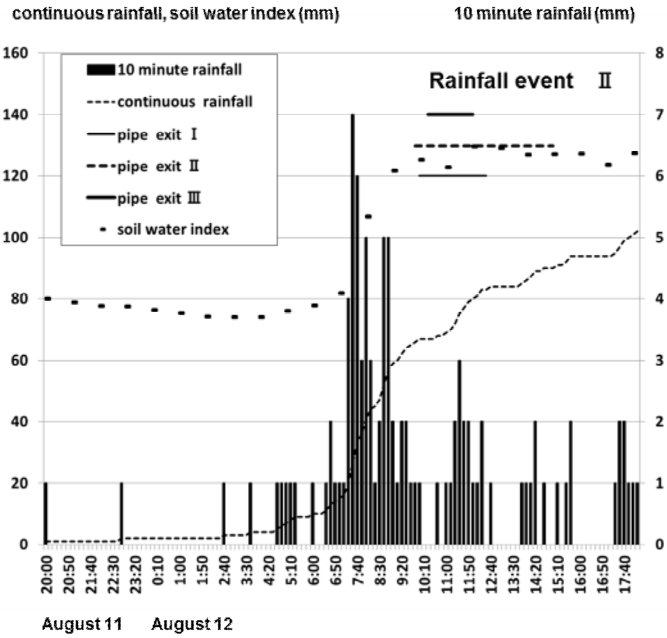

Fig. 9 Actual situation of subsurface flow spouting from pipe exits of torrent bed material on August 12, 2010

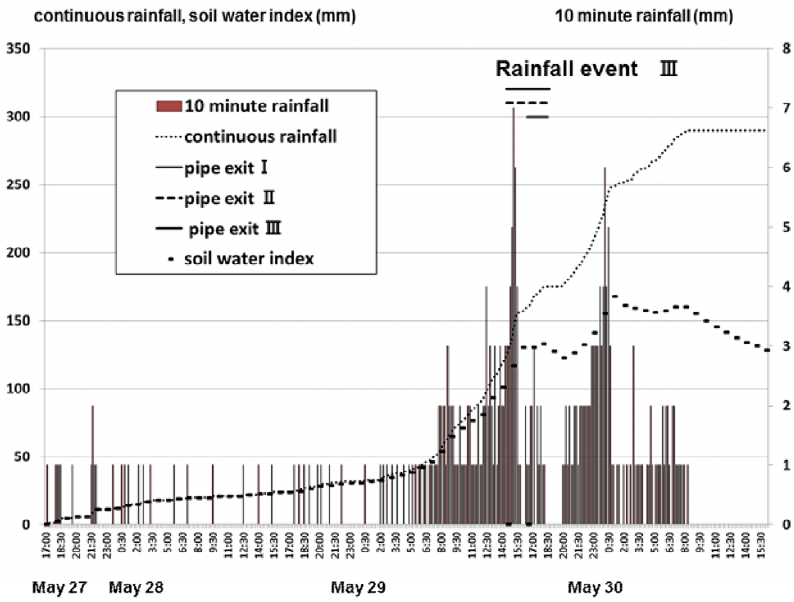

Fig. 10 Actual situation of subsurface flow spouting from pipe exits of torrent bed material on May 29, 2011

3.2.2. Actual situation of the subsurface flow spouting from the cross section of torrent bed material and the clogging of pipe exits at the No. 6 sabo dam 150 m upstream

Fig.12, Fig.13 show the generation times of subsurface flows spouting from pipe exits at time of rainfall (typhoon No. 12) of September 3-5, 2011. The subsurface flows spouting from pipe exits generated immediately after the peak of 142 mm continuous rainfall, 120.7 mm soil water index and rainfall intensity for 10 minutes. Due to the interval cameras specification, photos after 18:00 on September 4 were not able to be obtained. Therefore, the situation of the subsurface flows spouting from pipe exits after the time cut off and settling are unknown .The subsurface flows from pipe exits were settled in accordance with the photo of 6:00 of Sept. 5.

During the rainfall event of June 19, 2012, phenomena ranging from the subsurface flow spouting from the pipe exit, to the sediment discharge, to the clogging of the pipe exit, to the collapse of the cross section excavated for groundsel construction were observed 150 m upstream of the No. 6 sabo dam. Results of photo analysis of these phenomena suggested that the collapse was triggered by the subsurface flows spouting from new places caused by the clogging of the original pipe exits.

3.3 Critical rainfall thresholds for pipe flow and debris flow using an RBFN method

In case of 10 minute rainfall data using, the optimum critical rainfall threshold for pipe flow generation could be determined on the condition that the RBFN value was 0.9, however, the hit rate for occurrence rainfall, 28.5%, was low. The optimum critical rainfall threshold for debris flow generation could be determined on the condition that the RBFN value was 0.6 with a hit rate for occurrence rainfall of 87.5% and a hit rate for non-occurrence rainfall of 22.2%. Both hit rate are respectively defined as follows:

Hit rate for occurrence rainfalls = number of occurrence rainfalls exceeding CL / number of all occurrence rainfalls

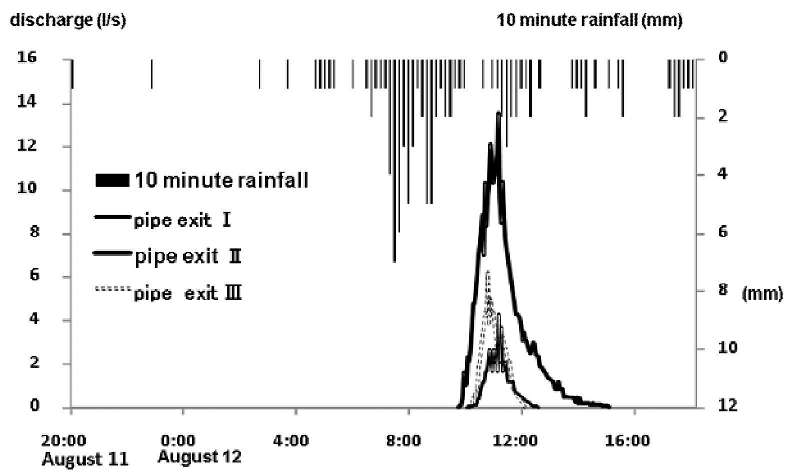

Fig.11 hydrograph of subsurface flow spouting from pipe exits of torrent bed material on August 12, 2010

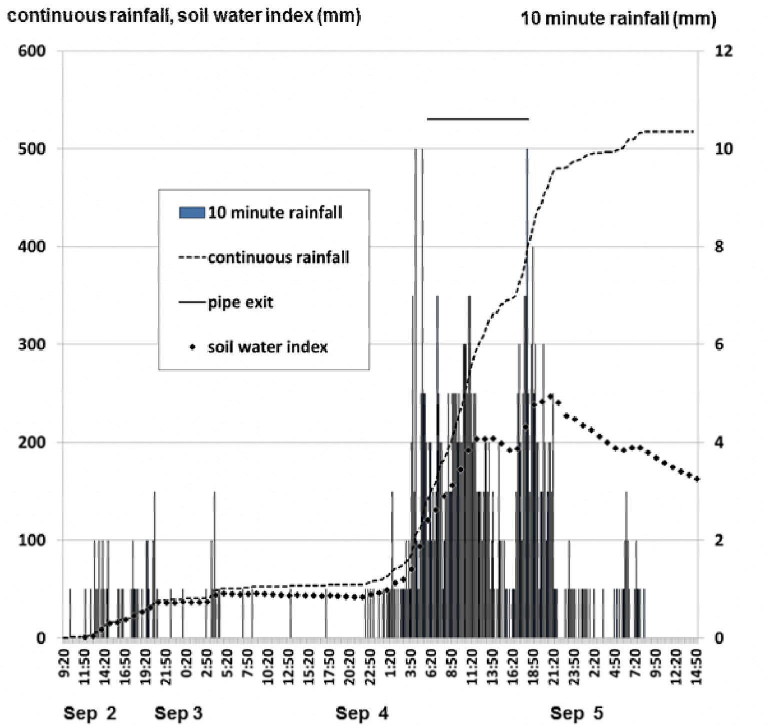

Fig.12 Actual situation of subsurface flow spouting from pipe exits of torrent bed material on September 4 , 2011

Fig.13 Subsurface flow spouting from pipe exit of torrent bed material on September 4, 2011

Hit rate for non-occurrence rainfalls= number of non-occurrence rainfalls not exceeding CL / number of all non-occurrence rainfalls

In case of hourly rainfall data using, the optimum critical rainfall threshold for pipe flow generation could be determined on the condition that the RBFN value was 0.7 with a hit rate for occurrence rainfall of 85.7% and a hit rate for non-occurrence rainfall of 0%. The optimum critical rainfall threshold for debris-flow generation could be determined on the condition that the RBFN value was 0.6 with a hit rate for occurrence rainfall of 100% and a hit rate for non-occurrence rainfall of 43%. (Fig. 14).

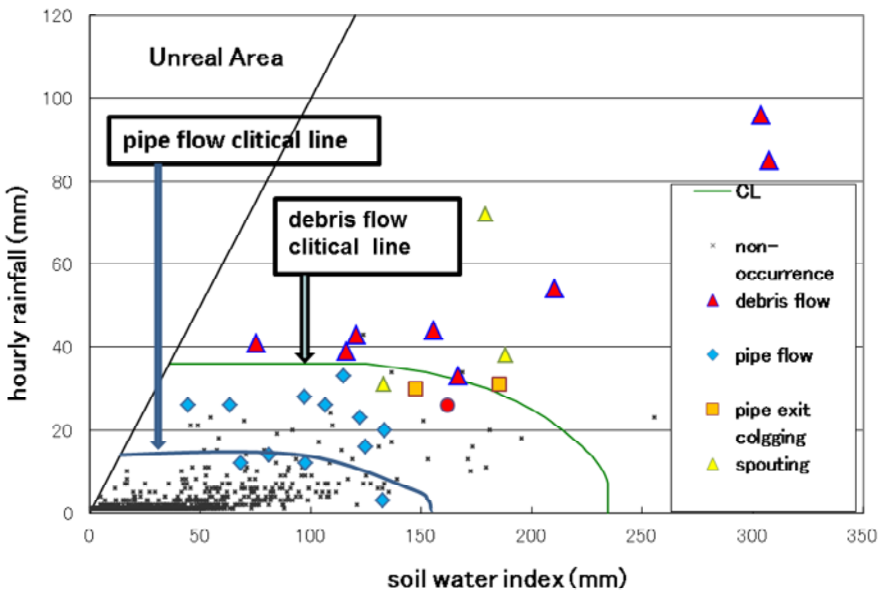

Fig.14 Critical rainfall threshold for pipe flow and debris flow generation determined by the RBFN

According to Fig. 14, it can be said that, even if a pipe flow generates, there is a time lag before the generation of debris flow (the difference in the maximum rainfall amount: 13 mm, difference in soil water index: 74.9 mm), therefore, it does not lead to debris flow immediately. When the rainfall becomes close to the critical rainfall needed for debris flow, the clogging of the pipe tends to occur. The subsurface flows spouting from new places caused by the clogging of pipe exits that are observed in normal time are considered to lead to the destabilization and collapse of torrent bed material (generation of debris flow).

4. Conclusion

This study clarified the following:

1) There are a number of pipe exits on the cross-section of torrent bed material exposed by its collapse at the immediate upstream part of the No. 6 sabo dam of Nishinokaito River. The depths of the pipe exits were confirmed to be around 1.0-1.5 m from the surface of the torrent bed material (mainly sand and gravel).

2) The sub-angular breccicas of 10 cm to several decimeters in diameter with each other on the exit. The inner diameters of all pipe exits were several 10 cm. There were also gravels of several cm as well as sand mixed with silt on the bottom surface of the pipe exit.

3) Although there was no big difference between the inner diameters and structures of the surrounding areas of each pipe exit, there were differences in the generation time, settling time, spouting duration, peak discharge and total discharge of the subsurface flow spouting from each pipe exit.

4) The critical rainfall thresholds for the generation of pipe and debris flows were studied using an RBFN method. Although pipe flow does not generate debris flow immediately, it can be considered from the results that when rainfall comes close to the critical rainfall threshold for debris flow, the clogging of the pipe tends to occur. If subsurface flows spout from other places caused by the clogging of the pipe exit, the torrent bed material is destabilized and its collapse (generation of debris flow) occurs.

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