Original Article

Hydrological Observation of Subsurface Flows Spouting from Pipe Exits in Torrent Bed Material and its Triggering Rainfall Conditions 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. These exits were 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 5 to 7 mm in 10 minutes and the soil water index exceeded about 110 mm. Due to hydrological processes, subsurface flows spouting at the new pipe exits during heavy rainfall may lead to debris flow generation. We studied the critical rainfall thresholds using the radial basis function network (RBFN) method.

Keywords: 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") on September 2 to 3, 2008. (Hereafter, it is referred as the "2008 Debris Flow".) A photo analysis of the hydrological process leading up to the generation of the debris flow showed an increase in discharge and turbidity of the subsurface flows from the cross-section of the torrent bed material [*Yamada et al*., 2009]. (In this paper, this is defined as water spouting from pipe exits.) Due to clogged pipe exits, subsurface flows spouted from several places, and a cross-section of torrent bed material collapsed (excavation cross-section area for the Sabo Dam construction) [*Yamada et al*., 2009] (**Fig. 1**). These observations indicate that when subsurface flows spout, pipe flows occur within the torrent bed material. Therefore, these hydrological phenomena should be studied to elucidate the process for generating torrent bed scouring-induced debris flow at the Nishinokaito River.

Several models to generate torrent bed scouring-induced debris flow have been proposed by a theoretical study [*Takahashi*, 1977]. However, due to difficulties of onsite hydrological observations, the study is based mainly on hydraulic modeling experiments and numerical simulations. Since then, only a few studies have observed areas of debris flow generation [*Berti et al*., 1999; *Berti and Simoni*, 2005; *Imaizumi et al.*, 2006; *Coe et al.*, 2008; *Gregoretti and G. Dalla*, 2008]; however, the targets of these limited observations have centered around flowing conditions and the hydraulic characteristics of sediment discharge after channel runoff or small scale debris flow. Recently, a study on the rainfall and pore water pressure demonstrated that the saturated and unsaturated zones are mixed within the torrent bed material during heavy rainfall and that infiltration flows flow down through parts of the sediment deposit layers [*Mizutani et al*., 2008]. However, the hydrological phenomena that generate a debris flow have yet to be clarified and the necessary conditions have yet to be quantitatively evaluated.

To accurately predict debris flow generation, it is

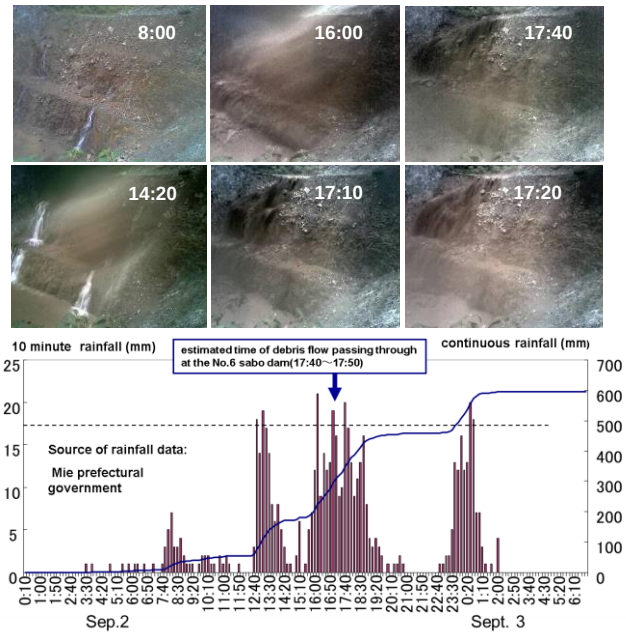

Fig. 1 Subsurface flows with sediment spouting from cross section of torrent river bed material just before debris flow generation (taken on September 2, 2008)

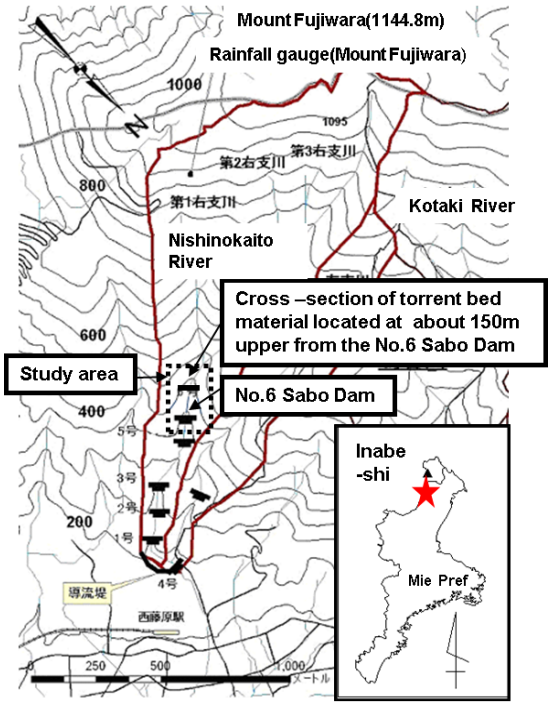

Fig. 2 Study area

extremely important to clarify how pipe flow is generated during heavy rainfall as well as subsequent related hydrological phenomena.

The purpose of this study is to observe pipe exits in the torrent bed material at the Nishinokaito River as well as subsurface flows spouting from these pipe exits during heavy rain. We then consider the critical rainfall thresholds for pipe flow and debris flow generation.

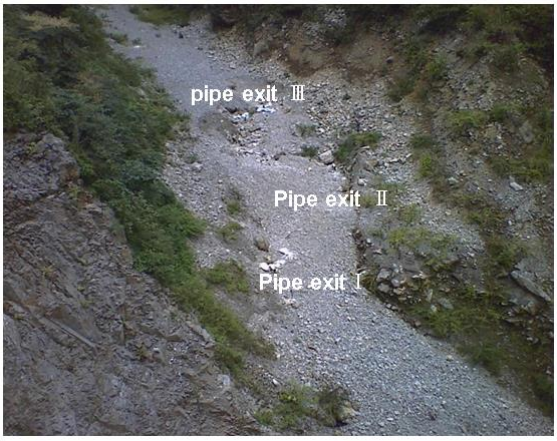

Fig. 3 Exposed pipe exits (I~III) at the torrent bed material due to its scouring on October 24, 2008

2. STUDY METHOD

The study area was the upstream section of the No. 6 Sabo Dam of Nishinokaito River (**Fig. 2**). The basin in the study area consisted of a Mesozoic-Paleozoic limestone layer with an area of approximately 0.75 km^2 and an average gradient of 24.3 degrees. (See previous report for more information [*Yamada et al*., 2009].) Due to 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), about a 10-m section of the torrent bed material (approximately 20 m wide, average gradient: 24 degrees of the immediate upstream section of No. 6 Sabo Dam) collapsed, but no debris flow was generated at that time.

This exposed torrent bed material cross-section allowed three pipe exits (pipe exits I, II, and III) to be identified (**Fig. 3**). In 2009, the positions and surrounding areas of these pipe exits was measured. The internal structure of the exits were observed using a borehole camera [Mini Sea Snake (KDM200SLM), diameter of camera head: φ 35 mm]. The furthest downstream pipe exit, exit I, was used as a baseline. When compared to the baseline, pipe exits II and III were positioned higher by 2.2 m and 4.9 m, respectively. The slope distance between pipe exit I and pipe exit II was approximately 8 m; between pipe exit I and pipe exit III it was approximately 15 m. The photos confirmed 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.

The borehole camera revealed a deposit depth of the torrent bed material of approximately 9.6 m, 60 m upstream from where the pipe exits were exposed (the layer under it was a bed rock of limestone[*Kuwana Construction Office, Mie*

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

Prefectural Government, 2010]). The deposit was mainly composed of sub-angular breccias of φ 2-3 mm, and coarse and medium-coarse sands partly mixed with cohesive soil between the surface of the deposit to a depth of 3 m. Below this surface was a layer of approximately 1 m of sandstones mixed with cobbles. Although the deposit stratigraphy in the neighborhood of the pipe exits was not investigated, the deposit stratigraphy where the pipe exits was likely composed of sand gravel given the images from the camera immediately upstream of the exits and from cross-sections observations of the deposits.

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 near each pipe exit in July 2010. Interval camera observations indicate that thus far, granules and fine sands often spouted from the pipe exits together with subsurface flows. In order for the flume to flow under natural conditions as much as possible, we spread fast-drying instant cement (as rough as fine sand) on the bottom plate of the flume. The gradients of the flumes placed in pipe I, II, and III were 12.1 degrees, 15 degrees, and 12.9 degrees, respectively. (The relationship between the water level and discharge was previously clarified by a hydraulic model test.)

To acquire photos of the water levels at the exits of the flumes, interval cameras (KADEC21-EYE II and Brinno Garden WatchCam) were set approximately 2-3 m downstream of each flume (**Fig. 4**). The cameras acquired photos in 10-minute intervals. In addition, two interval cameras were

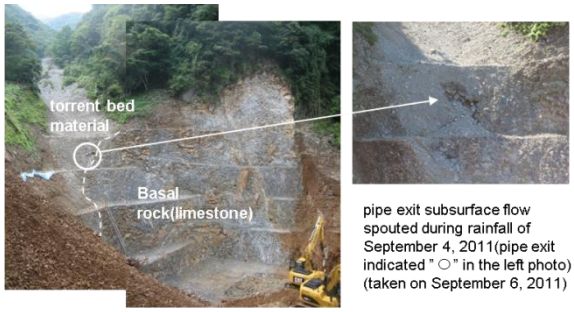

Fig. 5 Cross section of excavated torrent bed material about 150 m upper from No. 6 Sabo dam

placed at the wing crown of the No. 6 Sabo Dam to take panoramic photos of subsurface flows spouting from these pipe exits during heavy rainfall at 10-minute intervals. Since July 2011, the immediate upstream region of the No. 6 Sabo Dam has been filled with sediment in order to construct a machine-carrying road. Thus, it has been impossible to observe pipes I, II, and III. Consequently, both the occurrence and the duration time of the subsurface flows were observed from the pipe exits on the cross-section of the torrent bed material (excavated for construction).

Figure 5 shows a cross-section of the torrent bed material. The pipe exits were at a depth of approximately 1.5 m from the surface of the torrent bed material. The results of the investigation conducted by the Mie prefectural government showed that the depth of the torrent bed material in the vicinity of the center of the excavation site for groundsel construction is approximately 6.6 m. (The layer under it is a bed rock of limestone.) The material was mainly composed of sub-angular breccias of φ 2-50 mm, and coarse and medium-coarse sands partly mix with cohesive soil between the ground surface to a depth of 5.5 m. Under this layer, a 0.6-m layer of sand and gravel of φ 2-20 mm mixed with cohesive soil, and below that was a 0.6-m layer of sub-angular breccias of φ 2-20 mm. The deposit stratigraphy of the pipe exits was similar to the pipe exits confirmed at the immediate upstream section of the No. 6 Sabo Dam.

To determine the relationship between the soil water index and the 10-minute rainfall intensity, we defined a rainfall event as a single instance of rainfall without any other rainfall within 6 hours before and after the recorded instance. The accumulated rainfall within this period was determined to be continuous rainfall. We used the rainfall data from the Mount Fujihara Observatory (Mie Prefectural Government) to determine when spouting started and stopped using photos of the discharge conditions from the cameras, which acquired an image every 10 minutes. The point in

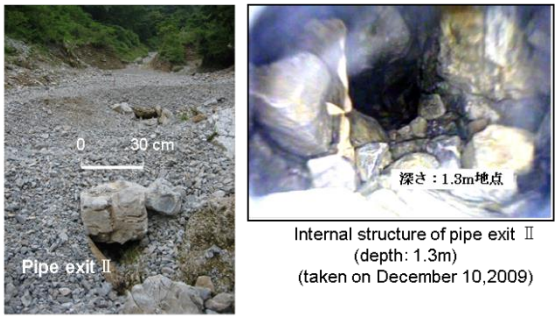

Fig. 6 Expose pipe exit II at the torrent bed material due to its scouring on October 24, 2008 and its internal structure

time when subsurface flow spouting started and stopped was considered to be the “generation” and "settling," respectively.

Using the data above, we determined the relationship between the soil water index and the 10-minute rainfall intensity. Furthermore, because only a few cases where the generation of pipe flows could be observed, we used the RBFN (Radial Basis Function Network) method [*Oishi et al*., 2011] to determine the critical rainfall for pipe flow, clogging of pipe exits, and debris flow generation at the Nishinokaito River.

In Japan, the method to establish a nonlinear Critical Line (CL) based on the RBFN has been developed to mitigate damage to the 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 can also be employed to establish a unique nonlinear CL for a target area using statistics from past rainfall data. This method is characterized by detecting a safe rainfall index by considering rainfall data resulting in a sediment disaster (occurrence data) as well as rainfall data without any adverse effects (non-occurrence data) [*Oishi et al*., 2011].

To establish the threshold for the critical rainfall for debris flow and pipe flow (subsurface flow spouting), we employed the RBFN methods. The rainfalls targeted for the CL analysis for debris flow and pipe flow (subsurface flow spouting) were 855 events from September 2002 to September 2012 and 60 events from May 2010 to September 2012, respectively.

3. RESULTS AND DISCUSSION

3.1 Actual situation of the pipe exits in the torrent bed material

Figure 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). All pipe exits contained gravel, which was several decimeters in diameter, supporting the notion that the walls of the pipe exits are surrounded by a few cm of sand and gravel. 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 identified (Dec. 12, 2009). The inside of all pipe exits showed a cylindrical shape that appeared to continue upstream. The gradient of the bottom surface of the inside of the pipe exit was approximately 7 degrees.

The photos revealed that the inside of each pipe exit contained nearly circular gravel pieces measuring 10 cm in diameter, several cm in diameter, and fine particle components such as sand and granules mixed with silt at the bottom surface of the pipe exits. Analysis of the photos obtained on and after Sept. 2, 2009 revealed that increasing subsurface flow spouting from the cross-section of the torrent bed material increased the turbidity [*Yamada et al*., 2009]. This behavior was attributed to mixing of sediment with silt at the bottom surface of the pipe outflow when the subsurface water was concentrated into a pipe and its discharge became large.

3.2 Actual situation of subsurface flow spouting from pipe exits

3.2.1 Area immediately upstream of the No. 6 Sabo Dam

Figure 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), between 8:00-12:20. Subsurface flows started spouting from pipe exits II and III at 8:00, and pipe exit I started spouting at 8:10. The amount of water spouting from each pipe exit appeared to increase until 9:00. We confirmed that the subsurface flows started spouting from each pipe exit almost simultaneously, and that the flow ceased at 11:10 for pipe exit I and at 12:20 for pipe exits II and III. The torrent bed material immediately below pipe exit I collapsed downstream when the discharge of subsurface flow increased between 9:00 and 9:20, damaging an area measuring several meters in length and width.

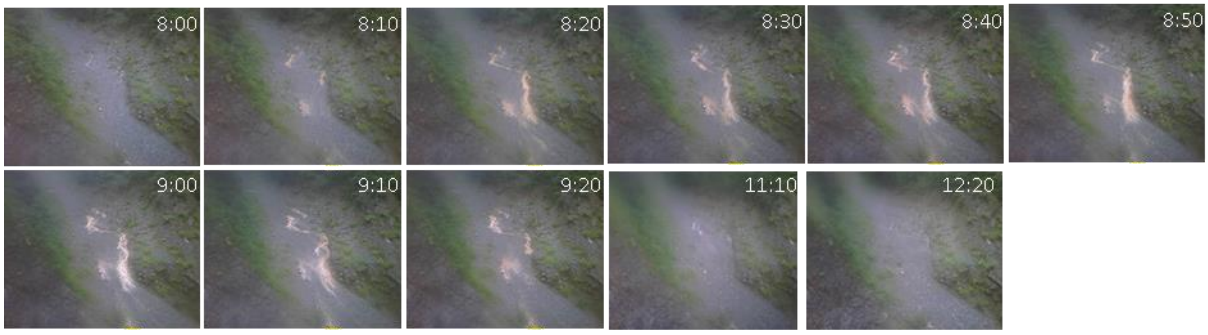

Fig. 7 Subsurface flow spouting from pipe exist of torrent bed material on August 8, 2010

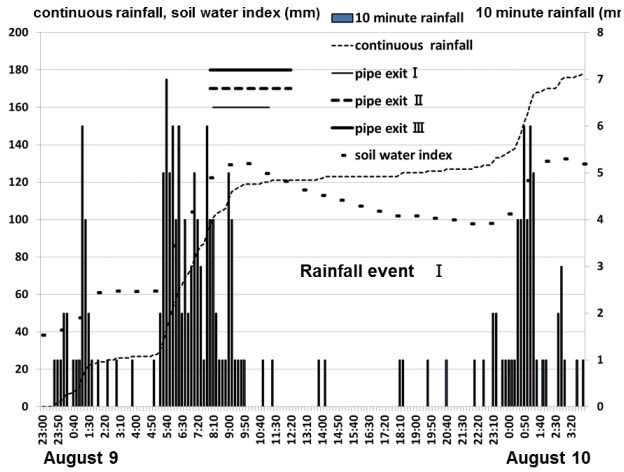

Fig. 8 Actual situation of subsurface flow spouting from pipe exist of torrent bed material on August 9, 2010

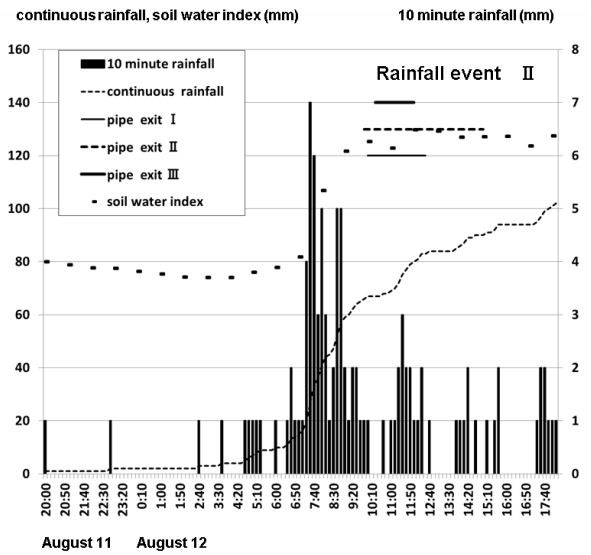

Fig. 9 Actual situation of subsurface flow spouting from pipe exist of torrent bed material on August 12, 2010

Figure 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. **Figure 9** shows the rainfall on Aug. 12, 2010 (hereinafter referred to as rainfall event II), while **Fig. 10** shows the same data for the rainfall in May 29, 2011

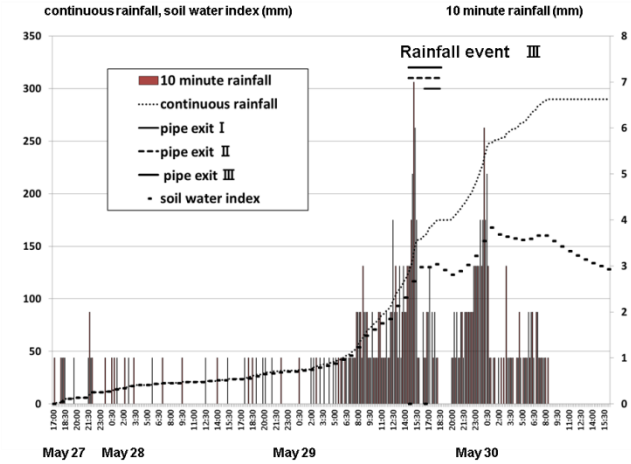

Fig. 10 Actual situation of subsurface flow spouting from pipe exist of torrent bed material on May 29, 2011

(hereinafter referred to as rainfall event III).

The continuous rainfalls when the subsurface flow spouted from pipe exits during rainfall events I, II, and III were 97-101 mm, 66-67 mm, and 126-160 mm, respectively, while the soil water indices (structure of tank model, value of each parameter, and calculation method were the same as those previously reported by the Mie prefectural government [*Mie Prefectural Government*, 2003]) were 122.5 mm, 125.4 mm, and 109-130 mm, respectively. Although the values of the continuous rainfall varied by event, subsurface flow spouting was generated at a soil water index of about 110 mm-125 mm.

The duration of the subsurface flow spouting from pipe exit I during rainfall event I was 3 hours. The subsurface flow spouting from both pipe exits II and III were 4 hours and 20 minutes, which was longer than the duration for pipe exit I. During rainfall event II, the duration of subsurface flow spouting from pipe exit I was 2 hours and 30 minutes compared to 5 hours 18 minutes and 1 hour and 57 minutes for pipe exits II and III, respectively. During rainfall event III, the duration of subsurface flow spouting from pipe exit I was 3 hours, but was 4 hours 10 minutes for pipe exits II and III.

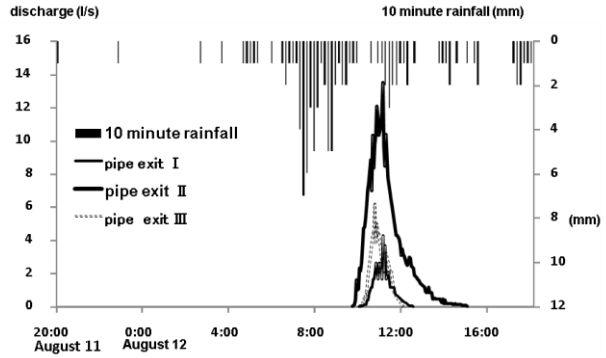

Fig. 11 Hydrograph of subsurface flow spouting from pipe exist of torrent bed material on August 12, 2010

During rainfall events I and II, intermittent heavy rain (5-7 mm in 10 minutes) occurred for several hours before spouting was confirmed from the pipe exits. During rainfall event III, immediately prior to spouting from the pipe exits, the rain fell at a rate of 1-3 mm in 10 minutes, after which it rained 5-7 mm in 10 minutes, which is equivalent to the approximate peak value in 10 minutes.

Figure 11 shows rainfall event II, where a hydrograph of the subsurface flow from the pipe exit was obtained. (For rainfall events I and III, some issues occurred with the observations, including sediment deposit in the flume and the subsurface flow flowing out of the flume.) The hydrograph of each pipe exit showed a relatively sharp curve. The peak discharge and total discharge of the subsurface flow spouting from each pipe exit were largest in Pipe exit II [the depth from the soil surface (1.5 m) was deeper than the two other pipe exits] followed by pipe exit III and I. The generation times of the peak discharge of subsurface flow spouting from pipe exits were 11:11 for pipe exits I and II, and 10:47 for pipe exit III.

To date, there are only a few examples of observations of subsurface flows from pipe exits, and the developmental states of a pipe in the torrent bed material remains unclear. Thus, the relationships between the location of a pipe exit and the generation time, settling time, and duration of subsurface spouting from the pipe exit are uncertain. Their influences on the peak flow rate and total flow are unknown. Although the inner diameter of each pipe exit as well as the gravel at the pipe exits are similar, as shown in **Fig. 5**, the peak discharge and total discharge of pipe exits I, II, and III differ. Factors contributing to the degree of water gathering in the pipe and the ability to flow include the pipe length, cross sectional configuration, gradient variation, flow in a circular pipe under conditions of a full water level, and the pressure gradient in the case when a Hagen-Poiseuille flow is assumed.

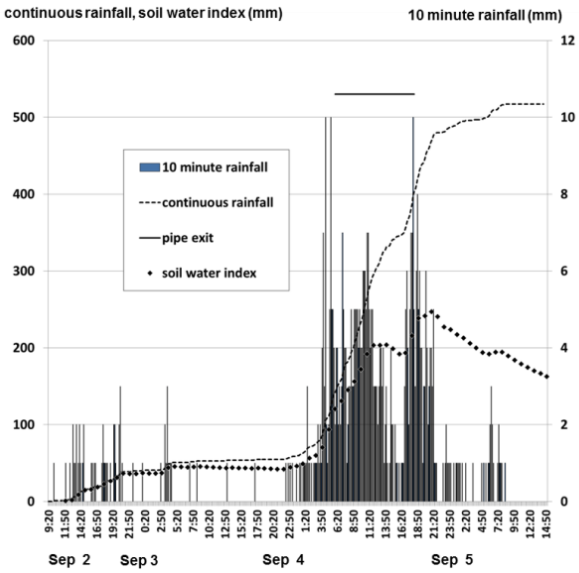

Fig. 12 Actual situation of subsurface flow spouting from pipe exist of torrent bed material 150-m upstream at the No. 6 Sabo Dam on September 4, 2011

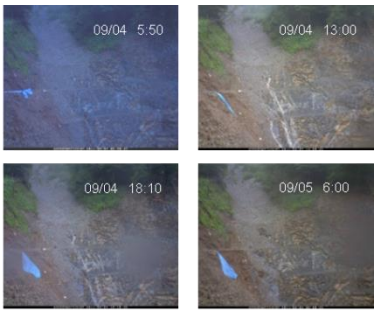

Fig. 13 Subsurface flow spouting from pipe exist of torrent bed material on September 4, 2011

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

Figures 12 and **13** show the generation times of the subsurface flows spouting from pipe exits during the rainfall (typhoon No. 12) of September 3-5, 2011. The subsurface flows spouting from pipe exits began immediately after the continuous rainfall peaked at 142 mm, a soil water index of 120.7 mm, and rainfall intensity for 10 minutes of 10 mm. Since the cameras were not designed to operate under low-light conditions, photos were not obtained after 18:00 on September 4. Therefore, the situation of the subsurface flows spouting from pipe exits after 18:00 and subsequent settling are unknown. The subsurface flows from pipe exits settled in accordance with the photo of 6:00 of Sept. 5.

During the rainfall event of June 19, 2012,

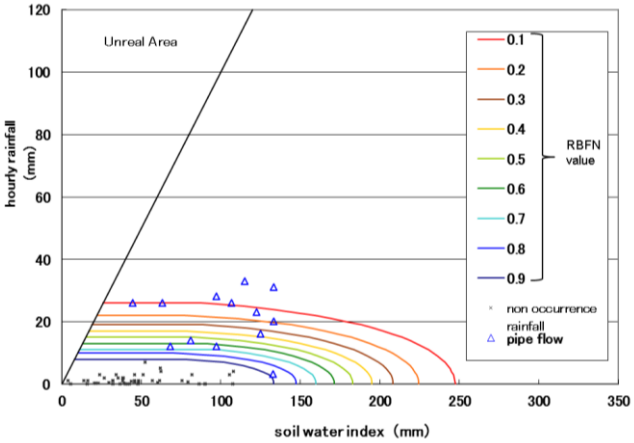

Fig. 14 Critical rainfall threshold for pipe flow generation determined by the RBFN

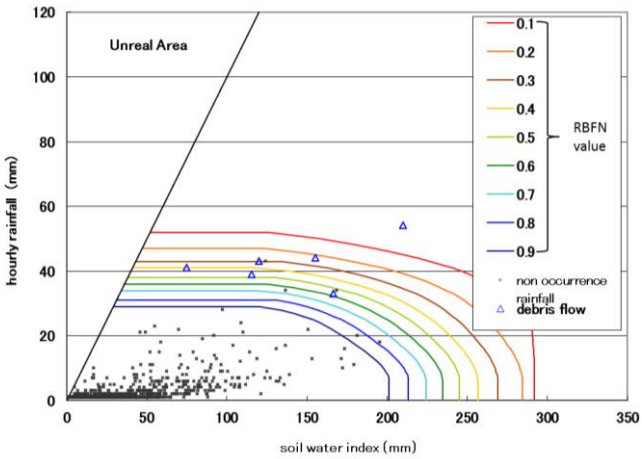

Fig. 15 Critical rainfall threshold for debris flow generation determined by the RBFN

various phenomena, including the subsurface flow spouting from the pipe exit, sediment discharge, clogging of the pipe exit, and collapse of the cross section excavated for construction, were observed 150-m upstream of the No. 6 Sabo Dam. The collapse was likely triggered by subsurface flows spouting from new locations due to clogging of the original pipe exits.

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

To decide CL, we employed the evaluation concept of a "large RBFN value for the hit rate in the occurrence rainfall, but a small value for the non hit rate for non-occurrence rainfall exceeding CL."

Both rates are defined as follows:

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

● Non hit rate for non-occurrence rainfalls exceeding CL= (number of non-occurrence rainfalls exceeding CL) / (number of non-occurrence rainfalls exceeding CL or occurrence rainfalls exceeding CL)

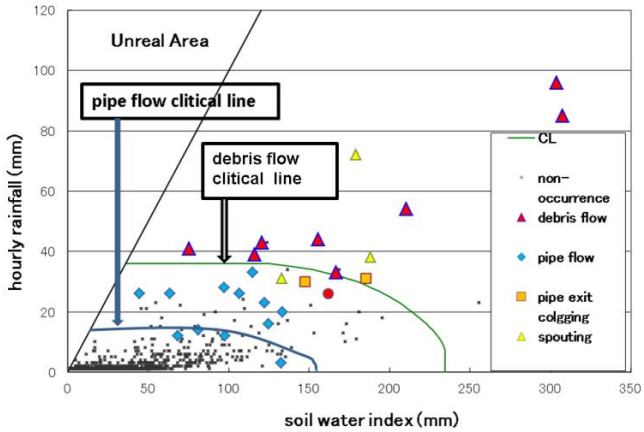

Fig. 16 Critical rainfall threshold for pipe flow and debris flow generation determined by the RBFN

For the 10 minute rainfall data, the optimum critical rainfall threshold for pipe flow generation could be determined if the RBFN value was 0.9; however, the hit rate for occurrence rainfall was low (28.5%). The optimum critical rainfall threshold for debris flow generation could be determined if the RBFN value was 0.6 with a hit rate for occurrence rainfall of 87.5% and a non hit rate for non-occurrence rainfalls exceeding CL of 22.2%.

In the case of hourly rainfall data, the optimum critical rainfall threshold for pipe flow generation could be determined if the RBFN value was 0.7 with a hit rate for occurrence rainfalls of 85.7% and a non hit rate for non-occurrence rainfalls exceeding CL of 0% (**Fig. 14**). The optimum critical rainfall threshold for debris-flow generation could be determined if the RBFN value was 0.6 with a hit rate for occurrence rainfalls of 100% and a non hit rate for non-occurrence rainfalls exceeding CL of 43% (**Fig. 15**).

As shown in **Fig. 16**, there is a time lag between the beginning of pipe flow and the generation of debris flow (the difference in the maximum rainfall amount: 13 mm, difference in soil water index: 74.9 mm). When the rainfall approached the critical rainfall needed for debris flow, the pipe tended to clog. The subsurface flows spouting from new places caused by the clogged pipe exits led to destabilization and collapse of torrent bed material (generation of debris flow).

4. CONCLUSION

This study clarified the following:

1) Numerous pipe exits on the cross-section of torrent bed material are exposed immediately upstream of the No. 6 Sabo Dam on the Nishinokaito River. The depths of the pipe exits are

around 1.0-1.5 m from the surface of the torrent bed material (mainly sand and gravel).

2) There are sub-angular breccias of 10 cm to several decimeters in diameter at the exit. The inner diameters of all pipe exits are several decimeters. Additionally, gravel of several cm and sand mixed with silt on the bottom surface of the pipe exit are present.

3) Although the inner diameters and structures of the surrounding areas of each pipe exit are similar, the generation time, settling time, spouting duration, peak discharge, and total discharge of the subsurface flow spouting differ by pipe exit.

4) The critical rainfall thresholds to generate debris flows were studied using an RBFN method. Although pipe flow does not generate debris flow immediately, when the rainfall approaches the critical threshold for debris flow, the pipes tend to clog. If subsurface flows from other places due to a clogged pipe exit, the torrent bed material becomes destabilized, leading to its collapse (generation of debris flow).

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