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Field experiments on coarse-sediment displacement upstream of flood mitigation dams

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Abstract

This study deals with the transport behavior of the coarse-sediment at Masudagawa flood mitigation dam (FMD), Japan. Radio frequency identification system (RFID) was used to trace the displacement of the IC tagged particles following major flood events since June 2011. Through this, the relationship between recovery rate of the tagged particles and distribution of shear stress over the FMD bed was investigated. Moreover, this study attempts to provide a primary concept for sediment transport processes within the FMDs and to identify a linkage between governing morphological characteristics within the FMD and the transport behavior of coarse-sediment. This study shows that recovery rate of the RFID tagged particles is closely associated with hydro-morphological characteristics of each sub-zone upstream of FMDs. The upstream retention area of Masu-dagawa FMD was classified into three hydro-morphological regions. It was found that the characteristics of tractive force during a flood event within these three regions are different, resulting in transport behavior of the coarse-sediment. In addition, it was found that a small flood event may cause a larger volume of sediment deposition within the FMD compared to a major flood event.

Keywords:*.Sediment, Gravels transport, Cobbles transport, Flood mitigation dams, RFID*

1. Introduction

Flood mitigation dam is a gateless outlet dam designed only for the purpose of flood controls whose bottom outlet is located at the original bed level of the river. During flood events this type of dam significantly mitigates the flood flow downstream. However, in normal river flow condition, there is no water impoundment upstream in the dam. Due to gateless outlet in FMDs, in the normal river flow condition the flow can naturally pass through the outlet. For this reason, it was surmised that the gateless bottom outlet in a flood mitigation dam (FMD) allows fish passage and minimizes sedimentation through naturally sluicing incoming sediment. Hence, it was believed that FMDs are the eco-friendliest hydraulic structures amongst flood control measures. However, Sumi (2008) pointed out that FMDs worldwide disturb the sediment transport continuity; specifically, they trap the coarse portion of sediment. Trapping of the coarse-sediment by FMDs is a potential threat for our life and environment; since on the one hand it reduces the flood control efficiency and on the other hand decreases the habitat structure variety in the river downstream. Therefore, it is highly necessary to think of countermeasures for the sediment deposition issue within FMDs.

To realize practical solutions, the first step is to understand the process of sediment transport for individual particles within the FMD. In this regard, the traditional flux-based measurements may be not suitable, because these methods do not take into account the dispersion and speed characteristics of individual particles (Bradley & Tucker, 2012). Trapping of the coarse sediment within the FMD on the one hand reduces the flood control efficiency and on the other hand decreases the habitat structure variety along the river reach downstream. Tracer methods may help us understand the following: what segment of sediment size cannot be flushed out from FMDs, where the regional deposition spots are located, and how long is the residence time of sediment particles. These are all the fundamental questions whose answers would provide realistic insights on the development of a robust sediment transport model for FMDs. Sear et al. (2000) suggested that the data obtained from the application of tracer methods is a reliable input for both development and validation of sediment transport models. Considering the fact that FMDs, in general, are build up near the upstream area in the catchments, one expects that the sediment transport process upstream of the FMD should be similar to that of steep mountain streams. As it is stated in the literature in steep mountain streams, small variations in flow velocity, roughness, and channel geometry can lead to an extremely unstable sediment transport process (Hassan et al., 2005). However, Sumi et al. (2012) pointed out that sediment transport mechanism within the retention area of the FMD is neither similar to the riverine condition (due to the stagnation process caused by the dam wall) nor to the reservoir condition (due to the permanent flushing process from FMD gateless outlet).

One of the first implementations of the RFID technique in river systems was conducted by Nichols (2004). Most of reported researches examined the sediment displacement along the river reach (e.g. Carre et al., 2007; Liébault et al., 2009; Schneider et al., 2010), and some of them for tracking the large woody debris in rivers (e.g. MacVicar et al., 2009; Schenk et al., 2014), and also application of RFID technique in sediment transport along the shorelines (e.g. Allan et al., 2006; Osborne, 2010).

However, there is hardly any information about using RFID for FMDs. To our knowledge, no publication has focused on the interaction between course sediments and the retention area of the FMDs compared with for example, high-gradient mountain rivers. It should also be noted that the outcomes of utilizing RFID system in rivers and shorelines are not applicable to FMDs. This is mainly due to a different hydraulic condition governing the FMD retention area compared to other applications. Thus, field experiments are being conducted and are still ongoing to monitor the coarse-sediment displacement following each flood event. We chose the Masudagawa FMD as the area of study (constructed in 2005). One of the unique points of the present study, in addition to the new application of RFID technique, is that this research is supported by reach data covering a relatively long term period (2011-2013).

The main objectives of this study are: i) providing a primary concept for sediment transport processes upstream of the FMD; ii) identifying a linkage between governing morphological characteristics within the FMD and the transport behavior of coarse-sediment;

and finally iii) investigating the effect of shear stress on recovery rate of the coarse-sediment.

1.1. SEDIMENT TRANSPORT PROCESS

1.1.1. Sediment transport within an FMD

Sumi (2008) mentioned that displacement of coarse-sediment varies in response to the time varying governing hydraulic condition within the FMD. He classified the sediment transport process within an FMD into three successive phases, namely rising, peak, and drawdown. Through this classification, he provides a qualitative yet substantial insight on understanding the sediment transport process within an FMD. Fig.1 illustrates the schematic view of the model. The rising phase, in the model, refers to the time period that begins with flood approach until flood peak (Fig.1a). When a flood approaches, the FMD is faced with a dry dam (empty of water), resembling the riverine sediment transport condition. However, due to constant increases in both the flood discharge and the mitigation (stagnation) effect of the FMD wall, the water level within the FMD gradually rises. Thus, the hydraulics of the FMD would be gradually varied from riverine to reservoir condition. This results in formation of a spectrum for the sediment transport process. One end of this spectrum resembles the riverine and the other end the reservoir condition.

Since there is no initial impoundment upstream of a FMD, the incoming flood flow will travel a relatively long distance into the FMD without being sorted and/or settled compared to conventional dams. The second phase is commenced when the water level within the FMD reaches its maximum level, namely the peak phase (Fig.1b). At peak level, the FMD functions as a reservoir. It stills the incoming flow, resulting in deposition of a considerable proportion of sediment, particularly the coarse fraction. The siltation process, due to the reservoir condition, also stops the flux of sediment that could travel into the FMD during the rising phase. This results in a deltaic shaped deposition, which although is closer to the dam wall, is also similar to that in a conventional dam. Furthermore, the peak phase sorts the incoming sediment by size.

After the peak, the drawdown phase starts. It mostly contributes to the removal of sediment from the FMD (Fig.1c). In this phase, both the flood discharge and the water level in the FMD drops. It creates a similar situation to that of the operation of the flushing technique in conventional dams. However, due to the quick decrease in the rate of the incoming flow from upstream (i.e. lack of high flow velocity), a significant amount of sediment would be deposited at side banks. Evidently, the deposited sediment at side banks has a lesser chance of being flushed out. These sediments reside within the FMD for a longer period of time and actively contribute to the formation of the alternating sandy bars along the main channel.

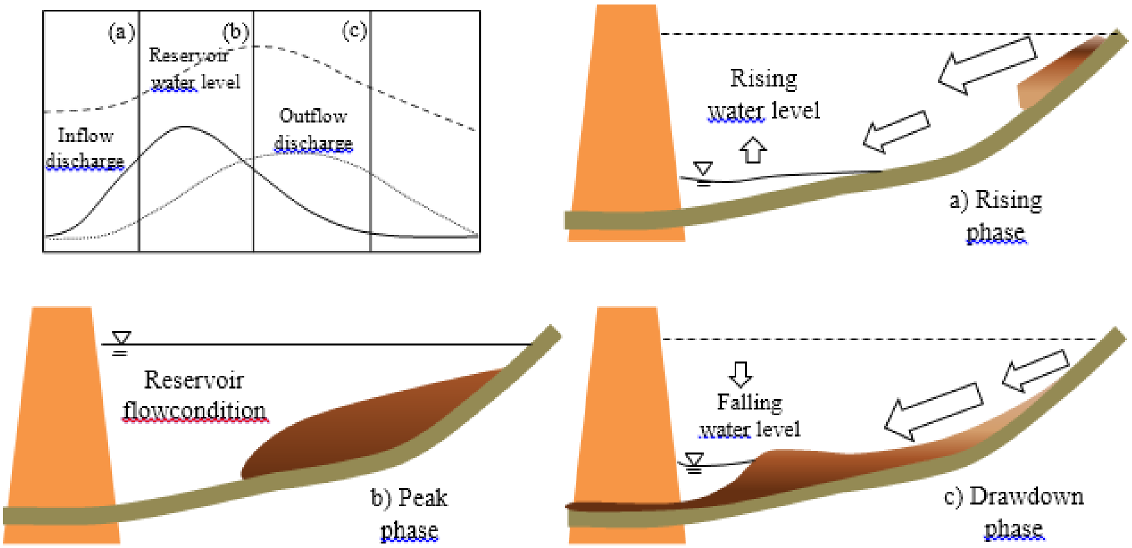

Fig. 1. Conceptual schematic view of the sediment transport process within the FMD.

2. Materials and Methods

2.1. Case study

The present study chose the last 0.6 km of the retention area in Masudagawa FMD as the study location. Masudagawa FMD aims to mitigate floods on Masuda River, which flows across the Shimane Prefecture in Western Japan and eventually enters the Japan Sea. The discharge of Masuda River in normal river conditions is provided by springs and snow melts. However, during rainy seasons (mid-June to mid-September), this river regularly experiences torrential rainfall. The orange markings in Fig.2 outline the study area.

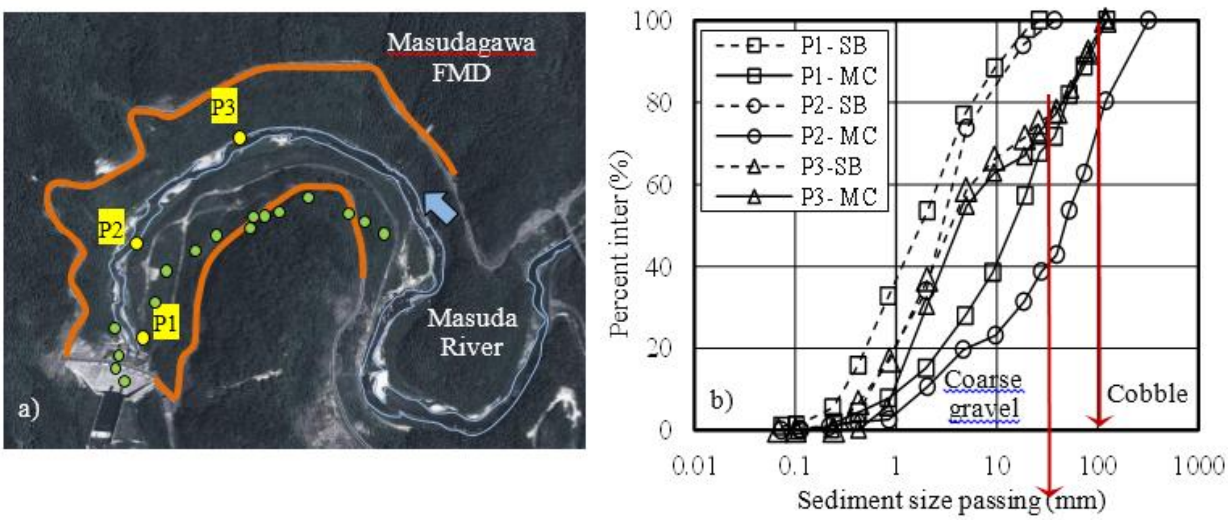

Fig. 2. a) Location map illustrating the study area (Google Maps); b) Size distribution of FMD bed in three different locations, namely P1, P2 and P3.

2.2. Bed material size

To identify surficial size distributions of the FMD bed, we sampled the surface sediment in three different locations in the study area, as shown by labels P1, P2, and P3 in Fig. 2a. Two points were sampled for each location; one at the side bank (SB) and the other from the main channel (MC). A total of 6 samples were analyzed. Fig.2b depicts the size distributions of the sampled sediment. The particle size distribution led us to choose the suitable size of the tagged particles as close as possible to the native coarse materials. The particle size distributions revealed that the coarse fraction of the bed in Masudagwa FMD mainly consist of coarse gravels and cobbles. Based on ISO-14688-1 (2002) a particle with a diameter of 20-63 mm is known as a coarse gravel, and a particle with a diameter be-tween 63–200 mm is a cobble. Hence, two tagged particles with the width of 50 and 80 mm, were selected as the coarse gravels and cobbles, respectively.

2.3. Radio Frequency Identification System

As described in the preceding section, this study makes use of hexahedral shaped concrete particles with suitable mean sizes. The concrete particles were drilled in order to insert the IC tags (passive identification codes) into them. The hole were sealed using special glue and particles were numbered on their surface. For the sake of brevity, we shall name these hexahedral shaped particles as tagged particles, hereafter. This study examines two different sizes of tagged particles, i.e. small (60×50×40mm) and large (100×80×70mm). Fig.3a-c illustrate the RFID system including the main hardware, the frame shaped antenna, and the tagged particles, respectively. Using this method, we were able to detect tagged particles up to 50 cm from the antenna.

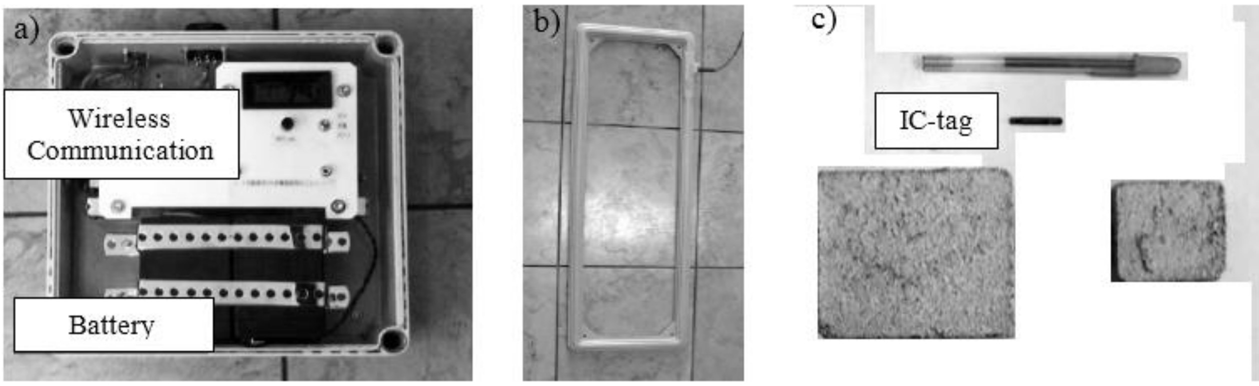

Fig. 3. RFID system used in the present study: a) main hardware, b) frame shaped antenna and c) tagged particles.

2.4. Tagged particles distribution

The tagged particles were distributed throughout Masudagawa FMD in early June, 2011. The tagged particles were initially placed over 16 cross sections. The green circles in Fig.2a distinguish the area where the tagged particles were initially installed. At each of the 16 points, three groups of tagged particles were placed, namely at the right side bank, the main channel, and the left side bank with a random transversal interval. Therefore, we were able to sample full range of flow conditions at each cross section. Each group of the particles consisted of a small number of small and large tagged particles. In addition, attempts were made to place each tagged particle in a natural position by substituting gravel from the reservoir bed with a tagged particle. The inspections for tagged particles took place following major flood events when the water level was low, allowing us to efficiently search within the FMD.

2.5. Major flood events

There were three rainy seasons since the beginning of this study in early June, 2011. Fig.4a and 4b depict hydrographs of floods in 2011 and 2013, respectively, as well as the corresponding water level in Masudagawa FMD. The beginning of the rainy season, in 2011, coincided with the largest flood event of whole the year, which peaked at 102.5 m^3/s and was then followed by a number of smaller flood events (Fig.4a). The pattern of floods in 2012, however, was different. The largest flood in 2012 showed a 50% decrease in peak compared to 2011 and occurred in the middle of a few smaller events. The floods in 2013 differed considerably. During this year, two large events took place at the beginning and at the end of the rainy season along with a number of smaller events in between. The 2013 peak discharge was one of the highest recorded floods in Masuda River over the past few years with a peak discharge equal to 261.6 m^3/s, which is about two times larger than the average recorded flood peaks from 2010 to 2013.

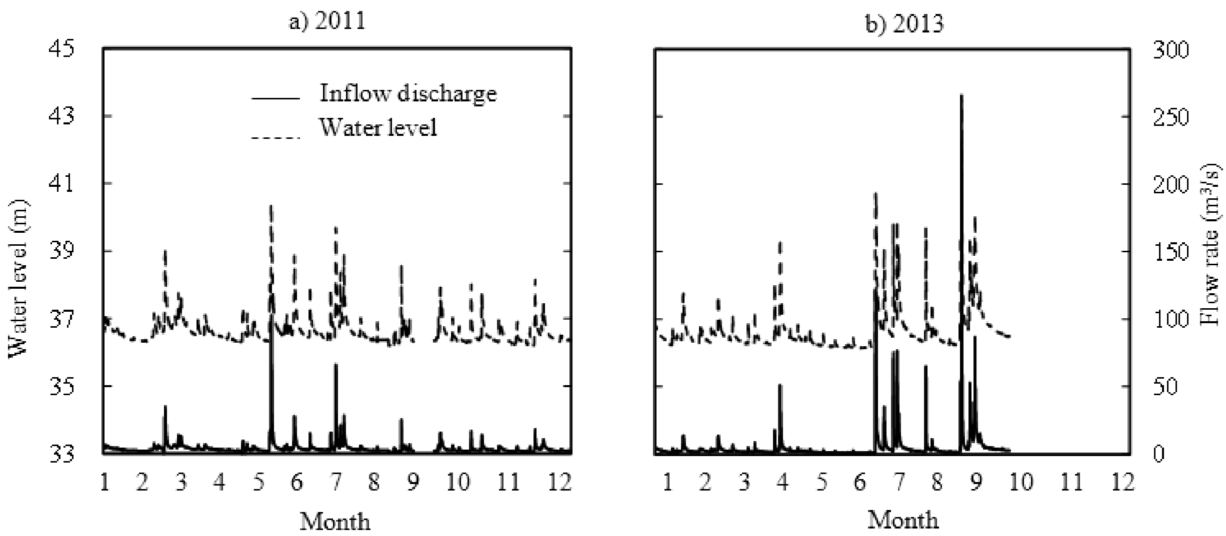

Fig. 4. Inflow discharge and water level in Masudagawa FMD in a) 2011 and b) 2013.

3. Results

3.1. Coarse sediment displacement

To evaluate the tagged particles displacement, bed shear stress equation was used. This equation is depicted as:

$$\tau = \rho g R i_e \qquad \text{Eq (1)}$$

where τ is the critical shear stress, ρ is the mass density of water, g is the gravitational acceleration, R is the hydraulic radius, and i_e is the energy gradient in order. It was assumed tagged particles would move if the shear stress at the reservoir bed became larger than the threshold called critical shear stress. The critical shear stress, τ_c, is described as:

$$\tau_c = \rho {u_{*c}}^2 \qquad \text{Eq (2)}$$

Where u_{*c} is the critical shear velocity. Iwagaki's expression was applied to calculate the critical tractive force (Iwagaki, 1986). Iwagaki's method is known as one of the most robust methods to calculate the critical tractive force on sediment particles in Japanese rivers. Assuming = 2.00 and the kinematic viscosity of ν= 0.01308 cm^2/s, R_* for two sizes of tagged particles (i.e. small with 50 mm and large with 80 mm diameter) can be calculated as follows:

$$R_* = \left\{ (\frac{\sigma}{\rho} - 1) g \right\}^{1/2} d^{3/2} / \upsilon \quad \text{Eq (3)}$$

Since, the value of R_* for the examined size of tagged particle was larger than 671, it satisfied the governing condition for Iwagaki expression. Using Equation (4), it was found that the critical shear stress for small and large tagged particles were 0.0245 and 0.0392 t/m/sec^2, respectively.

$$u^2_{*c} = 0.05(\frac{\sigma}{\rho} - 1) g d = 49 d \quad \text{Eq (4)}$$

3.2. Recovery rate analysis

The recovery rate was defined as the number of detected tagged particles divided by total number of tagged particles. Table 1 summarizes the recovery rate for each inspection over the period of study. With a quick comparison on the recovery rates of small and large tagged particles, one notices that the recovery rate of large tagged particles is slightly higher than small ones. Small particles are, indeed, more easily displaced, flushed out, broken, or buried compared to large ones. However, as can be seen in Table 2a larger number of particles have been lost again, particularly the small ones. In other words, small tagged particles have a higher chance of being temporally found by a flood event. While, from a long-term point of view, a large tagged particle shows a better consistency of being detected.

Table 1. The recovery rate of tagged particles from the beginning of the study.

Surveys	Date	Elapsed days	Observed tagged particles		
			Small	Large	Total
Installation	2011.6.9	0	64	64 (100%)	128 (100%)
1st survey	2011.8.12	64	22 (34%)	26 (41%)	48 (38%)
2nd survey	2011.9.13	96	31 (48%)	27 (42%)	58 (45%)
3rd survey	2012.5.29	355	20 (31%)	26 (41%)	46 (36%)
4th survey	2013.6.1	723	5 (8%)	5 (8%)	10 (8%)
5th survey	2013.9.28	842	7 (11%)	8 (13%)	15 (12%)

Moreover, for those inspections conducted with a relatively short time interval (e.g. 1st and 2nd or 4th and 5th) the value of the recovery rate were realized to be close to each other; in spite of the fact that a major flood event took place between those surveys. We believe that during a major flood event, both exposure and burying of tagged particles happen. Thus, the recovery rate do not change. Having said that, the recovery rate from the 3rd to the 4th survey, with a time interval of about a year, shows a drastic reduction in the total number of tagged particles from 46% to only 10% (Table 1). It is noteworthy to mention that there was no major flood between these surveys, but a few number of small sized floods were observed. It was discovered that small sized floods may lead to a larger deposition compared to a major flood, resulting in a gradual coverage of tagged particles by new incoming sediment. These findings are evaluated in sections 4.2 and 4.3, from a different perspective considering the hydro-morphological characteristics of the area of study.

Table 2 reveals that there is no single tagged particle that could be detect over all 5 field surveys. In addition, a total of 29% of tagged particles were not being detected, however, it is believed that the possibility of tagged particles being flushed out form the FMD is very low. There are two reasons for this statement: i) no tagged particles were found downstream of Masudagawa FMD; and ii) in each field survey, a few number of new tagged particles were found.

Table 2. Historical data on new recorded tagged particles for each field inspection.

Field Surveys History	Observed tagged particles		
	Small	Large	Total
Initial	64 (100%)	64 (100%)	128 (100%)
Always been detected	0 (3%)	0 (0%)	0 (0%)
Only in 1st survey	2 (3%)	0 (0%)	2 (2%)
Only in 2nd survey	14 (22%)	4 (6%)	18 (14)%
Only in 3rd survey	8 (13%)	4 (6%)	12 (9%)
Only in 4th survey	0 (0%)	0 (0%)	0 (0)%
Only in 5th survey	2 (3%)	2 (3%)	4 (3%)
Never been detected	15 (23%)	22 (34%)	37 (29%)

Effect of the maximum shear stress

Critical bed shear stress was used to evaluate the displacement of the tagged particles. To calculate the critical shear stress, Iwagaki's expression was applied (Iwagaki, 1956). Fig.5a and b illustrate the relationship between number of detected particles in each field survey and the distance of their detection place from the FMD wall for the small and large particles, respectively. Additionally, they depict variation of the maximum shear stress along the retention area of the FMD for two representative flood events in 2011 and 2013. At first glance, one realizes that the number of detected particles in respect to their detection locations was independent of their size; since both small and large particles showed more or less a same trend. This trend can be described as "the farther from the FMD wall, the fewer is the number of the detected particles".

Despite earlier observations, the reported relationship is not linear. It is believed that this irregular distribution of particles over the distance maybe related to the morphological characteristics of the FMD bed. Field observation showed, that within the present study area of 0.6 km long, the morphological characteristics differ considerably. The vicinity of the FMD wall is a relatively wide valley. The FMD bed in this area is mainly covered by silt and sand. Further upstream from the FMD, the bed is characterized by a complex morphology with heterogeneous sediment deposition. Upstream from this middle reach, there is a narrower valley with a steep slope covered by gravels. Based on these facts, the study area (the last 0.6 km of the retention area in Masudagawa FMD) was classified into three sub-zones, namely upper, middle, and lower part.

The upper part refers to the area in which the total number of detected tagged particles in all 5 inspections was less than 2% of the total tagged particles. The middle part refers to the middle reach where no detection were made beyond 10% of the total particles in each inspection. The lower part, covers the area in the vicinity of the FMD where the number of detected particles was more than 10% of the total particles at least in one of the inspections. The vertical lines in Fig.5a and b highlight the borders between these subzones.

Furthermore, Fig.5a and b reveal that there is an indirect relationship between the magnitude of the maximum shear stress and the number of detected particles. This happens because a large shear stress easily displaces the particles to the farther downstream. Then, there is a minor chance for detecting any particles in the upper part, which is exposed to a very high shear stress. Regarding the middle part, it was believed that, due to the intermediate value of shear stress in addition to the new sediment deposition, the previously deposited layers were scrambled to some extent. This results in both exposure and burying of the tagged particles from/under the FMD bed, which indicates an intermediate rate of recovery.

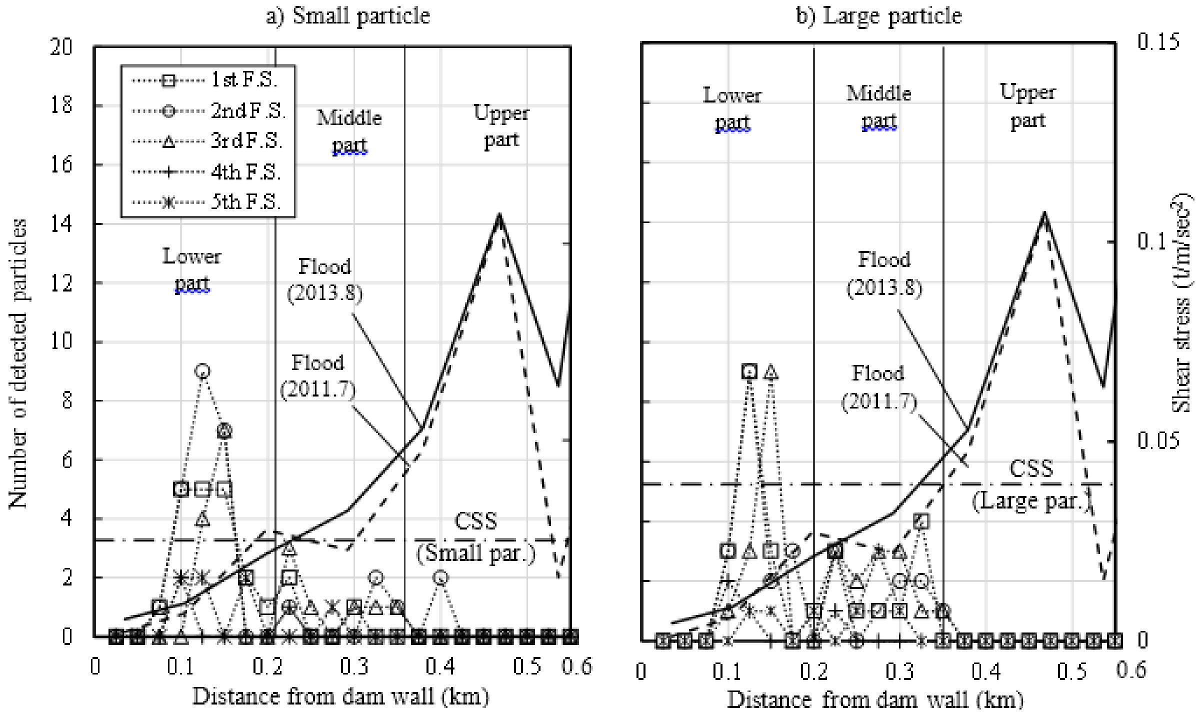

Fig. 5. Variation of the maximum shear stress in respect to both the distance from the FMD and the critical shear stress (CSS) for a) small particles; b) large particles.

3.3. Effect of exposure duration of the shear stress

Fig.6a and 6b illustrate the evolution of the shear stress from the beginning of the flood until its end, with a time interval of a few hours for the flood in 2011 and 2013, respectively. In spite of the fact that the peak of flood in 2013 is about 1.5 times larger than that in 2011. It was noticed that both floods have almost the same tendency in variation of the shear stress in respect to the distance from the FMD wall, with an equal maximum shear stress of 0.1 t/m/sec^2.

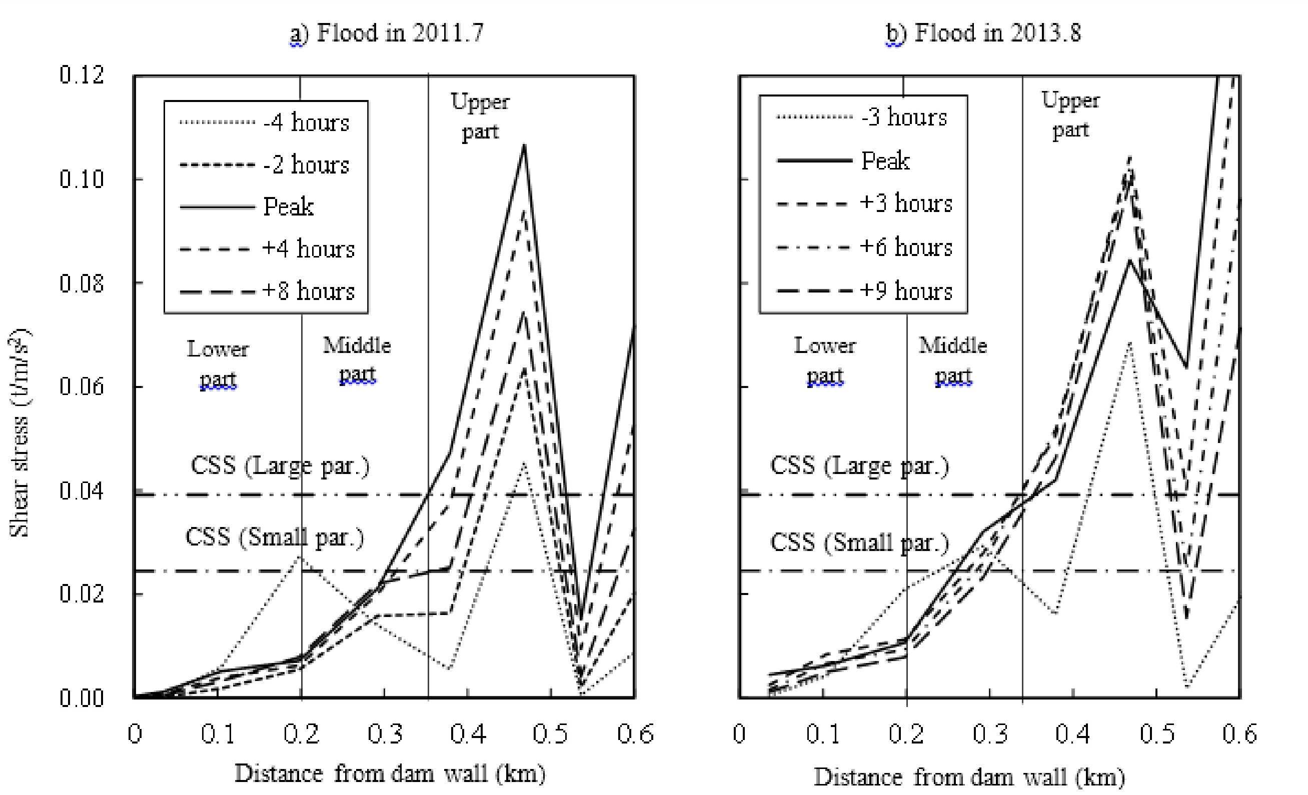

Fig. 6. Evolution of the shear stress in respect to both the distance from the FMD wall and the critical shear stress (CSS) for flood in a) 2011.7; b) 2013.8.

Thus, the major difference between a mid-sized flood event (e.g. 2011.7) and a very large one (e.g. 2013.8) is the exposure duration of the maximum shear stress that FMD beds endure. It was observed that longer exposure duration of high shear stress did not lead to a higher rate of coarse-sediment transportation. This is due to the fact that long exposure duration endures the upper part, whereas, the settling effect is dominant in the middle part. As a result, severe erosion occurs at the upper part and mainly deposition at the middle part. In other words, huge floods are not able to scramble the FMD bed in the middle part of the study area where finding many buried IC tagged particles is anticipated.

The ideal situation would occur if the pulse of high shear stress were shifted from the upper part to the middle part. Then, the exposure duration of high shear stress may effectively increase the coarse-sediment displacement. For this purpose, we are required to narrow the valley in the middle part by placing huge boulders at side banks. Lastly, as can be seen in Fig. 6, shear stress before the peak is hardly larger than the threshold of the critical shear stress for large particles. Hence, within the first half of the rising phase the flood flow is unable to displace them. However, as time passes towards the peak, shear stress becomes sufficiently large (mainly in the upper part) and the major portion of coarse-sediment transport occurs. However, as Sumi (2008) described, near to the peak, the settling/sorting effect diminishes the sediment transportation capacity within the FMD. As a result, the coarse-sediment transport within the FMD occurs in a very limited time period, namely the second half of the rising phase. One may anticipate some amounts of coarse-sediment to be transported in the draw-down phase (after the peak), similar to the free flushing operation. However, it is supposed that this will not be significant; evidently due to the drastic reduction in the upstream flow velocity and concentration of the flow in only the main channel.

4. Discussion and Conclusion

This study integrates both hydraulic and morphological characteristics of Masudagawa FMD to justify the recovery rate of IC tagged particles. Data analysis showed that the tractive force throughout the Masudagawa FMD is relatively low. In the upper part region which is located at a distance of at least 0.25-0.3 km from the FMD wall, the recovery rate for tagged particles is very low while a higher tractive force was found in this region. The reservoir bed in this region is active where by each flood event the tagged particles were gradually buried under the reservoir bed and could not be detect by RFID antenna. This interpretation was consistent with the bathymetry survey in the Masudagawa FMD. However, in the lower part region, the area between the FMD wall and 0.25-0.3 km upstream from it, the recovery rate for tagged particles were significantly higher compared to the up-per part. The hydraulic condition on the lower part region in the Masudagawa FMD is different compared to the upper part region. The valley in the lower part region is wider and influenced by the FMD wall; where the stagnation process on flood flow occurs quicker and over a wider distance. Thus, the tractive force in the lower part is lower than the upper part region, resulting in the reservoir bed of the lower part region being less active. Therefore, the chance for tagged particles to be detected is higher. Finally, we recommend the following practical modifications for FMDs aiming to enhance the coarse-sediment transport process within FMDs: i) feasibility study on installing an outlet that is able to ad-just its size. We believe a large outlet during the rising phase and the small outlet during the drawdown phase increases the rate of coarse-sediment transport; and ii) a narrower valley in the middle part of FMD which may result in a larger volume of coarse-sediment to be transported.

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