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Flume experiment on the influence of particle size distribution on sediment capturing efficiency of open-type steel Sabo dams

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Abstract

The purpose of this study is to clarify the influence of particle size distribution on the sediment capturing effect of open-type steel Sabo dams constructed in the sediment sheet flow section. First, we conducted a flume experiment in order to clarify the minimum boulder size contributing to blockage (flume gradient was 5 °). Based on the result, we set the particle size distribution for a flume experiment to clarify the effect of particle size distribution on the sediment capturing effect of the open-type steel Sabo dams in the sediment sheet flow section. We found that the minimum boulder size contributing to blockage is 1/3 to 1/2 of the individual grid width. We tested the volumetric effects of sediment larger than the minimum boulder size on sediment capturing efficiency through its contribution to blockage. In addition, we defined the value obtained by dividing the blockage-contributing sediment volume per unit area by the average particle size as "dimensionless sediment volume contributing to blockage ". We found that this “dimensionless sediment volume contributing to blockage” and sediment capture rate have a logarithmic approximation relationship. Thus, this value can be expected as a new index for setting the individual grid width of the open-type steel Sabo dams.

Keywords: sediment sheet flow; flume experiment; open-type steel Sabo dams; boulder size distribution; dimensionless sediment volume contributing to blockage

1. Introduction

In Japan, as a countermeasure against debris flow, it is recommended to construct open-type steel Sabo dams that trap not only sediment but also driftwood. When planning open-type steel Sabo dams, setting the individual grid width is one of the important considerations. In Japan, the individual grid width is set at 1.0 times the sediment of 95% particle diameter as per guidelines(National Institute for Land and Infrastructure Management). Although it is known that boulders smaller than the individual grid width block individual grids due to arching, there is little knowledge of the boulder size contribution to blockage and the influence of particle size distribution on open-type steel Sabo dams installed in the sediment sheet flow section.

So, in this study, we conducted a flume experiment to clarify the effect of particle size distribution on the sediment capturing effect of open-type steel Sabo dams in the sediment sheet flow section, and organize the relationship between particle size distribution and sediment captured rate. The names of the various parts of an open-type steel Sabo dam are as shown in Fig.1(a).

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2. Outline of experiment

2.1. Equipment and conditions

The water flume used in this study was a straight rectangular water flume with a length of 10 m, a width of 30 cm, a height of 50 cm, and a channel slope of 5 ° (Fig. 1(b)). The water flume floor was fixed. Also, a roughness plate with experimental sediment (Fig. 2(a)) was affixed to the water flume floor. Mixed sand, 95% of which had a particle diameter of 32 mm and 50% a particle diameter of 8 mm, was used as the test sediment so that the maximum particle size was about 1 m when the model scale was set to 1/30. In addition, an open-type steel Sabo dam was installed at a point 2.25 m from the downstream end of the water flume. In order to analyze the effect of backwater and grid area on the sediment capturing performance of open-type Sabo dams, we prepared two kinds of open-type Sabo dams with different opening widths (Fig. 2(b),(c)). In addition, the individual grid width was set to 95% particle diameter 1.0 times for both horizontal and vertical intervals based on Japanese guidelines.

(a) (b)

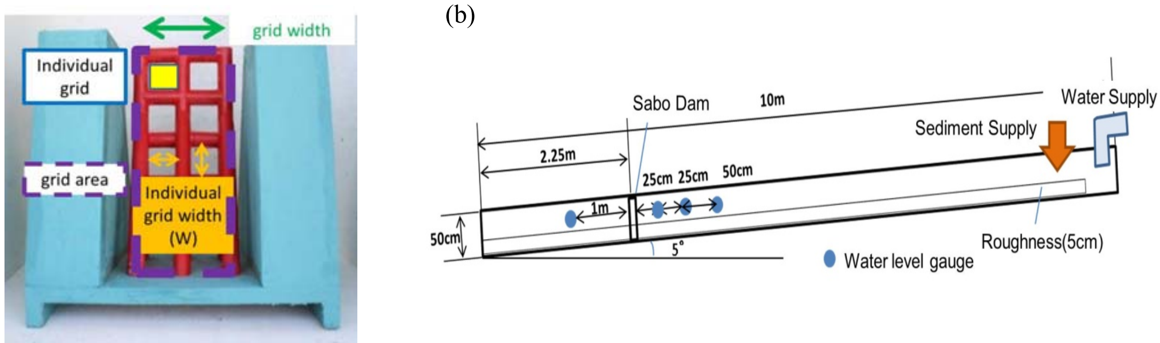

Fig. 1. (a) Names of parts of an open-type steel Sabo dam; (b) Water flume

(a) (b) (c)

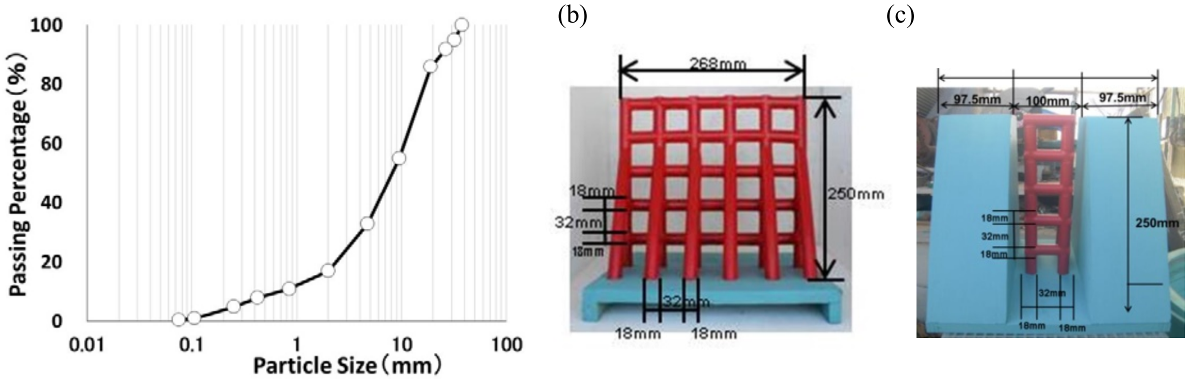

Fig. 2. (a) Particle size distribution; (b) Full-open-type Sabo dam model; (c) Partially-open type Sabo dam model

2.2. Experimental method

For water and sediment supply methods, water was supplied from the upstream end of the water flume and the amount of supply water was controlled by programing the opening and closing of the electrically operated valve. Based on the set hydrograph, the sediment was supplied manually according to the equilibrium sediment amount calculated by the gradual equation (Ashida et.al., 1978). The hydrograph was rectangular with a stable flow rate of sediment and water at 18 l/sec for a duration of 5.5 minutes (Fig. 3(a)). In addition, the amount of sediment was supplied so that the sediment gradient was equal to the capacity (321 liter) when accumulated at 2/3 the gradient of the original riverbed. At the downstream end of the water flume, the outflow flow rate to the downstream and the discharge sediment volume were collected at intervals of 30 to 60 seconds and measured. The experimental situation was recorded on video from the side wall of the water flume and the deposited sediment situation was measured.

2.3 Preliminary experiment for identifying the minimum particle size capable of blocking the opening section

This study aimed to investigate the influence of the particle size distribution constituting the sediment sheet flow on the sediment capturing performance of open-type steel Sabo dams. Therefore, the particle size distribution was set after identifying the minimum particle diameter that closes the grid area. First, we removed the sand of coarse particles so that the maximum sizes of the experimental sediment shown in Fig. 2(a) were 9.5 mm and 19 mm. We carried out preliminary experiments to supply water and sediment from the upstream of the water flume and to check whether or not the sediment blocked the open-type steel Sabo dam. Judgement was based on whether or not the lowermost stage of the dam was blocked. We supplied water and sediment under the conditions shown in Fig. 3(a). We halted supply when it was confirmed that the lowest stage was assuredly blocked. Also, even in the case where the lowest stage was not blocked, we halted supply after 4 minutes, which was adequate time to supply the amount of sediment equivalent to the planned deposited sediment volume. Preliminary experiment cases are shown in Table 1. In Cases 1 and 2, 3 minutes after the start of supply, we confirmed that the lowest stage of the Sabo dam was surely blocked. On the other hand, in Cases 3 and 4, we confirmed that, even 4 minutes after the start of supply, the lowest stage of the Sabo dam was not blocked at all. From the above results, in this study, we treated grain sizes of 9.5 mm to 19 mm or more as the particle sizes contributing to the blockage of open-type steel Sabo dams (hereinafter referred to as "blockage-contributing particle size") .

Table1. Preliminary experimental case

CASE	Maximum Particle Size	Dam-type
1	19mm	Full-open type
2	19mm	Partially-open type
3	9.5mm	Full-open type
4	9.5mm	Partially-open type

2.4 Setting of particle size distribution in this experiment

Using the particle size distribution shown in Fig. 2(a) as the basic pattern, we set three particle size distributions in which the ratio of the blockage-contributing particle size was changed. The concept of setting the particle size distribution is as follows.

(1) 95% of the particles of the basic pattern are 32 mm in diameter and contribute 45% to the blockage.
(2) Since individual grids can be blocked by one particle of 32 mm or more in diameter, the proportion of the blockage-contributing particle size changes according to the reduction ratio of the sediment amount of 32 mm or more. For example, in Pattern 1, since the sediment of 32 mm or more in diameter was reduced to 0.83% (reduction ratio: 0.166), the blockage-contributing particle size was set to 7.5% (= 0.45 × 0.166).
(3) Regarding Patterns 2 and 3, an amount of sediment having a particle size of 32 mm or more, capable of closing all individual grids of a Sabo dam was set. If it is assumed that one particle of 32 mm or more in diameter is simply a sphere, in order to block individual grids, 0.0171 ℓ (= 17.1 cm 3) of sediment is required. Since the full-open type steel Sabo dam has 25 individual grids, 0.428 l (= 0.0171 × 25) is necessary. Also, assuming the porosity to be 0.6, 0.71 ℓ (= 0.428 / 0.6) of sediment is required. Since this is 0.2% (= 0.71 / 321) (reduction ratio: 0.04) of the supplied sediment volume, the overall proportion of the blockage-contributing particle size is about 2% (= 0.45 × 0.04). Similarly, Pattern 3 was determined.

Based on (1) to (3) above, the particle size ratio and the particle size distribution are shown in Fig. 3(b) and Fig.4(a). Fig. 4(b) is an enlargement of the passing percentage of 80-100%.

2.5 Experimental cases

Based on 2.2, 2.3 and 2.4, a total of 7 experimental cases combining the particle size distribution of Fig. 3(b) and the Sabo dam model of Fig. 2(b),(c) were set (Table.2).

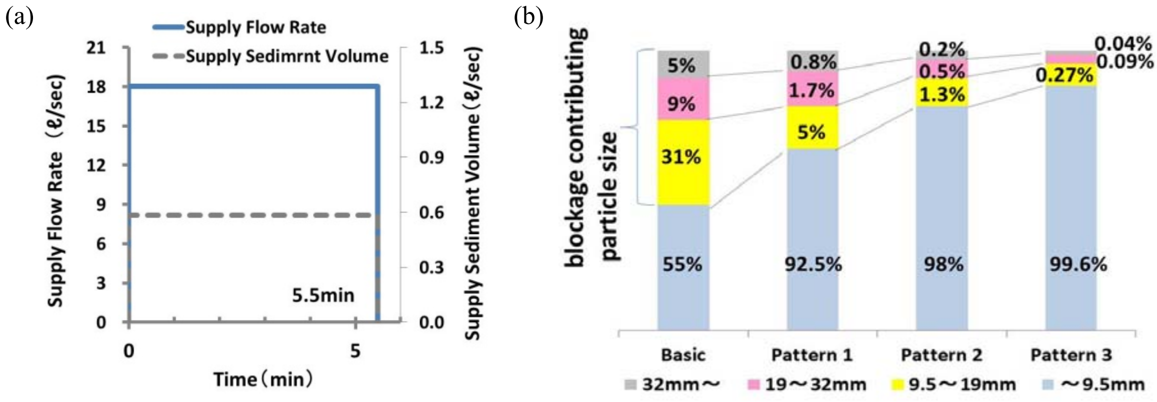

Fig. 3. (a) Hydrograph and sedigraph; (b) Particle size ratio

Table 2. Experimental cases

CASE	Particle Size Ratio	Dam-type
Basic	Basic	Full-open type
1	Pattern 1	Full-open type
2	Pattern 1	Partially-open type
3	Pattern 2	Full-open type
4	Pattern 2	Partially-open type
5	Pattern 3	Full-open type
6	Pattern 3	Partially-open type

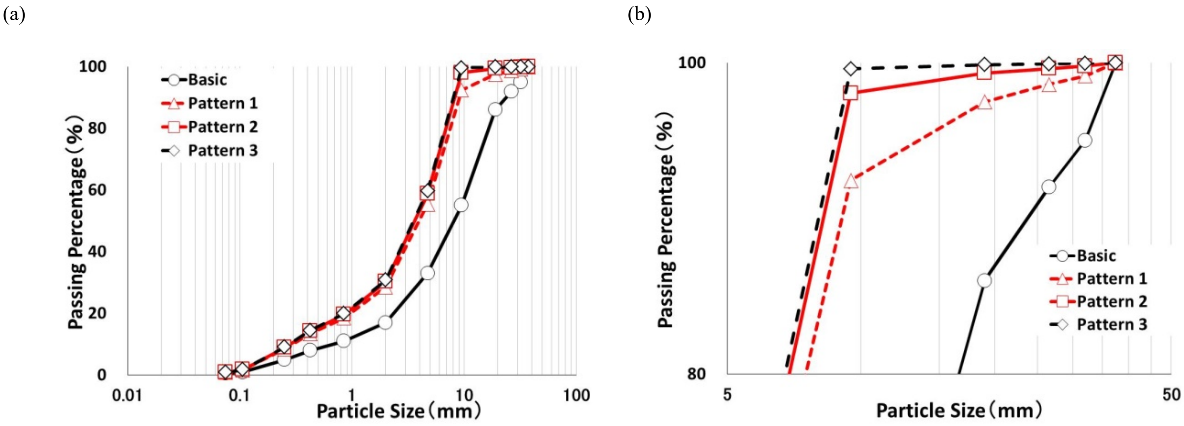

Fig. 4. (a) Particle size distribution of the main experimental sediment; (b) Particle size distribution enlarging 80-100%

3. Results

3.1. Sediment captured rate

The sediment captured rate is the ratio of the amount of sediment captured by the Sabo dam (sediment captured volume) to the supplied sediment volume (Fig. 5(a)). The amount of sediment captured by the Sabo dam was calculated by subtracting the amount of sediment discharged from the supplied sediment volume to the downstream of the Sabo dam. As for the Basic Case and Cases 1, 2, and 4, since the sediment captured rate is 88 to 94%, it can be seen that most of the supplied sediment was captured by the Sabo dam. On the other hand, in Case 5, since the sediment captured rate is 16%, it can be seen that much of the sediment flowed out downstream without being captured by the Sabo dam.

Next, we focused on the difference in dam-type. The sediment captured rate of full-open type dam is 92% for Case 1, 70% for Case 3, and 16% for Case 5. The sediment captured rate decreases as the sediment volume of blockage-contributing particle size (hereinafter referred to as "blockage-contributing sediment volume") decreases. Meanwhile, the sediment captured rate of the partially-open type dam is 89% for Case 2, 88% for Case 4, and 76% for Case 6. Case 6 with the smallest blockage-contributing sediment volume has a lower sediment captured rate than the other cases (Cases 2 and 4).

We then focused on the difference in blockage-contributing sediment volume. Cases 1 and 2 with large blockage-contributing sediment volume had almost equal sediment captured rates. On the other hand, in Cases 3 - 6 with small blockage-contributing sediment volume, the partially-open dam of Cases 4 and 6 had a larger sediment captured rate than the full-open dam of Cases 3 and 5. Especially, in Cases 5 and 6 with smallest blockage-contributing sediment volume, the partially-open dam of Case 6 captured about 5 times more sediment volume than the full-open dam of Case 5.

3.2. Sediment deposition process

Fig.5(b) plots the sediment-deposited height at a point 25 cm upstream of the dam, taken from video image. In the Basic Case and Cases 1, 3, and 5 of the full-open dam, the sediment reached the Sabo dam immediately after the start of the experiment in each case. Also, in the Basic Case, Case 1, and Case 3, the sediment-deposited height reached 25 cm of the dam height after the experiment was completed. In other words, this means that the Sabo dam is full of sediment. Also, in the Basic Case, the sediment-deposited height reached 14 cm at 60 seconds and 18.6 cm at 120 seconds after the start of supply. In Case 1, the sediment-deposited height reached 11.6 cm at 60 seconds and 17.3 cm at 120 seconds after the start of supply. In Case 3, the sediment-deposited height reached 9.3 cm at 60 seconds and 11.6 cm at 120 seconds after the start of supply. As can be seen from the above, the sediment-deposited speed tends to be slower as the blockage-contributing sediment volume becomes smaller. That is, it can be seen that it takes a long time for the dam to fill up with sediment. On the other hand, Case 5 with the smallest blockage-contributing sediment volume was about 10 cm in sediment-deposited height after the experiment.

In Cases 2, 4, and 6 with the partially-open dam, sediment was deposited while forming sediment shoulders in each case. Also, in all cases, the sediment-deposited height reached 25 cm of the dam height after the experiment was completed. However, in Cases 2 and 4, the sediment shoulder reached the dam 90 seconds after the start of supply, whereas Case 6 was 120 seconds after the start of supply. In Cases 2 and 4, the sediment-deposited height reached 25 cm of the dam height at 240 seconds after the start of supply, whereas Case 6 was 300 seconds after the start of supply. As a result, it can be said that it takes a long time for the dam to fill up with sediment when the blockage-contributing sediment volume becomes less than 2% as in Case 6.

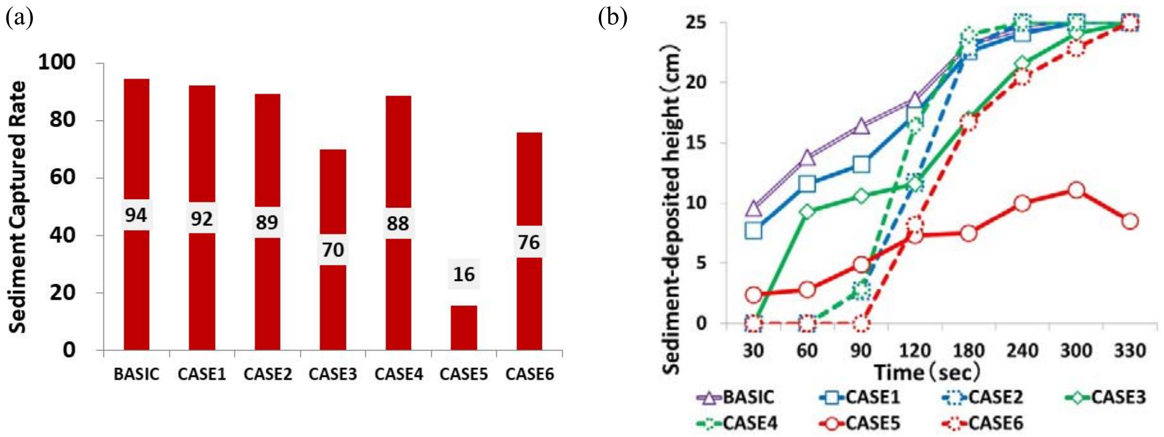

Fig. 5. (a) Sediment captured rate (Numbers in bars refer to the percent captured.); (b) Sediment-deposited height

4. Discussion

4.1. Distance between steel pipes ratio and sediment captured rate

In this study, we conducted flume experiments on the influence of particle size distribution on sediment capturing performance of open-type steel Sabo dams. We first considered the relationship between the ratio of the individual grid width to a certain particle size (hereinafter referred to as " $D_{[particle\ size]}/W$") and the sediment captured rate. For example, in Japan, the individual grid width is set at 1.0 times the 95% particle diameter (D_{95}/W). Fig.6 (a) shows the relationship between D_{95}/W and the sediment captured rate. In this study, the 95% particle diameter is 32 mm for the Basic Case, 24.5 mm for Cases 1 and 2, 9.13 mm for Cases 3 and 4, and 8.94 mm for Cases 5 and 6. Also, in the same figure, the past experimental results are also plotted for comparison (Ashida et al., 1987: Takahara et al., 2007: Horiuchi et al., 2009: Nakatani et al., 2015). When the D_{95}/W is about 1, the sediment captured rate is 80% or more in all cases, but it can be seen that the sediment captured rate largely varies when the D_{95}/W is larger than 1.5. Also, in this study result, it was confirmed that the sediment captured rate greatly differs from 10 to 90% or more. Next, Fig.6 (b) shows the relationship between D_{80}/W and the sediment captured rate. The sediment captured rate is 80% or more until the D_{80}/W is about 2.0, but it can be seen that the sediment captured rate largely varies when the D_{80}/W is larger than 2.0. As a result, there is no noticeable correlation between the $D_{[95\ or\ 80]}/W$ and the sediment captured rate.

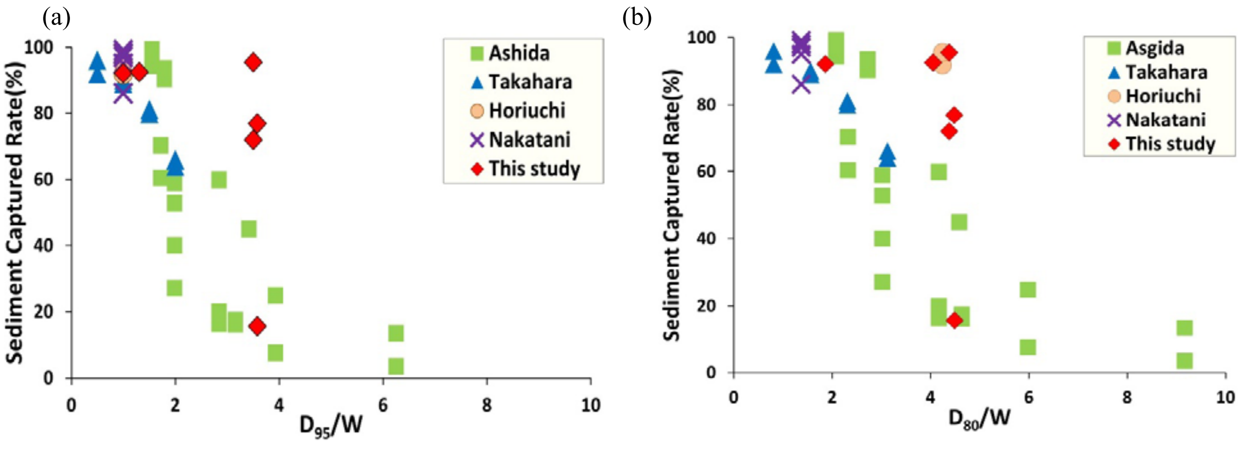

Fig. 6. (a) D_{95}/W and sediment captured rate; (b) D_{80}/W and sediment captured rate

4.2. Blockage contributing sediment volume and sediment captured rate

Next, we consider the relationship between the blockage-contributing sediment volume and the sediment captured rate. Cases 1 and 2, Cases 3 and 4, and Cases 5 and 6 are the experimental cases with the same blockage-contributing sediment volume. From Fig. 5 (a), the sediment captured rates of Cases 1 and 2 are 92% and 89% respectively, which are almost equal. The sediment captured rates of Cases 3 and 4 are 70% and 88% respectively, while a somewhat narrow type of Sabo dam shows a high sediment captured rate. The sediment captured rates of Cases 5 and 6 are 16% and 76% respectively, which are largely different. As a result, there is no noticeable correlation between the blockage-contributing sediment volume and the sediment captured rate.

4.3. Dimensionless blockage-contributing sediment volume and sediment captured rate

It was found that there is no significant correlation between the $D_{[95 \text{ or } 80]}/W$ and the blockage-contributing sediment volume and the sediment captured rate. Here, we consider the relationship between sediment captured rate for grid area and blockage-contributing sediment volume. The grid area is a value obtained by multiplying the area of an individual grid of the Sabo dam by the area of all individual grids.

It is reasonable to consider the blockage-contributing sediment volume per unit area (blockage-contributing sediment volume / grid area). However, it is more convenient to make it dimensionless if we also look into application on site. However, if we actually design an open-type Sabo dam, it would be more useable if we made it dimensionless. Therefore, we define the value obtained by dividing the blockage-contributing sediment volume per unit area by the average particle size as "dimensionless blockage-contributing sediment volume".

Fig.7 and Fig.8 show the contribution of dimensionless blockage-contributing sediment volume and the sediment captured rate. Fig.7 shows a case where sediment having a particle diameter of 1/2 or more of the individual grid width is set as the blockage-contributing particle size and the dimensionless blockage-contributing sediment volume was calculated. Also, Fig. 8 shows a case where sediment having a particle diameter of 1/3 or more of the distance between steel pipes is set as the blockage-contributing particle size and the dimensionless blockage-contributing sediment volume was calculated. Like 4.1, in the same figure, the past experimental results are also plotted for comparison. From both figures, there is a tendency to increase logarithmically between the dimensionless blockage-contributing sediment volume and the sediment captured rate.

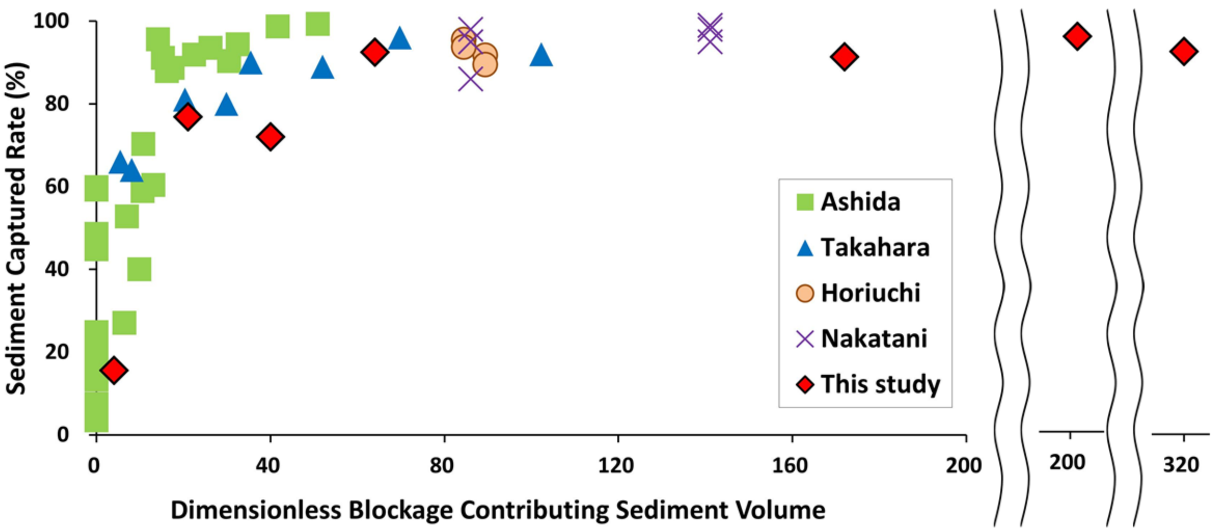

Fig. 7. Dimensionless blockage-contributing sediment volume (1/2) and sediment captured rate

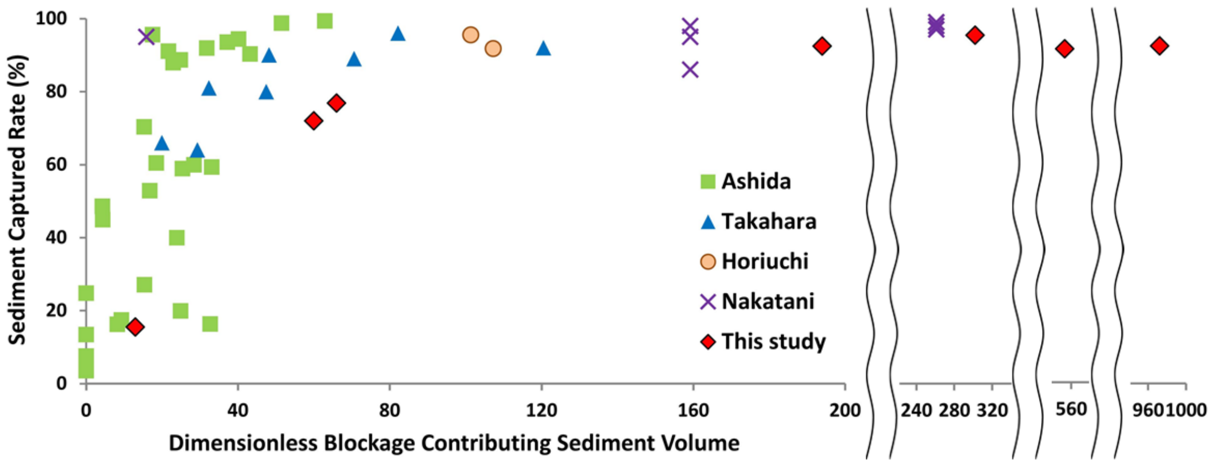

Fig.8. Dimensionless blockage-contributing sediment volume (1/3) and sediment captured rate

Conclusions

In this study, we conducted flume experiments on the effect that differences in particle size distribution have on the sediment capturing effect of the open-type steel Sabo dams in the sediment sheet flow section, and obtained the following results.

(a) The individual grid width of open-type Sabo dams is set with $D_{95\text{ or }80}/W$. When D_{95}/W is set to 1.0 of Japan's setting standard, sufficient sediment capturing performance can be expected. On the other hand, it was confirmed that the sediment captured rate greatly varies when the distance between steel pipes ratio is 1.5 or more. In addition, it was confirmed that even when the individual grid width was set based on the D_{80}/W, there was a variation in sediment captured rate.

(b) "Dimensionless blockage-contributing sediment volume", which is a value obtained by dividing the blockage-contributing sediment volume by the grid area, and the sediment captured rate were found to be logarithmically correlated. That is, it appears that the "dimensionless blockage-contributing sediment volume" may be effective for setting the individual grid width.

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