Original Article

Sediment Trap Function of Open-type Steel Sabo Dam with respect to Shape and Installation Slope

Motoki HIURA¹, Kana NAKATANI¹, Yuji HASEGAWA², Yoshifumi SATOFUKA³
and Takahisa MIZUYAMA⁴

¹ Dept. of Erosion Control Engineering, Kyoto University (Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto, Kyoto 6068502, Japan)
E-mail : hiura@kais.kyoto-u.ac.jp

² Disaster Prevention Research Institute, Kyoto University (Yoko-oji Shimomisu Higashinokuchi, Fushimi-ku, Kyoto 6128235, Japan)

³ Dept. of Civil Engineering, Ritsumeikan University (1-1-1 Noji-higashi, Kusatsu, Shiga 5258577, Japan)

⁴ National Graduate Institute for Policy Studies (7-22-1 Roppongi, Minato-ku, Tokyo 1068677, Japan)

In this study, we consider the debris flow trap function of the open-type steel sabo dam using channel experiments. Various studies have been conducted on the sediment trap function of open-type sabo dams due to boulder blocking in steep-slope areas, considered as areas with a slope of 15° or greater. However, many open-type sabo dams have been built in moderate-slope areas, which have a slope less than 15° . Few studies have been conducted on open-type sabo dams built in mild-slope areas. Therefore, we consider the trap function of the open-type sabo dams in areas having slopes of 12° , 9° , and 6° . In addition, we consider different shapes of the open-type steel sabo dam : grid-type, vertical-type, and horizontal-type. The results show that the trap functions were effective for all slope cases and for all types of dams. Steeper slopes resulted in higher trap functions. The grid-type and vertical-type dams trapped particles more effectively, with higher trap functions than the horizontal-type dams, and large differences appeared in cases where the slope was 6° .

Key words: Open-type sabo dam, trap function, debris flow, shape, installation slope, channel experiment

1. INTRODUCTION

Open-type steel sabo dams have the advantage of having enough capacity to trap debris flow because they normally allow sediment to pass through. Various shapes of the open-type sabo dams have been suggested to trap debris flow effectively. Some of them are made of steel and their trap performance is based on boulders blocking. As they are installed in watercourses in mountainous areas, they work to reduce the sediment volume, i.e., not only debris flow but also other types of sediment transport.

Channel experiments and numerical simulations have been widely used for examining the trap function of the open-type steel sabo dam. Satofuka and Mizuyama (2005) suggested a model that expresses the stochastic boulder blocking processes [Takahashi *et al.* 2001] based on the results of channel experiments, and this model is widely accepted for use in engineering and research. This model is based on grid-type and vertical-type steel sabo dams, when they are set in steep-slope waterways with high sediment concentration such as in debris flow. Therefore, the

blocking processes for dams in moderate-slope waterways or horizontal-type dams are not represented well by the model. While some reports indicate that some open-type sabo dams in moderate-slope streams trapped debris flow with the boulder blocking shown in Hiramatsu *et al.* (2014), most experiments and studies on the trap function have focused on grid-type or vertical-type sabo dams in streams with a slope greater than 15° (e. g. Mizuyama *et al.* 1995, Katade *et al.* 2011). In addition, other reports showed that instead of boulders blocking, open -type sabo dams set in moderate slope areas showed trap performance sufficient to debris wood blocking, as shown in Matsumura *et al.* (2014). Considering the various mechanisms of open-type sabo dams to trap debris flow in moderate-slope streams, there are many studies on slit-type concrete sabo dams, whose trap performance is based on the backwater effect, such as Mizuyama *et al.* (1997) and Mizuyama and Oda (2000). There are few studies on open-type steel sabo dams in moderate-slope streams. Horiuchi *et al.*(2009 a), (2009 b) focused on the effect of the open-type steel sabo dam on sediment concentration, specifically

considering the spacing between columns and the sediment diameter. In their study, the grid-type sabo dams were constructed in a straight flume with the basin model at a gradient of 4.2° . They did not vary the gradient or examine the performance differences of the vertical-type and horizontal-type dams. There was a study focused on the different shapes of dams [Harada and Satofuka, 2014], but it was only for dams in waterways with a slope greater than 15° .

Therefore, in this study, we collected information about actual open-type steel sabo dams and conducted channel experiments. We examined the effect of dam shapes on trap performance using three types of steel dam models. We focused only on boulder blocking, and did not consider debris wood blocking.

2. DATA OF OPEN-TYPE STEEL SABO DAMS INSTALLED IN PRACTICE

Table 1 shows the number of open-type steel sabo dams installed in practice. We classified the data from the Research Association for Steel Sabo Structures in Japan, 2014; in accordance with the installation slope gradients and the number of dams. In the three sediment transport areas, open-type sabo dams are most constructed in areas of debris flow deposition. Some dams are constructed in watercourses milder than 2° . In the area of debris flow deposition, dams are most installed in streams with gradients of $5\text{--}10^\circ$, and second-most installed in streams with gradients of $2\text{--}5^\circ$.

3. CHANNEL EXPERIMENT

3.1 METHOD

We used a rectangular straight channel, 450 cm long and 10 cm wide, with an adjustable gradient (**Fig. 1**). We set uniform roughness by distributing 1.4 mm diameter silica sand over the riverbed. We uniformly set 5-cm-thick sediment on 150 cm from the upstream end. We supplied water from the upstream end, and the sediment was eroded and a debris flow was generated. We collected sediment flowing from the

Fig.1 Overview of experiments

downstream end with a movable sampler consisting of four containers.

Figure 2 shows the sediment grain size distribution. The total volume of sediment is 6.7 L, including voids. We set 6.7 L from considering the sediment volume which 131 mm height sabo dam on 15 degree can trap with 1/2 deposition of original bed slope.

The sediment density was 2.50 g/cm^3 and the sediment concentration in the movable bed was 0.669 in volume. The maximum diameter (D_{95}) of the sediment was 10.35 mm. The sediment larger than 2 mm diameter is natural material and smaller than 2 mm diameter is artificial material.

After each trial, we separated the sediment trapped at the sabo dam and runoff sediment from the downstream end via screens into three different-sized groups: sediment over 9.5 mm (which can block with only one particle), 5.6–9.5 mm (which can block with

Fig. 2 Particle size distribution of sediment

Table 1 Number of open-type steel sabo dams installed

Region of sediment transport	Installation slope	The number of installation	
Occurrence of debris flow	over 15°	124	
Succeeding of debris flow	$10^\circ\text{--}15^\circ$	131	
Deposition of debris flow	$5^\circ\text{--}10^\circ$	104	156 (Sum of under 10°)
	$2^\circ\text{--}5^\circ$	46	
	under 2°	6

Picture 1 Dam models

two or three particles), and under 5.6 mm (which cannot block with this size group alone), and weighed each group. In this experiment, the runoff sediment indicate the sediment that passed through the dam and the sediment that flowed over the dam top was not contained.

We used three different-shaped open-type sabo dam models, as shown in **Picture 1** ; grid-type, vertical-type, and horizontal-type, composed of aluminum rods with a diameter of 8 mm. The dam models were 9.8 cm wide and 150 mm high, but the mean height were 131 mm when placed in the channel. Based on the technical standard for designing sabo facilities against debris flow and debris wood [Ministry of Land, Infrastructure, Transport and Tourism, 2007], sticks were placed at 10 mm intervals, which approximately correspond to the maximum particle size, but the lowest horizontal bar was set 15 mm above the riverbed. In order to trap sediment effectively, the grid-type dam with vertical columns was placed on the upstream side [Harada and Satofuka, 2014].

The experiments conducted are shown in **Table 2**. The water was supplied at the same friction velocity for each gradient. In order to confirm the results, we conducted three time-trials for each case.

3.2 RESULT and DISCUSSION

The sediment trap rates are shown in **Table 2** (No.1-3 indicate the trial number in the same experimental arrangement). The sediment trap rates are given by formula (1) as follows.

$$T[\%] = \frac{V_s}{V_s + V_{out}} \times 100 \quad (1)$$

Here, V_s indicates the volume of trapped sediment and V_{out} indicates the volume of runoff sediment as collected at the downstream end. In this experiment, the runoff sediments indicate the sediment that passed through the dam and the sediment that moved over the

Table 2 Experiment cases

Case	Slope (deg.)	Type	Discharge (L/s)	Time of water supply (sec.)
1-1	12	no dam	1.0	15
1-2		grid		
1-3		vertical		
1-4		horizontal		
2-1	9	no dam	1.4	19
2-2		grid		
2-3		vertical		
2-4		horizontal		
3-1	6	no dam	2.2	26
3-2		grid		
3-3		vertical		
3-4		horizontal		

Table 3 Sediment trap rate

Case	①	②	③
1-2	98.1 %	98.7 %	98.1 %
1-3	97.2 %	96.8 %	97.1 %
1-4	96.0 %	94.9 %	95.0 %
2-2	96.7 %	98.0 %	97.4 %
2-3	96.2 %	95.4 %	95.6 %
2-4	89.3 %	92.7 %	90.0 %
3-2	98.0 %	98.5 %	98.4 %
3-3	95.5 %	96.4 %	95.9 %
3-4	93.6 %	80.1 %	87.4 %

Fig. 3 Sediment trap rate

dam top is not contained.

Figure 3 indicates the sediment trap rate, comparing the difference between slope gradients and the shapes of dams. First, we compared the differences between slope gradients. The sediment trapping rates decreased when the slope decreased for horizontal-type dams ; however, for grid-type and vertical-type dams, the sediment trap rates were almost stable. For the range of gradients we conducted, as slope gradient decreased, the sediment concentrations also decreased. The grid-type-dams showed a very high sediment trapping rate, and the sediment trapping rates for vertical-type dams were stable, although the trapping rates were slightly less. However, the sediment trapping rates of horizontal-type dams were strongly influenced by changes in the gradient ; as the slope gradient decreased, the trapping rate also decreased. When comparing the shapes of the dams, the sediment trapping rates were the highest for the grid-type dam, second highest and almost similar for the vertical-type dam, and lowest for the horizontal-type dam.

Figures 4-6 show the sediment composition which passed through (a) and that trapped by dams (b). When we compared the performance of the different dam shapes, the horizontal-type dams demonstrated the

Fig. 4 Composition of runoff sediment (a) and trapped sediment (b) for grid-type dams

Fig. 6 Composition of runoff sediment (a) and trapped sediment (b) for horizontal-type dams

Fig. 5 Composition of runoff sediment (a) and trapped sediment (b) for vertical-type dams

greatest runoff of the biggest and the second biggest particles, the vertical-type dams demonstrated the second greatest, and the grid-type demonstrated the least runoff, regardless of slope gradient. The composition of runoff sediment showed little change across the different shapes in the 12° and 9° cases. However, in the 6° cases, the volume of total sediment, especially the biggest particles, trapped by horizontal-

type dams was smaller than the amount trapped by the other two types.

Second, we compared the performance of the trap function across the different shapes of dams. Hereafter, the value given for volume indicates the average value for each shape of dam. The difference in composition of trapped sediment by grid-type dams was 0.04 L of the biggest particles and 0.08 L of the second biggest particles. The difference of biggest particles and the second biggest particles show a small volume 0.002 L in the runoff sediment, and mostly was composed of the smallest particles.

More sediment passed through vertical-type dams than grid-types. The runoff sediment from vertical-type is 0.12 L at 12°, 0.18 L at 9°, and 0.16 L at 6°. And the runoff from grid-type is 0.07 L at 12°, 0.11 L at 9°, and 0.06 L at 6°. In vertical-type dams, More sediment passed through as the slope gradient decreased from 12° to 9°. The runoff of the largest particles is 0.02 L at 12°, 0.03 L at 9°, and 0.04 L at 6°.

The trap performance of the horizontal-type dams was degraded when the slope gradient decreased at 9° and 6°. A smaller volume of sediment was trapped, and more passed through the dams. The composition of trapped sediment differed as well. Horizontal-type dams trapped fewer of the biggest and second biggest particles than grid-type and vertical-type dams. The volume of runoff sediment became larger, especially in the amount of biggest and the second biggest particles. When we compared the volume of the runoff sediment for trials at 12° and 6°, the portion of the runoff

composed of the biggest particles increased from 0.05 L to 0.13 L and that of the second biggest particles increased from 0.08 L to 0.21 L. The total volume increased from 0.18 L to 0.51 L by a factor of 2.8 when the slope gradient decreased.

Fig. 7 Successive change of sediment concentration (a) and mean diameter (b) in cases without dams

Figures 7-10 show the successive changes of the concentration of runoff sediment (a) and the mean diameter (b). We also considered the cases without setting sabo dams. Since the sediment concentration changed largely during time series, the difference of

Fig. 9 Successive change of sediment concentration (a) and mean diameter (b) for vertical-type dams

Fig. 8 Successive change of sediment concentration (a) and mean diameter (b) for grid-type dams

Fig. 10 Successive change of sediment concentration (a) and mean diameter (b) for horizontal-type dams

sediment concentration between low concentration cases are not clear, the vertical axes that indicate sediment concentration are logarithmic. As the slope gradient steepens, the sediment concentration becomes higher and the mean diameter is bigger at the front of debris flow than in later flows. These results indicate that bigger particles were the first particles to move. When the slope decreased, this phenomenon occurred but showed a smaller change of the mean diameters over time. These results correspond to the recent studies such as Wada et al. (2015).

The runoff sediment concentration was much smaller in cases with dams than cases without dams. It appeared clearly for steep slopes and the shape of dams did not show specific differences. The horizontal-type dams, whose trap rate are smaller than the other type of dams, reduced the sediment concentration during the frontal flows. Without dam, the sediment concentration is 17% at 12° and 6% at 6° . Otherwise, when horizontal-dams are placed, the sediment concentration is about 5% at 12° and about 3.5% at 6° . Moreover, when vertical-dams are placed, the sediment concentration is about 2% at 12° and 6° , and when grid-dams are placed, the sediment concentration is under 1%.

With dams, the mean diameter became smaller earlier using grid-type dams than other types of dams. This effect is remarkable at 12° and 9° . It indicates that boulder blocking can easily occur although some big particles passed through the dams. In cases of vertical-type dams at 12° , the mean diameter of the frontal flow is slightly bigger and the smallest diameter reaching downstream later than in the grid-type. Therefore, the vertical-type dams do not block large particles as rapidly as the grid-type dams. In horizontal-type dams, the mean diameter of sediment during the frontal flow is bigger than in the other types. When compared to cases with no dam, the mean diameter of sediment in the later (after frontal) flow became smaller more quickly at slopes of 12° and 9° but became smaller later at 6° . Therefore, we can estimate that at 12° and 9° , the blocking occurs early in the flow, but at 6° blocking occurred more slowly and more sediment, including the biggest particles, passed through.

From these results, we can summarize as following :

When the slope gradient was mild, the trap rate of each dam differed by its shape. Namely, the trap rate of grid-type dams was stable. The trap rate of vertical-type dams was also stable but less than that of grid-type. However, the trap rate of horizontal-type dams decreased. This is because grid-type and vertical-type dams can trap sediment effectively during the frontal flow but horizontal-type dams cannot trap as much sediment as other types. Moreover, the grid-type could

trap better than the vertical-type due to horizontal column.

Figure 11 show the outline image of the trapping process with each dam type. When the sediment concentration is high (**Fig.11(a)**), and the sediment particle crowd each other so that distances between them are small, any type of dams can trap well. When the sediment concentration is low (**Fig.11(b)**), sediment particles only exist near the riverbed and the distance between each particle becomes larger. Therefore, the vertical-type and the grid-type, which have vertical columns from the riverbed, could trap from arch action process, (creating an “archway” where two or more particles wedge against each other) the same as in the high sediment concentration. However, in the horizontal-type cases, achieving boulder blocking was difficult to occur because the sediment particles frequently misses the horizontal column, which has a distance from the riverbed of 1.5 times the diameter of the maximum sediment.

Each type dam's opening rate is as follow, grid-type ; 0.29, vertical-type ; 0.48, and horizontal-type ; 0.48. The vertical-type and the horizontal-type are same. Dam up did not occur in all experiment cases. The vertical-type indicated higher trap rate than the horizontal-type. Therefore, vertical columns seemed to work for sediment trapping better than horizontal columns. The opening rate of the grid-type is smaller than other type dams. In addition, since several small sediment smaller than column interval was trapped between horizontal and vertical columns, the grid-type could trap much sediment than the vertical-type (**Fig.12**).

Once the sediment in the frontal flow is trapped, the dam shape has an effect on the sediment runoff of following flow. The horizontal-type dams can trap large particles that cannot pass through between columns or the surface of deposit sediment, but the smaller particles cannot block on the horizontal-type dam alone. When the sediment concentration is high, particles pile up and the possibility of blockading the

Fig. 11 The trapping process for open-type sabo dams when the sediment concentration is high (a) and low (b)

Fig. 12 The blocking condition with grid-type dam

opening of columns is higher than when it is low.

Even when the sediment concentration is low, as the sediment particles collide with each other, the smaller particles can be trapped via the arch action process. Furthermore, the grid-type dams have horizontal columns, decreasing the size of the openings and sediment runoff. Therefore, when considering the volume of trapped sediment from frontal flows that affects the dam's later trap performance, the grid-type dam traps the highest amount, the vertical-type dams trap the second highest amount, and the horizontal-type dams trap the lowest amount. The trapping performance of grid-type and vertical-type dam is stable although the gradient changes, but that of the horizontal-type dam is subject to variations in gradient, resulting in variations in the sediment concentration.

4. CONCLUSION

In our study, we collected information about actual open-type steel sabo dams, and conducted channel experiments to acquire information about the performance of different shapes of open-type steel sabo dams in trapping sediment at different slopes. Even when the slope gradient was moderate and the sediment concentration was low, the trap rates of the grid-type and vertical-type dams were stable, but that of horizontal-type dam decreased. When we compared the sediment trapping rates across the different shapes of dams, we found that it was highest in the grid-type dam, second highest and almost similar in the vertical-type dam, and lowest in the horizontal-type dam. The trap performance of the horizontal-type dam depends on the relationship between the sediment particle size and the interval between the blocking columns. Therefore, when the sediment concentration is low, if the sediment particle size is greater than the interval between columns, sediment is trapped and a blocking occurs. However, the vertical-type dam trap performance can be expected to increase via the arch action of smaller particles, resulting in an observed

improvement of the sediment trap rate. In addition to this process, the grid-type dams have smaller openings due to the horizontal columns, and the sediment trap rate is higher than that of the vertical-type dams.

In future studies, we are planning to consider the trap performance of open-type sabo dams for debris flows with debris wood, and we are aiming to propose a model that can express the blocking in lower-slope areas for open-type sabo dams based on the knowledge acquired from the experimental results.

ACKNOWLEDGMENT : This study was supported by the research grant from Sabo and Landslide Technical Center. Research Association for Steel Sabo Structures provided us precious data of the installation of open-type sabo dams in Japan. For the channel experiments, we used the facilities in the Ujigawa Hydraulics Laboratory of Disaster Prevention Research Institute, Kyoto University (Ujigawa Open Laboratory).

REFERENCES

- Satofuka, Y. and Mizuyama, T. (2005) : Numerical simulation on debris flow control by a grid dam, *Journal of the Japan Society of Erosion Control Engineering*, Vol. 57, No. 6, pp. 21-27.
- Takahashi, T., Nakagawa, H., Satofuka, Y. and Wang, H. (2001) : Stochastic model of blocking for a grid-type dam by large boulders in a debris flow, *Journal of Hydraulic Engineering*, Vol. 45, pp. 703-708.
- Mizuyama, T., Kobashi, S. and Mizuno, H. (1995) : Control of passing sediment with grid-type dams, *Journal of the Japan Society of Erosion Control Engineering*, Vol. 47, No. 5, pp. 8-13.
- Katade, R., Shibuya, H., Katsuki, S. and Shima, J. (2011) : Probabilistic prediction on capturing performances of rocks for steel check dam structure, *Journal of Japan Society of Civil Engineers A 1 (structural engineering and earthquake engineering)* Vol. 67, No. 3, pp. 477-492.
- Harada, N. and Satofuka, Y. (2014) : Debris flow controlled by steel-grid sabo dams according to grain-size frequency, *Journal of Japan Society of Civil Engineers B 1 (hydraulic engineering)*, Vol. 70, No. 4, pp. 1_931-936.
- Hiramatsu, S., Fukuyama, T., Yamada, T., Ohsaka, O., Nakatani, K., Matsumoto, N., Fujimura, N., Kato, N., Shimada, T., Kubo, T., Matsuo, S., Nishio, Y. and Yoshino, K. (2014) : Disaster report on the debris flow occurred on 9 July 2014 in Nagiso, Nagano prefecture, *Journal of the Japan Society of Erosion Control Engineering*, Vol. 67, No. 4, pp. 38-48.
- Matsumura, K., Hasegawa, Y., Fujimoto, M., Nakatani, K., Nishikawa, T., Kasahara, T., Yanagizaki, G., Kagamihara, S., Kato, T., Okano, K., Suzuki, T. and Hiraoka, N. (2015) : The debris flow occurred in the Tanba city by typhoon No.11 in 2014, *Journal of the Japan Society of Erosion Control Engineering*, Vol. 68, No. 1, pp. 60-67.
- Mizuyama, T., Ohkubo, S., Ido, K. and Ochi, H. (1997) : Planning of slit sabo dams to control bedload, *Journal of the*

- Japan Society of Erosion Control Engineering, Vol. 49, No. 5, pp. 49-52.
- Mizuyama, T. and Oda, A. (2000) : Sediment control with a slit sabo dam in a debris flow torrent, Journal of the Japan Society of Erosion Control Engineering, Vol. 52, No. 6, pp. 56-60.
- Horiuchi, S., Akanuma, J., Ogawa, K., Kuraoka, S., Sugiyama, M., Morita, T., Itoh, T. and Mizuyama, T. (2009) : Hydraulic model tests for evaluating sediment control function with a grid-type high dam in a straight flume, Journal of the Japan Society of Erosion Control Engineering, Vol. 62, No. 2, pp. 29-36.
- Horiuchi, S., Akanuma, J., Ogawa, K., Kuraoka, S., Sugiyama, M., Morita, T., Itoh, T. and Mizuyama, T. (2009) : Hydraulic model tests for evaluating sediment control function with a grid-type high dam, Journal of the Japan Society of Erosion Control Engineering, Vol. 62, No. 2, pp. 37-44.
- Ministry of Land, Infrastructure, Transport and Tourism (2007) : Technical standard for designing sabo facilities against debris flow and driftwood
- Wada, T., Furuya, T., Nakatani, K., Mizuyama, T. and Satofuka, Y. (2015) : Experimental study of factors that affect the concentration of larger particles at the front of debris flows, Journal of the Japan Society of Erosion Control Engineering, Vol. 67, No. 6, pp. 56 – 63.
- Moriyama, H., Kato, M., Takano, A. and Kawamura, T. (2010) : Experimental study of steel grid dam for debris flow composed by small rock, Journal of the Japan Society of Erosion Control Engineering, Vol. 62, No. 6, pp. 30 – 33.
- Received : 31 August, 2016
Accepted : 19 January, 2017