Experimental Study of Sabo Dam Physical Measures Against Subsequent Sediment Flow Following Debris Flow Deposition

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Typical countermeasures against subsequent sediment flow following debris deposition include channel works and sand pockets; however, these measures require extensive open areas. Therefore, alternative countermeasure designs must be considered for residential areas with high population density. The objective of this study was to propose a novel method for capturing subsequent sediment flow following debris deposition at a sabo dam. We installed three types of debris capture devices (subsequent sediment flow breaker, water-absorbing polymer, and sub-dam) to investigate their effects singly and in combination. Subsequent sediment flow characteristics were evaluated in flume experiments using models of the three capture devices. Simulated debris flow was trapped by the sabo dam model, and subsequent sediment flow was controlled by the three countermeasures installed downstream of the dam. Sediment was separated from water using the subsequent sediment flow breaker and then trapped by the sub-dam, and water was absorbed by the polymer. We measured 1) the volume of sediment collected by the breaker, 2) time elapsed from the sabo dam to the end of the flume, 3) peak discharge, and 4) concentration of the subsequent sediment flow. Sediment volume decreased and elapsed time increased as the sediment flowed through the experimental countermeasure structures, leading to dramatic reductions in peak discharge and sediment concentration downstream of the sabo dam.

Key words: subsequent sediment flow, hydrograph, peak discharge, concentration

1. INTRODUCTION

In the Japanese sabo dam (SD) system, a single dam is generally constructed at a valley outlet to capture debris flow in regions prone to torrential rainfall. New standards for SD design were proposed by the National Institute for Land and Infrastructure Management (NILIM) in 2016, highlighting the need to empirically and theoretically estimate the amount of debris flow that might accompany extreme rainfall events, characterized by 100-year exceedance probability for 24-hour or daily rainfall. Several studies have reported the effects of SDs in mitigating debris flow damage by trapping sediment [Senoo et al., 1983; Irazawa and Shimohigashi, 1988; Ohkubo et al., 1988].

SD trapped the debris flow, and then sediment flow flows to downstream in the lower of SD. Whereas, part of debris flow overflow through SD and deposit on downstream directly in the lower of SD in case debris flow volume is larger than SD designated capacity. And after, sediment flow flows to downstream. Phenomenon of mentioned first, it defines as a subsequent sediment flow (hereinafter “SSF”) in this study (Fig. 1). SSF may reach residential areas, and such events can be damaging to buildings, property, and human life, as well as the local economy [Handa and Yamada, 2011]. Also we recognized the actual situation of damaged by SSF where disaster occurred at Hiroshima in 2018.

Therefore, countermeasure against SSF are sometimes installed downstream of SDs such as channel works or sand pockets. However, such countermeasures require extensive open areas and are therefore difficult to construct near residential areas with high population density (Fig. 2). Additionally, in some regions, the cross-sectional area of SD drainage measures may be insufficient to control SSF. For these reasons, the Japan Society of Erosion Control Engineering (JSECE) emphasized the necessity of installing SSF countermeasures in residential areas following the 2018 Hiroshima disaster [JSECE, 2015]. To mitigate SSF, outflow discharge and sediment concentration must be reduced by separating sediment
from water. Debris flow breakers are one of the structures to prevent sediment-related disasters by separate sediment and water in mountain terrains and residential areas [ICHARM, 2008]. Watanabe et al. [1980] has shown that the capturing effect of debris flow (mud) by debris flow breaker, and separation of water and sediment by debris flow breaker was filmed in Mt. Yakedake [Kiyono et al., 1986; Imai et al., 1989]. The mechanisms of this process have been previously explained [Gonda, 2009], and quantitative and qualitative assessments have been performed using a flat-board SSF breaker [Kim et al., 2016]. This type of countermeasure is thus effective for the separation of water and sediment as long as the size of the breaker openings is narrower than sediment particle of the debris flow. Similarly, a water-sediment separation structure was recently proposed to remove coarse particles from debris flow [Xie et al., 2014, 2017]; it consisted of a drainage dyke, herringbone water-sediment separation grid, outflow channel, and deposit field. This structure was found to reduce the discharge of debris flow; however, sediment flow after separation was not controlled. The flow of water and fine sediments must be further mitigated downstream of the breaker to prevent damage.

Water-absorbing polymer is considered an efficient material for controlling the flow of water in SSF due to the polymer’s gelation properties. Flume experiments using such polymers have demonstrated their ability to mitigate debris flow [Arai et al., 1997; Kurihara et al., 1989]. Fine sediment could be further controlled by the installation of a sub-dam downstream of these measures.

The objective of this study was to propose a novel SSF countermeasure for installation at sabo facilities upstream of residential areas. We investigated physical measures against SSF that are applicable in narrow areas by performing flume experiments using models of three types of SSF countermeasures (SSF breaker, water-absorbing polymer, and sub-dam) to examine their effects on SSF discharge and duration (Fig. 3).

2. METHODS

In the flume experiment, we first trapped a simulated debris flow using a model SD and then controlled SSF using models of an SSF breaker, water-absorbing polymer, and sub-dam. The experimental conditions are shown in Fig. 4. The experimental flume comprised an upper part (140 cm long, 6.5 cm
wide, 10 cm high, 18° gradient) and a lower part (25 cm long, 7.8 cm wide, 10 cm high, 10° gradient). To generate a debris flow, we fixed debris (625 cm³, d₉₀ = 1.5 mm) at the upper part of the flume and provided a constant supply of water (250 cm³/s) from upstream of the debris for 2.5 s. The amount of supplied debris was determined according to the sediment volume in a SD at full deposition. The full depositional gradient was set at 1/2 θ, following a preliminary experiment, where θ is the gradient of the upper part of the flume. Water was supplied for a final debris flow concentration of approximately 40%, with a sediment : water ratio of 1 : 1.

One SD model was installed at the gradient inflection point (equivalent to a valley exit) to capture debris. An SSF breaker model (length, 15 cm) was attached to the SD model to induce sedimentation of SSF. The SSF generation process is shown in Fig. 5. We collected SSF samples at the outlet at the bottom part of flume; these samples were used to estimate particle diameter (mean : 0.7 mm, d₉₀ : 3 mm, dmax : 4 mm). We therefore varied the opening size of the breaker, setting it at 0, 0.5, 0.7, 1, 2, 3, 3.5, and 4 mm to determine the optimal breaker opening size (Fig. 6).

We selected CP-1 as the water-absorbent polymer and performed an absorption ability test (AAT) to determine the suitable amount of polymer for the experiment (Fig. 7). The AAT was conducted under the static condition using 600 mL SSF and 150, 300, 450, and 600 mL water (i.e., ratios of 1/4, 1/2, 3/4, and 1). The initial amount of polymer was 1.2 g, which is able to absorb up to 600 mL of water (about 300-500 times its mass); the polymer mass was set at 1.2, 3, 5, 10, 20, 30, 40, 50, and 60 g. The time elapsed until gelation was calculated by adding t₀ and t₁ (t₀ : the moment of water contact with polymer, t₁ : the moment of finishing the gelation).

A sub-dam model was installed in the flume to trap sediment and create a pool to increase absorption by the polymer. To determine the location and height of the sub-dam, we considered the effects of compaction. The sub-dam was placed at the point of sediment outflow from the SSF breaker, i.e., 12 cm downstream from the SD. A sub-dam with a height of 5.8 cm was found to trap the entire SSF. We therefore conducted experiments using four sub-dam heights: 2.2, 3.5, 4.6, and 5.8 cm (i.e., 1/4, 1/2, 3/4, and 1 of the total height).

Therefore, we performed a total of 18 experiments (Cases 1-18) with varying parameters (Table 1). Case
1 was designed to determine the fundamental SSF conditions of the SD model. In Cases 2-9, we added the SSF breaker model, varying the breaker opening size. The peak discharge, elapsed time, and SSF concentration results of Cases 2-9 allowed us to determine the effective SSF breaker opening size (2 mm, Case 6). In case 10, we added the water-absorbent polymer. In Cases 11-14, we added the sub-dam model to Case 6. Cases 15-18 were conducted using all three experimental countermeasure structures. We measured the time elapsed from the SD to the end of the flume, sediment volume at the SSF breaker, peak discharge, and concentration in all experiments to determine the effectiveness of the experimental countermeasure structures. All experiments were videotaped in side view. SSF samples were collected using a catchment box at an outlet at the bottom part of the flume to calculate sediment volume and weight; a hydrograph and SSF concentration was analyzed by using 10 samples. Concentration was calculated from the total SSF volume and sediment volume. SSF peak discharge was determined using the hydrograph, where peak discharge was the highest value.

3. RESULTS

3.1 Polymer absorption ability

The AAT results showed that the optimal amount of polymer was 20 g (Fig. 8); even if larger amounts of polymer supplied to water, resulted in gelation within approximately the same amount of time.

3.2 SSF breaker performance

Examples of the SSF breaker performance in Cases 2-9 are shown in Fig. 9. The breaker effectively reduced elapsed time, peak discharge, and SSF concentration (Fig. 10(a)). The longest elapsed time was observed in Case 6 (0.86 s), which took 0.14 s longer than Case 1. The highest peak discharge was observed in Case 1 (337.7 cm$^3$/s), followed by Case 2 (195.2 cm$^3$/s, a 42.2% decrease). The smallest peak discharge was observed in Case 6 (131.9 cm$^3$/s), which was 61.9% lower than that in Case 1. The largest sediment volume at the SSF breaker was observed in Case 2 (15 cm$^3$), and the smallest in Case 9 (2.3 cm$^3$).

| Experimental cases and result values of each case |
|-----------------------------------------------|
| **Case** | **$L_s$ (cm)** | **$S_s$ (mm)** | **$d_{SSF}$/$S_s$** | **$H_s$ (cm)** | **Elapsed time (s)** | **$V_s$ (cm$^3$)** | **C (%)** | **$Q_p$ (cm$^3$/s)** |
|----------|----------------|----------------|----------------------|----------------|----------------------|-------------------|-----------|---------------------|
| SD       | 1              |                |                      |                |                      |                   |           |                     |
| Case 1   |                |                |                      |                |                      |                   |           |                     |
| Case 2   | 0.00           |                |                      |                |                      | 0.72              | 14.34     | 337.65              |
| Case 3   | 0.50           | 2.13           |                      |                |                      | 0.56              | 15.02     | 195.19              |
| Case 4   | 0.70           | 1.53           |                      |                |                      | 0.77              | 14.05     | 154.59              |
| Case 5   | 1.00           | 1.08           |                      |                |                      | 0.84              | 12.12     | 147.80              |
| Case 6   | 2.00           | 0.54           |                      |                |                      | 0.86              | 9.53      | 131.89              |
| Case 7   | 3.00           | 0.36           |                      |                |                      | 0.85              | 4.85      | 136.37              |
| Case 8   | 3.50           | 0.33           |                      |                |                      | 0.76              | 2.91      | 150.62              |
| Case 9   | 4.00           | 0.29           |                      |                |                      | 0.77              | 2.26      | 146.98              |
| SD + SSF breaker + P(20)           | 15             |                |                      |                |                      | 2.20              | 9.21      | 352.31              |
| Case 10  |                |                |                      |                |                      |                   |           |                     |
| Case 11  |                |                |                      |                |                      | 2.20              | 1.52      | 10.18               |
| Case 12  |                |                |                      |                |                      | 3.50              | 3.61      | 8.24                |
| Case 13  |                |                |                      |                |                      | 4.60              | 4.85      | 10.02               |
| Case 14  |                |                |                      |                |                      | 5.80              | 8.88      | 0.00                |
| SD + SSF breaker + Sub-dam         |                | 2.00           | 0.54                 |                |                      |                   |           |                     |
| Case 15  |                |                |                      |                |                      | 2.20              | 1.44      | 9.37                |
| Case 16  |                |                |                      |                |                      | 3.50              | 2.76      | 10.66               |
| Case 17  |                |                |                      |                |                      | 4.60              | 5.13      | 11.15               |
| Case 18  |                |                |                      |                |                      | 5.80              | 10.98     | 0.00                |

*SD: Sub-dam, P(20): Polymer 20g, $L_s$: Length of SSF breaker, $d_{SSF}$: mean particle size of sediment on the SSF breaker, $S_s$: Opening size of SSF breaker, $H_s$: Height of Sub-dam, $V_s$: Volume of sediment on the SSF breaker, $Q_p$: Peak discharge.
breaker opening size of 2 mm.

3.3 Combined application of both SSF breaker and polymer

In Case 10, we recreated the Case 6 conditions and added the water-absorbing polymer. The result was an elapsed time of 0.82 s, peak discharge of 135.2 cm$^3$/s, SSF breaker sediment volume of 9.2 cm$^3$, and concentration of 2.51%. These values are nearly the same as those obtained in Case 6, demonstrating that polymer application had no significant effect on the measured parameters.

3.4 Combined application of both SSF breaker and sub-dam

In Cases 11-14, we applied both the SSF breaker and sub-dam; hydrographs for these experiments are shown in Fig. 10(b). The addition of the sub-dam clearly increased the elapsed time and decreased the concentration and peak discharge. Compared with Case 1, the elapsed time increased by 0.8 to 4.13 s, depending on the height of the sub-dam. Peak discharge was reduced by more than 82%. Sediment was deposited at the sub-dam, decreasing the concentration by 97%. The effects of the sub-dam were very similar to those observed in Cases 11-14 (SSF breaker and sub-dam). As in Case 14, we could not measure elapsed time, peak discharge, or concentration in Case 18.

For comparison, hydrographs of SSF for cases with only the SD and SSF breaker are shown in Fig. 10(d).

The relationship between peak discharge and elapsed time is shown in Fig. 11. The peak discharge was larger when there was less time for SSF to reach the bottom part of the flume. A comparison of Case 1 with Cases 2-10 shows the effect of the SSF breaker. In Case 2, SSF moved rapidly over the SSF breaker because there was no room for deposition; thus, peak discharge was large. However, in Cases 3-10, peak discharge decreased by 50-60%. In Cases 11-18, SSF was trapped by the sub-dam, lengthening the elapsed time and reducing peak discharge by ≥80% by decreasing SSF velocity.

The relationship between sediment volume at the SSF breaker and sediment concentration is shown in Fig. 12. In Cases 2-9, sediment volume at the breaker was affected by the breaker opening size. When larger amounts of sediment were deposited at the breaker, less sediment was discharged, thereby reducing sediment concentration. However, sediment concentration was larger in Case 2 than in Cases 3-6 because sediment overflowed the SSF breaker. In Cases 11-18, in which the SSF breaker opening size was the same as in Case 6, sediment concentration decreased by > 90% because the sediment passing through the breaker was trapped by the sub-dam. When the concentration was 0%, all sediment and water passing through the SSF breaker was trapped by the sub-dam.

Results for Cases 11-18 are shown in Fig. 13; these images were taken 60 s after the experiments. The red line indicates the height of sediment deposited and water gelated at the sub-dam (side view).
Fig. 10 Hydrographs of SSF
height of the sub-dam, it was difficult to determine the effect of the polymer in Cases 17 and 18. Although the gelation process took time, the effect of the polymer was confirmed for Cases 15 and 16.

4. DISCUSSION

Installation of the SSF breaker increased the amount of deposition from SSF. The optimal SSF breaker opening size to decrease peak discharge was calculated as $d_{50}/S_o = 0.54$ for the flume conditions in this study. The SSF concentration was lowest in Case 5 ($d_{50}/S_o = 1.08$). Larger values of $d_{50}/S_o$ were characteristic of SSF breaker overflow regardless of the amount of sediment deposited at the breaker. In such cases, sediment concentration was low, but peak discharge was high. Smaller values of $d_{50}/S_o$ were predictive of SSF passing through the SSF breaker to the flume outlet, increasing peak discharge and concentration.

Under the conditions of our flume experiments, the amount of water contained in SSF was nearly 650 mL. It took about 50 s for the 20-g polymer to gelate the water in our simulated SSF (Fig. 8). Despite the pool created by the sub-dam, very short periods were allowed for gelation by the polymer during our experiments (Table 2). Therefore, it was difficult to confirm the effectiveness of the polymer used in this study. However, the installation of the SSF breaker and sub-dam at the SD in our flume model decreased both peak discharge and SSF concentration, especially when the height of the sub-dam was large.

5. CONCLUSION

In this study, we conducted flume experiments to determine how installing an SSF breaker, polymer, and sub-dam downstream of a SD would affect SSF. We determined that the optimal value of $d_{50}/S_o$ was 0.54 to decrease peak discharge and SSF concentration under the conditions of these experiments. The installation of the SSF breaker decreased peak discharge and SSF concentration; the addition of a sub-dam considerably enhanced these effects, especially when the height of the sub-dam was large due to its greater ability to trap sediment.

Future studies should conduct detailed investigation of water-absorbing polymers in the field, as small-
scale experiments do not allow sufficient time for water gelation. Controlling the amount of water in SSF is important for mitigating damage in SSF-related disasters. The amount and grain size of supplied sediment should also be varied to obtain empirical data applicable to further field studies.

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REFERENCES
Ashida, K. and Takahashi, T. (1980) : Study on debris flow control-hydraulic function of grid type open dam, Annuals. Disaster Prevention Res. Inst., Kyoto Univ., No. 23 B-2, pp. 1–9 (in Japanese with English abstract).
Arai, M., Takahashi, T. and Kato, C. (1997) : Effect on particle size by controlling of debris flow by absorbent polymer, Proceeding of 2nd Annual conference of JSECE, No. 52, pp. 466–467 (in Japanese).
Gonda, Y. (2009) : Function of a debris-flow brake, International Journal of Erosion Control Engineering, Vol. 2, No. 1, pp. 15–21.
Handa, R. and Yamada, T. (2011) : Damage characteristics of houses in the subsequent sediment flow prone area, Proceeding of 60th Annual conference of JSECE, pp. 558–559 (in Japanese).
ICHARM (2008) : Debris-flow dewatering brakes : a promising tool for disaster management in developing countries, International Center for Water Hazard and Risk Management Newsletter, Vol. 3, No. 3, pp. 10.
Imai, K., Miyamoto, N. and Mizuyama, T. (1989) : Test of a debris flow breaker at the Kamikamihori valley, Mt.Yakedake (Part-2), Journal of the Japan Society of Erosion Control Engineering, Vol. 42, No. 2 (163), pp. 16–20 (in Japanese).
Irazawa M. and Shimohigashi H. (1988) : Study of disaster prevention with a sabo dam, Journal of the Japan Society of Erosion Control Engineering, Vol. 41, No. 3 (158), pp. 11–16 (in Japanese).
JSECE (2015) : Suggestion based on emergency survey by Japan Society of Erosion Control Engineering of Large-scale debris flow disaster in Hiroshima. Journal of the Japan Society of Erosion Control Engineering, Vol. 68, No. 1, pp. 103–105 (in Japanese).
Kim, Jin Hak, Kun Woo Chun, Jung Il Seo, Suk Woo Kim, Ju Ung Yun, and Kye Won Jun. (2016) : An examination of optimum slit aperture suited to flat-board debris-flow breaker in residential piedmont areas, Crisisonomy, Vol. 12, No. 4, pp. 73–83 (in Korean).
Kiyono M., Miyakoshi H., Uehara S. and Mizuyama T.(1986) : Test of a debris-flow brake in Kamikami valley, Mt.Yakedake, Journal of the Japan Society of Erosion Control Engineering, Vol. 39, No. 3 (146), pp. 15–19 (in Japanese).
Kurihara, J., Mizuyama, T. and Suzuki, H. (1989) : Effect on controlling the debris flow by absorbent polymer, Proceeding of 38th Annual conference of JSECE, pp. 161–164 (in Japanese).
NILIM (2016) : Manual of Technical Standard for establishing Sabo master plan for debris flow and driftwood, Technical note of National Institute for Land and Infrastructure Management, No. 904 (In Japanese with English abstract)
Ohkubo, S., Fukui, N., Mizuyama, T. and Sugasaki, M. (1988) : Analysis of sediment discharge control with sabo dams, Journal of the Japan Society of Erosion Control Engineering, Vol. 41, No. 4 (159), pp. 21–25 (in Japanese).
Senoo, K., Mizuyama, T. and Uehara, S. (1983) : Experimental study on checking of debris flows with sabo dams, Journal of the Japan Society of Erosion Control Engineering, Vol. 36, No. 2 (129), pp. 17–23 (in Japanese with English abstract).
Watanabe, M., Mizuyama, T. and Uehara, S. (1980) : Review of debris flow countermeasure facilities, Journal of the Japan Society of Erosion Control Engineering, Vol. 32, No. 4, pp. 40–45 (in Japanese).
Xie, T., Yang, H., Wei, F., Gardner, JS., Dai, Z. and Xie, X. (2014) : A new water-sediment separation structure for debris flow defense and its model test. Bull Eng Geol Environ, 73 (4) : pp. 947–958.
Xie, T., Wei, F., Yang, H., Gardner, J. S. and Xie, X. (2017) : A design method for a debris flow water-sediment separation structure. Eng. Geol. 220, pp. 94–98.

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