Influence of approach shape of debris flow on impact load subjected to open Sabo dam under an overturning experiment of open Sabo dam

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Abstract. Recently high intensity rainfall disaster induces some structural failure of steel pipe open Sabo dam. To prevent such failure of the dam, a new design concept is necessary at the severe load exceeding the present design load. However, influence of debris flow impact load on steel pipe open Sabo dam is not clear to make a design load. The study experimentally approaches a vertical load distribution shape and its time history based on comparison with a wedge approach shape or a front boulder concentrated shape. The load and moment action of a front boulder concentrated shape debris flow is greater than that of a wedge approach shape. Mechanism making the difference is made clear by observation of vertical detail measurement of impact load.

1 Introduction

The magnitude of debris flow caused by torrential rains and typhoons is increasing in Japan. Debris flow caused damage over a wide region in a short period of time. Debris flows are highly destructive to houses and public property. Sabo dams are required as a countermeasure structure. In recent years, open Sabo dam have been constructed mainly due to environmental considerations. The structural stability calculations are based on the design criteria for closed Sabo dams [1-3]. However, the design load originally acting on an open Sabo dam is different load. It is known that the approaching shape of a debris flow depends on the slope and flow rate. The debris flow loads acting on open Sabo dams differ due to the effect of the approach shape.

Mizuyama et al. [4] evaluated debris flow loads based on two patterns of debris flow shapes from the flow rates with dimensionless channel gradients. However, the loads acting on open Sabo dam with remain unexamined. Miyoshi et al. [5] showed from the relationship between maximum load and flow velocity that the shape of dynamic load waveform can be classified according to flow velocity. In particular, it was shown that approaching waves with high velocities produce loads with clear peaks in a short period of time. However, the velocity of the debris flow changes the shape of the approach, and the action load changes with the velocity. On the other hand, the effect of the approach shape of the debris flow together with the velocity of the flow on the applied load remains unexplored. The distribution with respect to the height direction used in design should be considered.

This study examines the effect of different debris approach shapes on debris flow impact loads. The dynamic difference of the impact load of the debris flow is studied under the condition of constant flow velocity.

2 Outline of experiment

2.1 Channel flume

Figure 1 shows the channel used in the experiment. The channel is 4.5 m length, 30 cm width, and 50 cm depth. The slope of the channel is adjustable from 0° to 20°.

2.2 Sabo dam model

Figure 2 shows an overview of Sabo dam model. The Sabo dam model was designed with a height of 26 cm due to limitation of the experimental channel. This is approximately 1/40 of the real height of 10 m by the Froude similarity rule.

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Figure 3 shows the load measurement device. The Sabo dam model consists of a main unit and a load measurement section. The mass of the weight at the top of the main unit can be varied. The moment of resistance for overturning can be adjusted as follows.

\[ M_r = W_B \cdot l_B + W_W \cdot l_W = m_B \cdot g \cdot l_B + m_W \cdot g \cdot l_W \]  

(1)

Where, \( M_r \) : moment of resistance, \( W_B, m_B \) : weight and mass of the main unit, \( W_W, m_W \) : weight and mass of deadweight, \( l_B, l_W \) : horizontal distance between \( W_B, W_W \) and the hinge, respectively, \( g \) : acceleration of gravity.

The main unit has an effective height of 260 mm and depth of 290 mm. The weight of the main unit is 48 N. It can be tipped over by connecting the rear end of the bottom plate to the bottom surface with a hinge. The distance between the hinge and the upstream face of the main unit is 245 mm. A total of 12 load cells (LMB-A-500 N-P) are installed on the upstream face of the load measuring section. The height of the first, second, third, fourth, fifth, and sixth stages are 5 cm, 8 cm, 13 cm, 17 cm, 21 cm, and 25 cm, respectively. It has an opening in the crosswise direction. Without the pressure receiving beams, both water flow and gravel can pass freely. Slider receiving plates (plastic plates) are attached to both sides of the body to catch the force of the slider.

Figure 4 shows the movement of the slider and the contact plate. Each stage of sliders can move independently in the horizontal direction. There is a roller at the downstream end, and when this roller contacts the slider receiving plate, the slider is pushed from the upstream side through the pressure receiving beam. When an action moment greater is generated than the resistance moment, the main unit rotates around the hinge, the slider support plate rises upward, and the slider moves downstream. The rollers are used to reduce friction between the slider and the receiving plate.

2.3 Debris flow model

Figure 5 shows the initial conditions for generating a front boulder concentrated shape debris flow. The classifying phenomenon of the debris flow has occurred, and surge has been formed. The bed slope was set to \( \theta = 15^\circ \), which is the section where the debris flows downstream. Referring to the Matsumura et al. [6], bottom roughness of 5.0 mm height and 10 mm width were placed on the bottom at intervals of 30 mm for a length of 50 cm upstream from the Sabo dam model. A portion of the gravel mass was spread over 2.0 m upstream from the top of the bottom roughness to a thickness of 3.0 cm to form a moving bed. About 40 kg of the gravel mass was placed in a trapezoidal shape 15 cm thick for 1.0 m upstream, and water flow was applied from the rear.

Figure 6 shows the initial conditions for generating a wedge approach shape debris flow. The bed slope was set to \( \theta = 13^\circ \). The acrylic bottom was placed 50 cm upstream from the Sabo dam model, and the bottom roughness was placed 50 cm upstream of the acrylic bottom. The initial placement of the gravel mass was made by spreading 45 kg of gravel from the top of the bottom roughness to a thickness of 3.0 cm over 1.5 m upstream of the top of the bottom roughness. A trapezoidal-shaped gravel mass was placed upstream of it, and water flow was applied from behind it. The water
flow was provided by a dam-break system in which 20 L of water was stored at a front depth of 30 cm and then released all at once.

### 3 Experimental results

#### 3.1 Total load comparison

Figure 7 shows the relationship between total load and time for each experiment near the limit of overturning for each approach shape. The total load is the sum of the measured loads at each stage. The maximum total load \( (P_t = 227 \text{ N}) \) for the front boulder concentrated shape reached 0.26 s after the tip of the debris flow impacted. The wedge approach shape total load \( (W = 5 \text{ kg}) \) reaches its maximum total load \( (P_t = 155 \text{ N}) \) when the time is 0.65 s. The maximum total load and sediment load are 46 % and 54 % higher, respectively, for the front boulder concentrated type. Therefore, the impact effect on the maximum total load is greater when the gravel is concentrated at the head.

#### 3.2 Comparison of load to time relationship for each stage

Figure 8 shows the relationship between load in each stage and time of the front boulder concentrated shape. The maximum load on each stage increases rapidly upon impact of the flow. Its impact occurs with a time lag of approximately 0.04 s at each stage. On the other hand, the maximum load generation time is 0.14 s for the first step, 0.17 s for the second step, 0.30 s for the third step, 0.31 s for the fourth step, 0.43 s for the fifth step, and 0.53 s for the sixth step.

The maximum load on each step is 113 N for the first step, 93 N for the second step, 61 N for the third step, 57 N for the fourth step, 54 N for the fifth step, and 39 N for the sixth step. The values decrease with the height of the impact point. This is thought to be due to the influence of the preceding stop gravel, which causes the following gravel to lose velocity due to repeated minor collisions with the preceding stop gravel [7-8].

Figure 9 shows the relationship between load in each stage and time of the wedge approach shape. Its impacts occurred with a time lag of approximately 0.06 s for each stage. The maximum load generation time is 0.24 s for the first stage, 0.35 s for the second stage, 0.49 s for the third stage, 0.61 s for the fourth stage, 0.68 s for the fifth stage, and 0.98 s for the sixth stage. Comparing the time difference between the onset of the maximum load at the first stage and the onset of the maximum load at the sixth stage, the time delay in the height direction is remarkable for the wedge approach shape, 0.74 s compared to 0.39 s for the front boulder concentrated shape. The maximum load for each stage is 95 N for the first stage, 34 N for the second stage, 33 N for the third stage, 27 N for the fourth stage, 31 N for the fifth stage, and 22 N for the sixth stage. The first stage is significantly larger than the sand and gravel load, but the impact load above the second stage is not as large as that of the front boulder concentrated shape.

#### 3.3 Total moment comparison

Figure 10 shows the relationship between total moment of action and time. The total moment of action is the sum of the moments of action at each stage, obtained by multiplying the load measured at each stage by the distance from the hinge. The maximum total acting moment \( (M_{ac} = 30.9 \text{ N} \cdot \text{m}) \) for the front boulder concentrated \( (W = 8 \text{ kg}) \) is reached 0.40 s after the impact of the debris flow. In the wedge approach shape \( (W = 5 \text{ kg}) \) of the relationship between total action moment and time, the maximum total action moment \( (M_{ac} = 22.2 \text{ N} \cdot \text{m}) \) is reached 0.72 s after impact. Comparing between the total reaction moment of the front boulder concentrated shape and the wedge approach shape, the maximum total reaction moment is 39 % greater for the front boulder concentrated shape. In other words, the front boulder concentrated shape has a greater impact effect on the moment of action as well as the impact load.

#### 3.4 Moment to time relationship for each stage

Figure 11 shows the relationship between moment of action in each stage and time of the front boulder concentrated shape \( (W = 8 \text{ kg}) \). The maximum total moment of action is almost the same as the time of the maximum moment under the fifth stage shown in Figure 9, indicating that the dominant factor is the upper impact load. The maximum moment for each stage is 5.7 N·m for the first stage, 7.7 N·m for the second stage, 7.6 N·m for the third stage, 9.7 N·m for the fourth stage, 11.6
N·m for the fifth stage, and 9.9 N·m for the sixth stage. The following is an example of the use of a single unit of the same size.

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Figure 12 shows the relationship between moment of action in each stage and time of the wedge approach shape (W = 5 kg). The maximum total moment is almost coincident with the time in the moment of the sixth stage shown in Figure 11. The maximum moment of action for each stage is 4.8 N·m for the first stage, 3.1 N·m for the second stage, 4.4 N·m for the third stage, 4.6 N·m for the fourth stage, 6.9 N·m for the fifth stage, and 5.7 N·m for the sixth stage. In the wedge approach shape type, the load in Figure 9 was maximum at the first stage, but the moment of action in Figure 12 was maximum at the fifth stage, and it increased in proportion to the height direction. Therefore, the height of the impact point has a significant effect on the total moment of action for both the front boulder concentrated shape and the wedge approach shape.

4 Conclusion

This study examines the influences of the shape of the approaching debris flow on the impact load acting on open Sabo dam. The results obtained can be summarized as follows.

1) The maximum total load of the wedge approach shape is about 70 % of that of the front boulder concentrated shape. The maximum moment of action is relatively small, about 80 % of that of the front boulder concentrated shape. After the maximum load, the load converges to a static gravel load, which is about 45 % of the maximum load.

2) The maximum total load of the wedge approach shape is about 70 % of that of the front boulder concentrated shape, and the maximum moment of action is about 80 % of that of the front boulder concentrated shape, which is relatively small. After the maximum load, the load converges to a static gravel load, which is about 45 % of the maximum load.

3) The impact load of a debris flow decreases gradually with height. This is because the velocity reduction effect due to fine collision friction with the gravel mass deposited after the preceding collision has a greater effect on the wedge approach shape type.

4) The front boulder concentrated shape has a higher impact load on the Sabo dam than the wedge approach shape. However, quantitative differences in their effects need to be investigated through structural analysis.

References