Heavy rainfall and earthquakes tend to cause large-scale landslides and create large landslide dams. Large landslide dams retain large amounts of water and often burst causing floods and catastrophic damages downstream. Therefore, the study of landslide dam deformation is essential for predicting potential floods to implement effective flood risk management. To understand landslide dam deformation and dam outflow discharge characteristics, we carried out flume experiments to measure the landslide dam deformation and outflow discharge by overtopping. In the flume experiments, we examined the effect of dam height, shape of dam and diameter of sand on the outflow discharge from the dam burst. In addition, we developed a numerical model to simulate the landslide dam erosion by overtopping flow. To improve predictions of outflow discharge, we incorporated the inertial debris flow model, the side bank erosion model, and the slope collapse model into our numerical model. We tested the proposed model by comparing the simulations with data from the flume experiments.

**Key words:** Landslide dam, flood prediction, inertial debris flow, numerical simulation

1. **INTRODUCTION**

For the last several decades, the climate has been changing all over the world. Recent trends show an increasing number of heavy rainfall events of greater than 100 mm per hour and a wide variation in the annual rainfall vary widely every year. Climate change increases the number of large-scale landslides that tend to create large landslide dams in mountain rivers. When such a dam retaining a large amount of water bursts, it causes floods and catastrophic damage downstream. Therefore, the study of landslide dam deformation and the prediction of the outflow discharge of dam bursts are essential for predicting flood potential and the risks associated with floods.

There are several types of landslide dam failures. In this study, we focused on landslide dam deformation and outflow discharge caused by overtopping flow. Previous studies have performed many experiments for landslide dam failure caused by overtopping flow as laboratory flume experiments. Takahashi and Nakagawa [1993] conducted flume experiments of landslide dam failure by overtopping flow. They evaluated the outflow discharge of dam bursts and erosion shapes by overtopping flow. Oda et al.[2006] performed experiments using sand and bentonite (a clay material exhibiting cohesion). They showed that the outflow discharge varies depending on the dam’s predominant material (a dam consisting of only sand has a higher peak outflow than a dam consisting of a mixture of sand and bentonite).

To predict outflow discharge, previous studies proposed numerical models for landslide dam failure by overtopping. Takahashi and Nakagawa [1993] proposed a two-dimensional numerical model for overtopping that incorporated three types of sediment transport models (bed load, immature debris flow, and stony debris flow) and the side bank erosion model. They applied the proposed model to laboratory flume experiments of landslide dam failure and were able to reproduce the observed flood runoff and erosion shapes. Satofuka et al. [2007] proposed a one-dimensional model that incorporated the two-layer model for immature debris flow (proposed by Takahama et al. [2000]) and the side bank erosion model. They applied the model to the Mimikawa River Basin in Miyazaki Prefecture at the site of the “Nonoo landslide dam”
and were able to reproduce the observed flood runoff.

In this study, we conducted flume experiments to understand the landslide dam deformation and outflow discharge caused by overtopping flow. In the flume experiments, we measured the deformation of artificial landslide dams. In addition, we developed a numerical model to simulate the landslide dam erosion caused by overtopping flow. The model calculates the process of overtopping erosion in two dimensions. To improve the prediction of the outflow discharge, we incorporated the inertial debris flow model proposed by Takahashi et al. [2002], the side bank erosion model, and the slope collapse model proposed by Sekine [2003]. The inertial debris flow model can handle stony debris flow, turbulent muddy debris flow, immature debris flow, and intermediate debris flow. Moreover, it can conveniently calculate the concentration of sediments and the resistance to the flow. Various types of sediment transport and the effect on the outflow discharge caused by overtopping can be considered using the integrated numerical model. To check the validity of our calculation results, we compared them with the flume experimental results.

2. EXPERIMENTS

2.1 Materials and method

To observe the deformation of landslide dam and the characteristics of outflow discharge by overtopping flow, we carried out laboratory flume experiments. Fig. 1 and Fig. 2 show the laboratory flume and landslide dam. We used a rectangular flume of width 18cm, depth 20cm and 0.1 (5.71°) slope. On the top of the dam and along the sidewalls, we created a cutout for flow overtopping. The flume sidewalls were clear tempered glass to allow the observation of the dam deformation from the side. We also used dried silica sand of two different sand sizes (mean diameter of 0.25mm and 0.15mm). The grain size distributions of the silica sand are shown in Fig. 3. A fixed inflow discharge of 17cm³/s that was supplied from the upstream part of the flume.

Table 1 shows the test conditions. Case 1, 2, 3 and Case 4, 5, 6 compared the outflow discharge differences owing to dam height. Case 1 and 4, Case 2 and 5, Case 3 and Case 6 compared the outflow discharge differences owing to the diameter of sand. Case 1 and 7, Case 4 and 8 compare the outflow discharge differences owing to the shape of the dam. In each case, we repeated the experiments two to three times to ensure the reproducibility.

The data collection and monitoring process is as follows:
1. The water level in the reservoir was continually measured using a scale installed in the flume sidewall.
2. The outflow discharge from the dam burst was calculated using the water level changes overtime. The calculated results was confirmed by the outflow

![Fig. 1 Schematic of the flume experimental setup (Top: Case 1, 2, 3, 4, 5, and 6; Lower: Case 7 and 8)](image)

![Fig. 2 Cross sectional view of the dam in the flume experiments](image)

![Fig. 3 Grain size distribution of the silica sand](image)
Fig. 4 Photographs of the flume experiment at the time of overtopping.

Fig. 5 Experimental outflow discharge data (Cases 1, 2, 3, 4, 5, and 6)

Fig. 6 Experimental dam deformation results (Cases 1 and 4)

discharge sampling at the flume end.

3. The landslide dam failure, including deformation, width of erosion, and dam height was recorded using video cameras.

2.2 Experimental results

The deformation of landslide dam starts by overtopping in eight cases. Fig. 4 shows the line of saturation at the time of overtopping. This suggests that nearly the entire dam was saturated at the time of overtopping. Fig. 5 shows the experimental outflow discharge data for Case 1, 2, 3, 4, 5, and 6. Fig. 6 shows the experimental dam deformation results for Case 1, and 4. The figure shows the dam deformation after flow overtopping in 10 s intervals. Fig. 5, which compares Case 1, 2, and 3 shows that the dam height strongly affects the peak outflow.

Fig. 7 Experimental outflow discharge data (Cases 1, 4, 7, and 8)

Fig. 8 Experimental dam deformation data (Cases 1 and 7)

The peak outflow in Case 1, 2, and 3 was 153 cm$^3$/s, 207 cm$^3$/s, and 97 cm$^3$/s, respectively. The difference between Case 1 and Case 2 was about 50 cm$^3$/s and Case 1 and Case 3 was about 50 cm$^3$/s. The data suggest that the peak outflow is proportional to the dam height. The comparison of Case 1 and 4 suggests that the peak outflow was also influenced by the diameter of sand. The Peak outflow in Case 4 was 115 cm$^3$/s and approximately 75% of that of Case 1. This probably caused by the slow erosion velocity of the small size sand in Case 4. In addition, the results suggest that the erosion velocity for sand of small diameter (Case 4) is smaller than that for sand of larger diameter (Case 1).

Fig. 7 shows the experimental outflow discharge data for Case 1 and 7. Fig. 8 shows the experimental results for the dam deformation for Case 1 and 7. The figure shows the deformation after flow overtopping the landslide dam in 10 s interval. The comparison of Case 1 and 7, Case 4 and 8 suggests that the peak outflow and shape of the outflow discharge is not affected by shape of the dam. This is because of nearly the same deformation from the middle. As shown in Fig. 8, Case 7 from 40s to 80s and Case 1 from 20s to 60s have almost the same dam height and erosion shape. The results suggest that the dam shape does not affect the outflow discharge.
3. OVERTOPPING FLOW EROSION MODEL FOR LANDSLIDE DAM

3.1 Overtopping flow model

The erosive action of overtopping flow removes material from the landslide dam surface. The main governing equations are briefly discussed here. The momentum equation for the flow mixture, the continuity equation for the flow mixture, and the equation for bed variation are given by Eqs. (1) to (5), respectively:

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial (h + z)}{\partial x} - \frac{\tau_x}{\rho_m h} \]  
\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial (h + z)}{\partial y} - \frac{\tau_y}{\rho_m h} \]  
\[ \frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = i + i_e \]  
\[ \frac{\partial C_{tr}}{\partial t} + u \frac{\partial C_{tr}}{\partial x} + v \frac{\partial C_{tr}}{\partial y} + \frac{i \Delta C_{tr}}{\partial x} + \frac{i \Delta C_{tr}}{\partial y} = 0 \]  

where \( x \) and \( y \) are the Cartesian coordinates (xy-plane is horizontal), \( u \) and \( v \) are the velocity components in the \( x \) and \( y \) directions, respectively, \( t \) is the time, \( g \) is the acceleration due to gravity, \( h \) is the flow depth, \( z \) is the bed elevation, \( \tau_x \) and \( \tau_y \) are the resistance to flow in the \( x \) and \( y \) directions, respectively, \( \rho_m \) is the apparent density of the flow, \( C \) is the sediment concentration by volume in the flow, \( \rho \) is the density of water, \( \sigma \) is the density of sand, \( i \) is the erosion or deposition velocity, \( i_e \) is the erosion velocity on the side bank, \( \Delta C \) is the difference in bed elevation between adjacent points. The resistance to flow is calculated by using the inertial debris flow model [Takahashi et al., 2002], described in the next section.

3.2 Equilibrium sediment concentration and resistance to flow by the inertial debris flow model

During overtopping flow, materials are washed away by sediment transport. The inertial debris flow model [Takahashi et al., 2002] was used to calculate the various types of sediment transport. The resistance to flow is calculated as

\[ \tau = \frac{u^2 u}{u^2 + v^2} \]  
where \( u_\tau \) is the friction velocity of the inertial debris flow. The friction velocity can be expressed using Eq.(7) as

\[ \frac{U^2}{u_\tau} = F \left[ A_1 + A_2 \log_{10} \left( \frac{h}{d} \right) + A_3 \log_{10} \left( \frac{h^2}{d} \right) \right] \]  
where \( U \) is the mean velocity, \( d \) is the mean diameter of the sediment particles, and \( F, A_1, A_2, \) and \( A_3 \) are numerical constants. The mean velocity \( U \) is given by the velocity components \( u \) and \( v \). The numerical constants \( F, A_1, A_2, \) and \( A_3 \) are calculated from the inertial debris flow model. For the details are provided in the original report [Takahashi et al., 2002].

The equilibrium sediment concentration is given by the equilibrium transport concentration from the inertial debris flow theory and is expressed as

\[ C_{tr} = a_1 + a_2 \xi + a_3 \xi^2 + a_4 \xi^3 \]  

where \( C_{tr} \) is the equilibrium transport concentration, \( \xi \) represents \( \sin \theta \), \( \theta \) is the angle of the flow-surface, and \( a_1, a_2, a_3, \) and \( a_4 \) are numerical constants. The numerical constants are calculated by using inertial debris flow theory [Takahashi et al., 2002].

3.3 Erosion velocity

The equation representing erosion velocity for an unsaturated bed proposed by Takahashi and Nakagawa [1993] is given by

\[ i = \sqrt{gh} \left( 1 - \frac{\sigma - \rho}{\rho} \left( \frac{\tan \phi}{\tan \theta} - 1 \right) \right)^{\frac{1}{2} \left( \frac{\tan \phi}{\tan \theta} - 1 \right) \left( C_{r} - C \right) \frac{h}{d} \right. \]  
where \( K_r \) is a numerical constant, \( C_{r} \) is the equilibrium sediment concentration, and \( \phi \) is the angle of the internal friction of the soil. The equation for the side bank erosion velocity [Takahashi and Nakagawa, 1993] is given by

\[ i_e = \sqrt{gh} \left( 1 - \frac{\sigma - \rho}{\rho} \left( \frac{\tan \phi}{\tan \theta} - 1 \right) \right)^{\frac{1}{2} \left( \frac{\tan \phi}{\tan \theta} - 1 \right) \left( C_{r} - C \right) \frac{h}{d} \right. \]  
where \( K_s \) is a numerical constant.
3.4 Slope collapse model

During landslide dam erosion, overtopping flow suddenly removes material from the top of the dam, which then creates a sharp gradient between the overflow bed and the side bank. If the difference between the overflow bed and the side bank exceeds a threshold, the side bank collapses. Therefore, the slope collapse model proposed by Sekine [2003] is incorporated to simulate such a phenomenon in the calculations. Fig. 9 shows a schematic of the slope collapse model.

If the gradient between the bed elevations exceeds the side bank limit angle $\theta$, the side bank collapses occurs and the soil moves from the high to the low beds. The amount of soil moved in the process is calculated using

$$\varepsilon = \frac{1}{2}\left\{z_{i,j} - (z_{i,j+1} + \Delta y \tan \theta_s)\right\}$$

(11)

where $\varepsilon$ is the amount of soil moved because of result of collapse and $\Delta y$ is the difference between the calculation points. In this study, the side bank limit angle $\theta_s$ was set to 75° because this angle approximately matches the 75° observed in the laboratory flume experiments.

4. NUMERICAL ANALYSIS OF THE FLUME EXPERIMENTS

4.1 Calculation conditions

The landslide dam failure and outflow discharge caused by overtopping were calculated using the proposed overtopping flow erosion model. The calculations were based on the flume experimental conditions. Sim 1 was based on the conditions of Case 1 and Sim 2 on the conditions of Case 4. Table 2 lists the parameters used in the calculations. Numerical constants $K_T$ and $K_S$ were decided by trial calculations that reasonably reproduced the results of Case 1. However, the numerical constants $K_T$ and $K_S$ are not widely accepted since verification of constants $K_T$ and $K_S$ are not enough.

4.2 Comparison between observation data and calculated results

Fig. 10 compares the measured and calculated outflow discharge. The figure shows the outflow discharge after the flow overtopping of the landslide dam. As shown in Fig. 10, the measured and calculated outflow discharge are approximately equivalent. The numerical model can reproduce the measured time of change in the outflow discharge for Case 1.

Fig. 11 compares the measured and calculated dam deformation data. The figure shows the deformation after the flow overtopping of the landslide dam in 10 s interval. As shown in Fig. 11, the calculated deformation in lower area differs from the flume experiment(Case 1). However, the calculated dam heights, which most affected the outflow discharge, are approximately consistent with the measured heights.

Fig. 12 compares the measured and calculated results for the overtopping flow width. The figure shows the overtopping flow channel width after the flow overtopping of the landslide dam. As shown in Fig. 12, the measured and calculated overtopping flow widths are not too far off. The numerical model can largely reproduce the measured overtopping flow width in Case 1.

Fig. 13, 14, and 15 compare the measured and calculated outflow discharge, dam deformation, and overtopping flow widths. The figures show the outflow discharge after the flow overtopping of the landslide dam. As shown in Fig. 13, 14, and 15, the match between the measured and calculated outflow discharge, dam deformation, and overtopping flow widths was poor. This is because the erosion velocity calculated using Eqs. (9) and

---

Table 2 Parameters used in the calculations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Set points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in the $x$ direction $dx$</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Difference in the $y$ direction $dy$</td>
<td>0.002 m</td>
</tr>
<tr>
<td>Time difference $dt$</td>
<td>0.002 s</td>
</tr>
<tr>
<td>Density of water $\rho$</td>
<td>1.0 g/cm$^3$</td>
</tr>
<tr>
<td>Density of sand $\sigma$</td>
<td>2.65 g/cm$^3$</td>
</tr>
<tr>
<td>Sediment concentration in the movable bed layer $C_s$</td>
<td>0.65</td>
</tr>
<tr>
<td>Internal friction angle $\tan \phi$</td>
<td>0.75</td>
</tr>
<tr>
<td>Numerical constant for erosion velocity $K_T$</td>
<td>0.002</td>
</tr>
<tr>
<td>Numerical constant for side bank erosion velocity $K_S$</td>
<td>0.021</td>
</tr>
<tr>
<td>Inflow discharge $q_{in}$</td>
<td>17 cm$^3$/s</td>
</tr>
<tr>
<td>Mean diameter of sand $d$</td>
<td>Sim 1 0.25 mm, Sim 2 0.15 mm</td>
</tr>
</tbody>
</table>
(10) is too high and thus the calculated dam erosion is fast as shown in Fig. 14 and 15. Eqs. (9) and (10) show that the erosion velocity is inversely proportional to the sediment particle size. However, the flume experiments show that the erosion velocity in small size sand (Case 4, 5, 6) is smaller compare with bigger size sand (Case 1, 2, 3). The results suggest that apparently other factors affect the erosion velocity. Therefore, additional research is required to reveal the erosion velocity of small sand.

5. CONCLUSION

We conducted eight laboratory flume experiments of landslide dam erosion caused by overtopping flow. We compare the differences in dam height and diameter of sand and shape of dam. Dam height strongly affected the peak outflow discharge, which was found to be proportional to the dam height. The diameter of the sand affected the peak outflow. In the experiments, the erosion velocity and peak outflow for small sand was smaller than that of bigger size sand. However, the peak outflow was not affected by the dam shape because of the nearly same deformation from the middle.

In this study, we incorporated the inertial debris-flow model, the side bank erosion model, and the slope collapse model to simulate the overtopping erosion of landslide dams. The model results were compared to experimental data. The proposed model largely reproduced the measured time of change in the outflow discharge, dam height, and the overtopping flow channel widths in the flume experiments for Case 1. However, for Case 4 (Sim2) and small size sand, the measured and calculated results did not agree because the erosion velocity...
calculated with Eqs. (9) and (10) is too high and thus the calculated dam erosion is fast. The Erosion velocity is inversely proportional to the sediment size in Eqs. (9) and (10). However, the data experiments show that the erosion velocity in small size sand is smaller than that for bigger size sand. These results suggest that other factors affect to erosion. Therefore, additional research is required to understand the erosion velocity of small sand.

ACKNOWLEDGMENT: We thank the members of the Watershed Design Laboratory of Ritsumeikan University for their help in the flume experiments.

REFERENCES