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Research

Experimental Study on Surge Overtopping Process of Earthen Embankments and Calculation of First Surge Wave Discharge

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Abstract:

The landslide-induced surge overtopping of embankments not only causes damage to the dam body but also poses a threat to downstream life and property. This paper explored the process of surge overtopping caused by landslides through model experiments, calculated the first surge wave overtopping discharge using empirical formulas, and evaluated the overtopping discharge at Vajont Dam in Italy. The study revealed that the first wave of landslide-induced surge carried higher energy than subsequent waves, and the surge waves action on the downslope of the embankment was non-uniform. The subsequent surge waves will cause localized "rills" on the dam body, and if there were enough subsequent surge waves, these "rills" may connect and ultimately lead to the failure of the embankment. The first surge wave overtopping discharge per unit width obtained in the experiments was 0.274 m^2/s. According to geometric similar, the overtopping discharge of the Italian dam was as high as 682,830 m^3/s.

1. Introduction

Landslide-induced surge was a common phenomenon occurring in mountain river valleys and lakes. They were formed when the slopes ruptured and disintegrated, causing a rapid impact on the lake water. During landslide events, the generated surge waves carried significant dynamic loads. Under intense rainfall conditions, the water level in the reservoir behind the soil and rock embankment rose rapidly to a critical overflow state. If the landslide-induced surges propagated to the embankment, they could directly result in the failure of the embankment, posing a serious threat to the safety of life and property along the downstream shore (Liu et al., 2022).

The stability and failure process of soil and rock embankments under the action of landslide-induced surges have been widely studied, but research on the surge action process and overtopping discharge was still in the early stages (Stefania, 2015; Liu et al. 2022). Some scholars used theoretical calculation methods to study surge volume and flood peak discharge. For example, Risley et al. (2006) studied the surge wave overflow and the flood peak discharge caused by dam overflow. Sattar et al. (2012) conducted a study on flow routing analysis and assessed the impact of flood surge wave inundation on dam failure. Huang et al. (2014) designed a flume system for model experiments to explore the development process and the characteristics of failure discharge induced by surge induced dam failures caused by ice or snow avalanches entering the lake, and analyzed the influence of different surge scales on the dam failure mechanism. Xiao and Lin (2016) simulated the diffusion process of landslide-induced surges using the VOF numerical method and obtained the corresponding maximum surge wave height. Liu et al. (2023) measured the discharge of dam failure in soil and rock embankments using LS-PIV and provided a rapid estimation method for surface flow velocity.

In summary, although there have been some research studies on the effects of landslide-induced surges on embankments, further research is still needed to gain a deeper understanding of the mechanisms through which these surges can cause damage to such embankments.

2. Experimental setup

The experiments were conducted in an L-shaped glass

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water tank with a length of 8.8m, a width of 0.4 m, and a height of 0.5 m, as shown in Figure 1. The dam body was constructed at the end of the test section, with a width of 0.3m along the direction of water flow at the dam crest and a width of 1.9m along the direction of water flow at the dam base. The dam body had a width of 0.4m along the width direction of the water tank. Two high-precision wave gauges, labeled LG1 to LG2, were installed at a distance of 2m from the upstream toe of the dam to record the changes in water level in the reservoir during the dam failure process. Two high-definition digital cameras, labeled Dv1 and Dv2, were fixed above the dam body and on the side, respectively. Dv1 was used to record the changes in the dam crest breach, while Dv2 was used to record the longitudinal variation of the breach. Meanwhile, a regular high-definition mobile phone was randomly used to capture footage downstream. Referring to Xu et al. (2015), a modified metal mesh frame filled with crushed stones was simplified as a sliding block, which was excited to generate surges by being released freely at a height level with the water surface. The dimensions of the sliding block were illustrated in Figure 2.

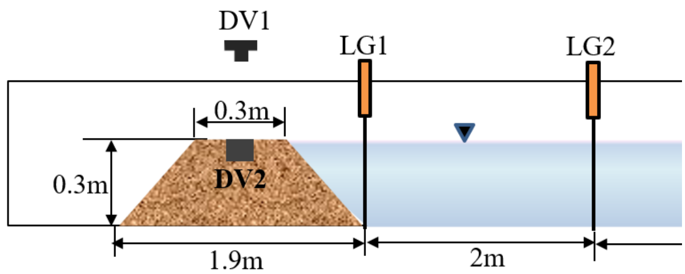
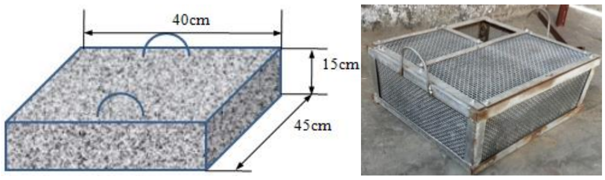


Figure 1 The test schematic diagram



（a）Scale （b）Photo

Figure 2 Generalized Model of Landslides [Li et al. (2023)]

3. Experimental results and discussions

2.1 Overtopping process

In this experiment, only the first two surge waves were able to clearly overtop the dam body (as shown in Figure 3). Figure 3(a) showed the first surge wave reaching the upper edge of the dam, Figure 3(b) showed the first surge wave reaching the lower edge of the dam, Figure 3(c) showed the complete overtop of the first surge wave surge, and Figure 3(d) showed the second surge wave reaching the dam crest. From the Figure 3, it can be observed that the erosion caused by the overflowing surge waves on the upper and lower edges of the dam was more severe than in other areas of the dam. This erosion led to a noticeable decrease in elevation and a reduction in width along the flow direction at these two locations. The height of the first surge wave overtopping the dam body was significantly greater than that of the second surge wave, indicating that the energy of the landslide surge waves was mainly concentrated in the first wave. There were some weak minor surge waves that also overtop the dam body after the second surge wave, but their flow rate was very small. The scouring of the downstream face of the dam body caused by the overflowing surge waves was also uneven. After the surge waves, localized "small gullies" appear on the dam body due to the minor surge waves that occur after the second wave, as shown in Figure 4. Due to the narrowing of the dam crest width caused by the surge waves, if there are enough minor surge waves, these "small gullies" may connect upstream and downstream, ultimately leading to the failure of the embankments.

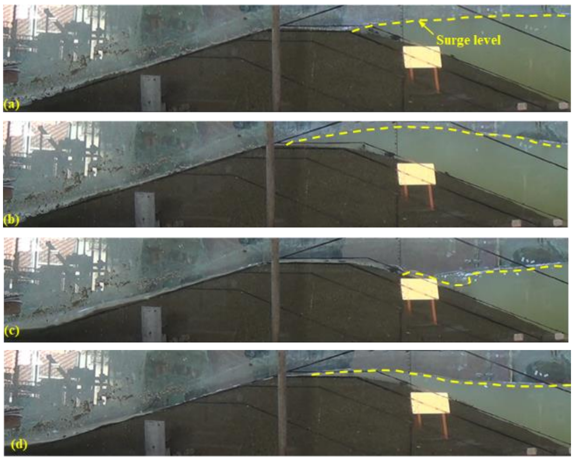


Figure 3 Overtopping Process (Side View)

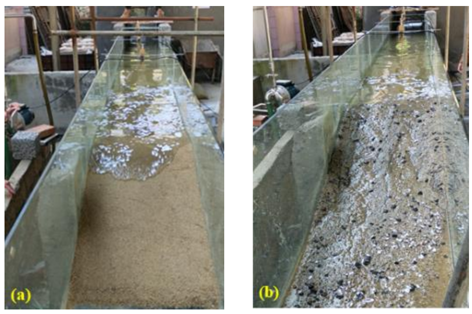


Figure 4 Comparison of downstream face undercutting before and after the surges overtopping the dam

3.2 Calculation of First Surge Wave Overtopping Flow Rate

The variation of water surface elevation during the process of overturning surge waves over the dam in this experiment was shown in Figure 5. From the Figure 5, it can be observed that the elevation of the first two surge waves was much higher than that of the subsequent minor surge waves, which confirms the phenomenon mentioned in Figure 3, where only the first two surge waves can significantly overtop the dam body. Additionally, the period of the subsequent minor surge waves was continuously decreasing, indicating an increasing frequency of erosion of the dam body by these minor surge waves. The irregular pattern in the image of wave gauge 1 between 4.5s and 6.5s may be due to the superposition caused by the reflection of the overflowing surge waves at the tail of the water flume.

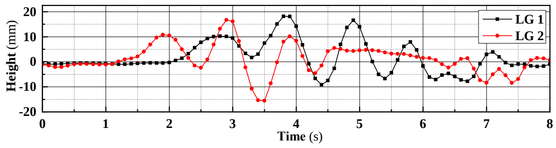


Figure 5 Water surface profile during the process of overtopping surge waves over the dam

The process of overtopping surge waves over the dam can not only cause damage to the dam structure but also have potential impacts on downstream life and property safety. Therefore, it was crucial to estimate the flow rate of overtopping surge waves. Referring to Pullen et al. (2007), the Formula (1) has been modified to calculate the small probability surge waves (the few waves that overtop the embankment), as shown in Equation (1).

$$\frac{q_w}{\sqrt{gh_m^3}} = 0.2 \cdot \exp(-2.6 \cdot \frac{R_c}{h_m} \cdot \frac{1}{\gamma_r \gamma_\beta}) \qquad (1)$$

where q_w represented the average discharge per unit width of the dam when surge waves act individually, R_c denoted the distance between the dam crest and the water surface, specifically the distance from the surge wave crest to the dam crest in this case. $\gamma_r\gamma_\beta$ represented the surge wave attenuation coefficients due to surface friction and oblique waves, respectively, according to Pullen et al. (2007), $\gamma_r\gamma_\beta$ = 0.49. h_m represented the effective height relative to the reference level, which was taken as the height of the dam in this context. g was the acceleration due to gravity, taken as 9.8 m/s^2.

Based on the data (the first wave) shown in Figure 5, the calculated single-width flow rate of the first surge wave in this experiment was 0.274 m^2/s. In 1963, a landslide with a volume of 300 million m^3 occurred and generated surge waves as high as 300 m, which overtopped the dam body and resulted in the deaths of nearly 3,000 people downstream of Vaiont Reservoir in Italy (the arc length of the dam top is 190.5 m, and the chord length of the dam top is 168.6m), and the power station was permanently abandoned (Peng et al, 2019). Comparing the calculation method for the first surge wave's flow rate in this experiment, the maximum discharge of Vaiont Reservoir reached 682,830 m^3/s, which was equivalent to 20 times the average flow rate of the Yangtze River. The Pullen formula was specifically designed for calculating surge wave overtopping flow rates in coast engineering, and it does not account for landslide-generated surge waves that have more energy than wind waves (Xiao and Lin, 2016). Therefore, the actual maximum discharge of Vaiont Reservoir was expected to be higher than the calculated result in this study. Since the calculation methods for surge wave overtopping discharge were still in the exploratory stage, future work in this study will involve a comprehensive investigation of empirical formulas for landslide-generated surge wave overtopping.

4 Conclusion

This study explored the process of landslide-generated surge wave overtopping through model experiments. The empirical formula was used to calculate the flow rate of the first wave, and an assessment of the overtopping discharge of Vaiont Dam in Italy was conducted, leading to the following conclusions:

1) The first surge wave of landslide-generated waves contains higher energy than subsequent waves. The first surge wave causes the most severe erosion on the upper and lower edges of the dam crest, leading to a reduction in width along the direction of water flow.

2) The erosion caused by subsequent surge waves on the downstream slope of the earthen dam was uneven, resulting in the formation of "small gullies" in localized areas of the dam body. If there were enough subsequent waves, these "small gullies" may connect upstream and downstream, ultimately leading to the failure of the earthen dam.

3) In this study, the calculated single-width flow rate of the first wave was 0.274 m^2/s. According to geometric similarity calculations, the overtopping flow rate of Vaiont Dam in Italy was estimated to be as high as 682,830 m^3/s.

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Author contribution statement

Yuan Tao: Investigation, Formal analysis, Conceptualization. **Hujun He**: Writing-original draft, Methodology, Investigation, Data curation. **Ningjun Wang**: Visualization, Formal analysis, Data curation. **Xin Jin**: Supervision, Writing-review & editing. **Qiushi Zhang**: Writing-review & editing.

Declaration of competing interest

The authors declare no known competing interests that could influence the work reported in this paper.

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