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Simulation of the Sediment Propagation During the Breaching of the Tangjiashan Landslide Dam

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Abstract: The breaching of a large-scale landslide dam does not only release a huge amount of water, but also incur massive soil and rock sediments by complex erosion and deposition. The sediment propagation would significantly change the topography and geological environment and affect the planning of the relevant buildings and infrastructure projects in a long term. Existing studies mainly focus on the development of the dam breach and the evolution of breaching floods. Less concern is given to the simulation of the dam materials propagation during the drastic dam breaching, which is of the major target of the present paper. A comprised model, which consists of a dam breaching model (DABA) and a debris flow model (EDDA) is developed to simulating the whole sediment propagation during dam breaching. In that model, DABA is applied to mimic the erosion of dam materials, EDDA is applied to mimic the deposition of the sediment downstream of the dam, and a model of DTE is applied to link these two models by mixing the soil and water and obtaining the hydraulic parameters of the mixed fluid. The comprised model is applied to simulate the whole breaching process of the Tangjiashan landslide dam caused by the 2008 Ms 8.0 Wenchuan earthquake. The timely water depth, flow velocity, and deposition thickness along the river are obtained from the simulation. It is found that the thickness of the soil and rock sediments gradually decreases along the river from the dam body to the Beichuan; the thickness in the vicinity of the dam can reach 40m, which is similar to the height of the residual dam; the thickness is about 15m near the Beichuan. The sediment thickness at the bend of the river is large, and the sediment is mainly distributed on the convex bank.

Keywords: Landslide dam; dam breaching; sediment propagation; Tangjiashan landslide dam; Wenchuan earthquake.

1 Introduction

The landslide dam is a natural dam formed by the slope failure bodies blocking the river, such as collapse, landslide, or debris flow. The breaching of the landslide dam includes the development of the breach, the transportation and accumulation of water and soil materials in the downstream. It is a complex process coupling water and soil materials for erosion, transportation and sedimentation. The hazard was mainly reflected on the accumulation of huge water volumes, which may cause a destructive flood in a very short period of time, and have a serious blow to the lives and property of people in the downstream. Of course, the hazard of breaching process was far more than the flood. It may have a sustained or even permanent impact on the river basin during its rapid failure process. The breaching process of landslide dam produced a large amount of earth and stone materials, directly burying the downstream area, and provided a large number of provenances for future water and soil transport. Therefore, the problem of the sediment propagation during the breaching of the landslide dam is urgently needed.

Due to the frequent occurrence of landslide dams and its serious hazards, people were paying more and more attention to them. In terms of numerical simulation, many scholars have proposed a large number of numerical models for simulating the breaching of artificial earth-rock dams, such as BREACH (Fread 1988), BRES (Visser 1998), MIKE11 DB (DHI 2012). However, there are great differences between artificial dams and landslide dams. Based on a large number of case studies, Peng and Zhang (2012) found that using the artificial dam model to predict the breaching parameters of landslide dam would greatly overestimate the peak flow and the size of the crater, and underestimate the time of the breaching, so this models cannot be simply applied to landslide dam. As to the study of the numerical models of landslide dam, Chang and Zhang (2010) proposed the DABA model based on the subsurface flow scouring and wire formulas, assuming the three stages of the breaching process. Chen (2014) proposed the DB-IWHR model, in which a hyperbolic erosion model for the erosion rate of the breach are used. Zhong (2017) proposed a dam-breaching model considering the failure of side slopes. More attention was paid to the scouring and outburst floods of landslide dams, and less attention was paid to the transportation and accumulation of earth and stone materials. As to the simulation of the coupled process of water and soil, Takahashi (1992) proposed an erosion and deposition model based on sediment volume concentration and flow velosity. Hungr (1995) proposed a one-dimensional mass integrated model based

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on momentum conservation, which was to describe the entrained or deposited materials during the coupled transportation of water and soil. There were also several procedures for debris flow analysis: DAMBRK (Boss Corporation 1989), FLO-2D (O'Brien 1993), DAN3D (Hungr and McDougall 2009) and RAMMS (Bartelt et al. 2013), and EDDA (Chen 2015). A comprised model, which consists of the DABA model, DTE model, and EDDA model, is developed to simulating the whole sediment propagation during dam breaching. In that model, DABA is applied to mimic the erosion of dam materials, EDDA is applied to mimic the deposition of the sediment downstream of the dam, and the DTE is applied to link these two models by mixing the soil and water and obtaining the hydraulic parameters of the mixed fluid. The comprised model is applied to simulate the whole breaching process of the Tangjiashan landslide dam caused by the 2008 Ms 8.0 Wenchuan earthquake (Peng et al. 2014).

2 Methodology

The breaching of the landslide dam is a complicated process, which is including the failure of the dam, flood evolution and sediment propagation. Therefore, the solution of the whole process was decomposed into three parts: the breaching of the landslide dam, the mixing of the soil and water, the coupled transportation of water and soil.

1. After the formation of the landslide dam, the water level in front of the dam rises and gradually flows over the dam crest. Then the dam is breaching under the scouring action of the water flow.
2. During the breaching of the landslide dam, the earth and stone materials separated from the dam is mixed with the water flow because of the erosive action and the instability of the bank slope.
3. After the water and soil mixed fluid flowing out of the dam, the process of erosion, transportation and accumulation in the downstream is beginning.

Each part has a different solution mechanism and has a complex relationship with other stages. Therefore, different models were used to describe the evolution of each part, and the DTE model acted as a connection.

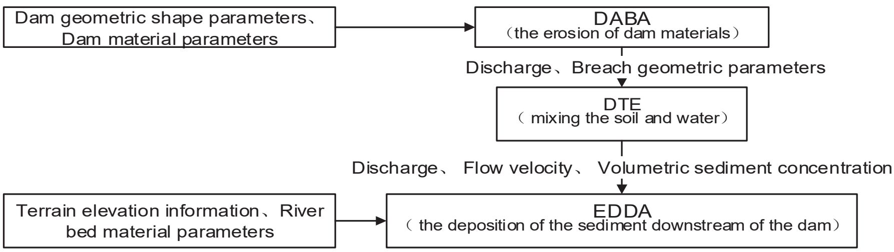


Figure 1. Framework of the comprised model

2.1 The DABA model

For the breaching of the landslide dam, the key problems were the geometric shape and the outflow of the crater. The flow into the breach depends on the elevation and width of the bottom of the breach. The characteristics of the breach depend on the erosion process of the mixed fluid, which in turn depends on the size and flow of the crater. The mechanism is complex. To complete the simulation of this part, the physical dam-breaching model, DABA (Chang and Zhang 2010), was used in this paper. In the simulations in DABA, the evolution of breach geometry is divided into three stages for a typical cross section.

In Stage 1, erosion occurs downward and sideward until the side slopes reach a critical value, which can be determined through a slope stability analysis. In this stage, the top width of the breach is unchanged, but the bottom width of the breach and the depth of the breach are gradually increasing.

In Stage 2, the breach expands in depth and width, keeping the side critical angle. This stage ends when the water flow meets low-erodibility soil layers or bedrock. In this stage, the bottom width, top width, and depth of the breach are constantly increasing.

In Stage 3, the vertical erosion stops but the horizontal erosion continues until the erosive stress is not enough to cause any additional erosion on the side slope. In this stage, the depth of the breach does not change any more, but the top width and the bottom width of the breach are gradually increasing.

In the longitudinal direction, the evolution of breach geometry is also divided into three stages. The breach evolution is similar to that in the cross section. The stages in the longitudinal direction are divided according to the erosion and stability of the downstream slope, while the stages in the cross section depend on the erosion and stability of the side slopes of the breach. The parameters we need to enter in this section are dam geometric shape parameters including cross section parameters and longitudinal section parameters and dam material parameters including physical property parameters and mechanical parameters, etc. The outputs in this section are outflow of the dam and top width, bottom width and depth of the breach, which need to be passed to the DTE for calculation.

2.2 The DTE model

The DTE algorithm (DABA to EDDA) is mainly determined by development of the breach. First of all, we need to get the source materials of each time step from the development of the breach. DTE is implemented by Matlab programming. The input parameters mainly include the outflow, the dam crest width, the downstream slope length, the downstream slope ankle, the top width and the bottom width of the breach. In this part, the study area is also the dam body. Based on the relative positions of A (the intersection of the dam crest and the downstream slope on the longitudinal section of the dam), A' (the intersection of the top section of the breach and the downstream section of the breach on the longitudinal section of the dam), and B'(the intersection of the breach and the bottom of the dam on the longitudinal section of the dam), we divide the calculation into three types. As shown in Fig.2, A is on the left of A' (the initial stage of the development of the breach), A is on the right of A', and the left of B' (The middle stage of the development of the breach), A is on the right of B' (the late stage of the development of the breach).

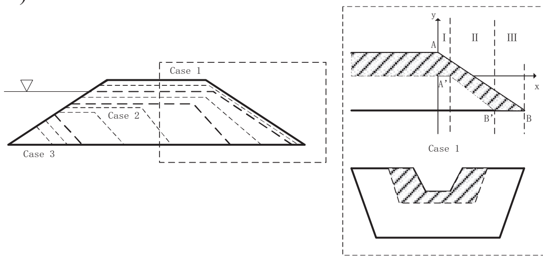


Figure 2. DTE calculation diagram

Case 1 was taken as an example, in which A is on the left of A'. According to the typical cross section of the crater, the depth of breach on the top section h_A can be obtained. Then the volume V_A, which described the top section of the breach, can be obtained easily,

$$V_A = (\frac{B_t+B_b}{2})\ (\frac{B_t-B_b}{2})\ B_c \tan\alpha \tag{1}$$

In which B_t is the bottom width of the breach, B_b is the top width of the breach, B_c is the length of the top section of the breach, α is the slope angle of the breach. The breach in the downstream of the dam was divided into three parts, as shown in the Fig. 2 (I, II, III). Then, the depth of breach on the downstream section h_B can be obtained based on the graphical coordinate system, which was created as shown in Fig. 2.

$$h_B = \begin{cases} h_A + \tan(\pi-\beta_1)\,x\,, & (0 < x < B_{ci} - B_{c1}) \\ h_A + \tan(\pi-\beta_1)\,x - \tan(2\pi-\beta_i)\,x + \tan(2\pi-\beta_i)\,(B_{ci} - B_{c1}), & \\ & (B_{ci} - B_{c1} < x < B_{ci} - B_{c1} + L_i cos\beta_i) \\ h_A + \tan(\pi-\beta_1)\,x - (-L_i sin\beta_i), & \\ & (B_{ci} - B_{c1} + L_i cos\beta_i < x < L_1 cos\beta_1) \end{cases} \tag{2}$$

In which β_1 is the original downstream slope angle , $\beta_i$is downstream slope angle of the i-th step, B_{c1} is the original length of the top section of the breach, B_{ci} the length of the top section of the breach in i-th step, L_i the length of the downstream section of the breach in i-th step. Then, the volume V_B, which described the downstream section of the breach, can be obtained by integration over different sections.

$$V_B = \int_0^{L_1 cos\beta_1} (\frac{B_t+B_b}{2}) h_B dl \tag{3}$$

In which l is the length of the downstream section of the breach. The overall volume V of the breach is the sum of the breach volume on the top and the downstream. The other two cases are similar. we can get discharge, flow velocity, volumetric sediment concentration.

2.3 The EDDA model

When the mixed fluid flow out of the dam, some mature models in the field of debris flow simulation can be cited. It was decided to use a debris flow model that considers erosion deposition and changes in fluid properties, the EDDA model (Chen and Zhang 2015). This model described the erosion process from a stress point of view: erosion occurs when the basal shear stress exceeds the critical erosive shear stress of the bedding material. The debris flow entrains and incorporates materials from the channel bed if the volumetric sediment concentration is smaller than an equilibrium value, for the channel gradient and the shear stress is sufficiently large. Some material separates from the debris flow mixture and deposits on the channel bed when the volumetric sediment concentration is larger than an equilibrium value for the channel gradient and the flow velocity is not sufficient to take all the material. Due to erosion and deposition, debris flow properties change significantly. The quadratic rheological model proposed by Julien and Lan (1991) considers the effects of frictional behavior, viscous behavior, and turbulent behavior plus the resistance arising from solid-particle contacts. Since the quadratic rheological model accounts for the most comprehensive flow behavior, it is adopted into the governing differential equations in this model. Depth-integrated mass conservation equations and momentum conservation equations are adopted to describe the movement of the mixed flow. An adaptive time stepping scheme is adopted in this model to ensure the numerical stability, especially for cases which involve a large number of cells so that the simulation time is likely long.

3 Numerical Simulation

In order to verify the feasibility of the comprised model, the breaching of Tangjiashan landslide dam was taken as an example to carry out the simulation study. On May 12, 2008, a major earthquake struck Wenchuan, Sichuan Province, and the Tangjiashan dam was created. This was because the right bank of the Tongkou river, branch of the Fujiang River, about 4 kilometers away from Beichuan County, had formed a large-scale landslide due to the impact of the earthquake. The left of the dam was high and the right side was low, the highest point on the left side was 793.9m, and the highest point on the right side was 775m. There was a groove along the River, which ran through the upstream and downstream. The bottom of the groove was 20~40m wide, and the highest point in the middle part was 752.2m. The upstream slope of the dam was about 200m long, and the slope was about 20^o (the slope ratio was about 1:4). The downstream dam slope was about 300m long, and the slope foot elevation was 669.55m. The upper steep slope was about 50m long, and the slope was about 55^o. The central gentle slope was about 230m long, and the slope was about 32^o.The lower steep slope was about 20m, and the slope was about 64^o (the average slope ratio was 1:2.4).

4 Result Analysis

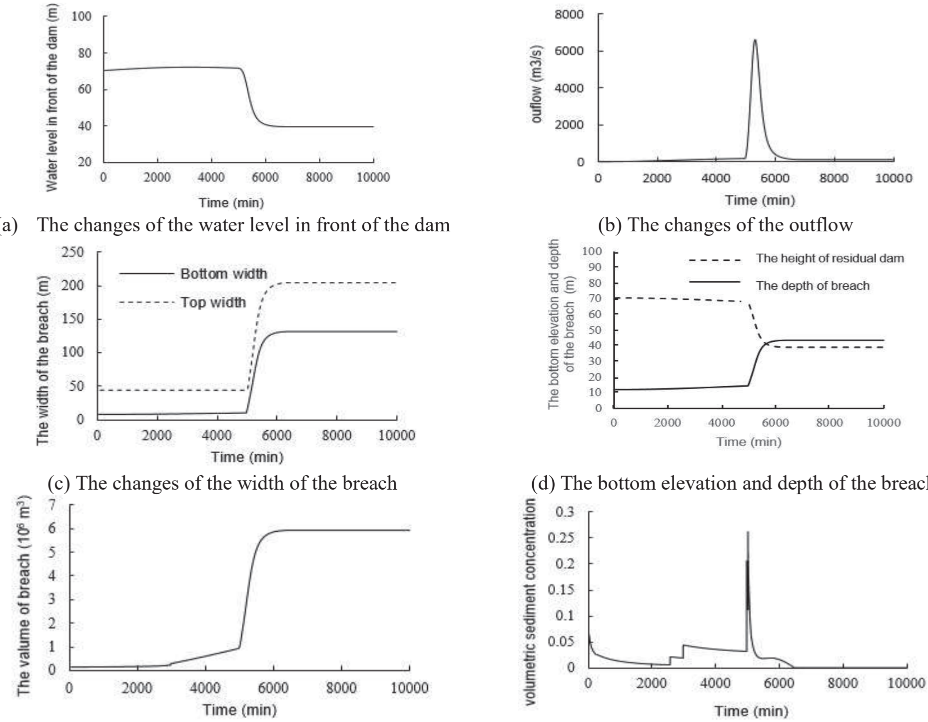
Simulation results of breaching process was shown in Fig. 3 After 0.03 hours, water began to flow into the spillway as shown in Fig. 3(b). After 82.87 hours, the dam started to breach, and the width of the breach was increasing, with the amount of flooding increasing sharply and the water level in front of the dam beginning to decrease. The entire process of the failure lasted 14.58 hours. During the breaching process, the peak flow rate was 6603.7m3⁄s. The highest water level was 742.24m and the maximum water depth was 12.36m. The final shape of the breach cross section was trapezoidal, the final breach depth was 43.42m, the final breach bottom width was 131.57m, and the final breach top width was 204.44m.

As shown in Fig. 3(a), the water level in front of the dam was in a slowly rising state before the failure process, and it dropped sharply during the process of breaching. At the end of the breaching, it began to return to a stable state. Fig. 3(b) showed the flow discharge hydrograph during the breaching period of the dam. Similar to the water level changes in front of the dam, the line shape was abrupt when the failure occurred. At about 83 hours, the discharge of the dam began to increase sharply. After the peak was reached, the discharge began to decrease rapidly. The area enclosed by the curve and the time axis reflected the amount of outflow during the break. Fig.3(c) showed the morphological changes in the breaching of the landslide dam. The breach began to expand rapidly at the beginning of the breaching, and at the end of the breaching, it tended to expand smoothly. It could be seen from the figure that the variation of the top width of the breach was faster than the change of the bottom width, which also revealed the two different erosion modes described in preamble.

The relationship between the depth of the crater and the residual dam height was shown in Fig.3 (d). As the outflow rate increased sharply, the erosion process also developed rapidly. At the same time, the residual dam height was also continuing to decline. When the flow rate of the crater tended to be stable, the dam body continued to be subjected to erosion, the crater continued to cut down and expand to the bank slope, and the residual dam height continued to decrease until the water flow can no longer washed the dam.

The three stages of the breaching process were clearly reflected in the calculation results. The three stages were divided according to the dam top width and the downstream slope angle. The downstream slopes continued to increase at the beginning. The critical value was reached at 44.21h and the downstream slopes began to remain unchanged. This was the boundary between the first stage and the second stage. In the second stage, the source erosion was intensified and the dam crest width began to decrease rapidly. At 83.71, the dam crest width became 0, that was, the longitudinal section of the dam became a triangle, which mean that the third stage was entered. Therefore, 44.21 h and 83.71 h were the two demarcation points of the three stages.

Figure 3(e) depicted the changes of the volume of the breach over time, with the apparent three stages visible. In the first stage, the volume of the breach increased slowly. In the second stage, the volume of the breach increased faster than the first stage, and the volume of the breach in the third stage increased rapidly. The increase in the volume of the crater affected the volumetric sediment concentration in the mixed water flow, which was the core result of the DTE section. Fig.3 (f) showed the changes in volumetric sediment concentration of the mixed fluid. We could still see the three stages of development of the breach. At the beginning, the volumetric sediment concentration was relatively high because of the increasing volume increment. As the flow rate increases, the concentration began to decrease. In the second stage, the volumetric sediment concentration began to increase. At the beginning of the third stage, the curve would be abrupt due to the lag of the flow. As the flow continued to increase, the volumetric sediment concentration began to decrease again until no erosion occurred.



(a) The changes of the water level in front of the dam (b) The changes of the outflow

(c) The changes of the width of the breach (d) The bottom elevation and depth of the breach

(e) The changes of the volume of the breach (f) The changes of volumetric sediment concentration

Figure 3. Simulation results of breaching process.

In order to simplify the calculation, the peak flow segment of 5000-6000min was used for the next calculation. The thickness of the soil and rock sediments gradually decreased along the river from the dam body to the Beichuan. The thickness in the vicinity of the dam can reach 40m, which was similar to the height of the residual dam; the thickness was about 15m in the Beichuan, and 33m in kuzhu dam. The actual observed data are 45m, 12m, 30m, respectively. At the same time, it can also be verified that the sediment thickness at the bend of the river is large, and the sediment was mainly distributed on the convex bank. At the same time, the water flow velocity at the convex bank of the river bend was much smaller than that of the concave bank. This value was close to the observed value.

At 100min, the sediment was mainly concentrated near the dam, and the thickness can reach more than 20 meters. This was because the mixed fluid just flowing out of the dam had a higher volumetric sediment concentration, which was much larger than the carrying capacity of the fluid. So large-scale deposition occurred. From the variation of sediment thickness at 200min and 300min, it can be concluded that as the water flows downstream, the sediments begin to spread gradually downstream, away from the dam. However, due to the steep slope near the Kuzhu dam, there was less sediment. Sediments were concentrated in the vicinity of the Kuzhu dam, because of the interception of it. The last three figures show that the maximum thickness of the sediment was 40.1m, and the place with more sediments in the downstream was mainly the Kuzhu dam and the bend of the river near it, the river bend at the front end of Beichuan County and the flat terrain at the end.

As shown in Fig. 5, the water gradually spread downstream at 100min, and the highest water level reached more than 30 meters. At 500min, the water had penetrated the entire research area and was constantly high. By the time of 1000min, the upstream water level becomes lower and the downstream water level rise, reflecting the process of flood peak movement. The flow was concentrated in the vicinity of the Kuzhu dam, because of the interception of it. There were two obvious processes in the change of water depth: the upstream water level was higher than the downstream water level before the flood peak; the upstream water level gradually decreases after the flood peak until it was lower than the downstream water level at a certain moment.

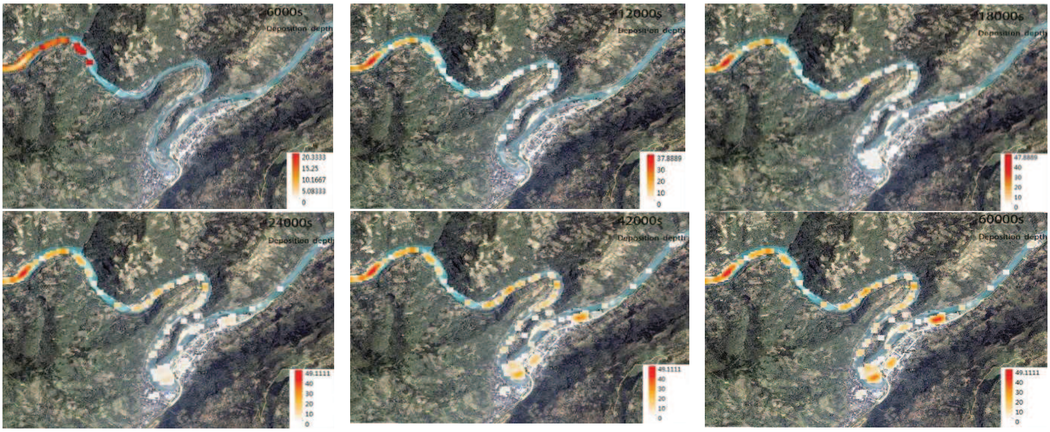


Figure 4. Developmental variation of sedimentary thickness over time in a wide range of research areas.

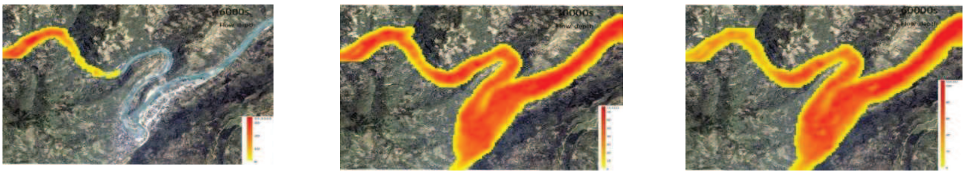


Figure 5. Developmental variation of water depth over time in a wide range of research areas.

5 Conclusions

A comprised model, consisting of the DABA, DTE, and EDDA models, is developed to simulate the sediment propagation during dam breaching. In that model, DABA is applied to mimic the erosion of dam materials, EDDA is applied to mimic the deposition of the sediment downstream of the dam, and the DTE is applied to link these two models by mixing the soil and water and obtaining the hydraulic parameters of the mixed fluid. The comprised model is applied to simulate the whole breaching process of the Tangjiashan landslide dam caused by the 2008 Ms 8.0 Wenchuan earthquake. It is found that the thickness of the soil and rock sediments gradually decreases along the river from the dam body to the Beichuan. The thickness in the vicinity of the dam can reach 40m, which is similar to the height of the residual dam; the thickness is about 15m near the Beichuan. The sediment thickness at the bend of the river is large, and the sediment is mainly distributed on the convex bank. At the same time, the water flow velocity at the convex bank of the river bend was much smaller than that of the concave bank. The simulation results obtained by the model can better fit the actual observation results.

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