Simulation Analysis of Mogangling Landslide Movement Process

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Abstract. The Mogangling landslide movement process was numerically simulated in this study and the occurrence and development of the landslide were reproduced. The calculation results show that the Mogangling landslide movement with certain characteristics has experienced several main stages of motion, that is, “front part start, front part acceleration, front part deposition / rear part start and rear part deposition”. The obtained final motion distance and the deposition form of the landslide are in perfect agreement with the actual situation, which verifies the correctness and effectiveness of the simulation. This study can provide reference for the prevention and control of landslide disasters.

1. Project overview
There are two rivers, Dadu River and Moxi River, in the area where the Mogangling landslide is located. The Moxi River flows into the Dadu River about 2.5km downstream of the landslide, which is the primary tributary of the Dadu River.

Mogangling is a nearly north-south thin mountain ridge cut by the Dadu River and Moxi River in China. The top of the mountain is 1800-2000m above sea level. The west and south sides of the mountain ridge is deep Moxi River ditch, and the elevation of the slope is 1115-1380m. The east side is the Dadu River, and the elevation of the slope is 1120-1125m. In the Mogangling area, the river valley is deep and the high mountains stand on both sides. The temperature changes drastically and the vertical climate is remarkable. The annual average temperature of the area is 18.5°C. The rainfall has uneven distribution in time and space. It is less rainy in winter and spring and the climate is dry. The Mogangling landslide occurred on the eastern slope of Mogangling, in Jinguang Village, Detuo Town, Luding County, China, and the slope is characterized by a “steep-smooth-steep” step-shape terrain. The landslide distribution area is below the smooth part, and the slope is N15°W. The Mogangling landslide was triggered by an earthquake and has a typical round chair shape. The main sliding direction is 75°, the length is about 450m, the width along the river is about 1000m, the plane area is 0.45km\textsuperscript{2}, the average thickness of the sliding body is about 100m, and the maximum thickness is 192m [1]. The basic seismic intensity in the landslide area is VIII degrees and the designed basic seismic acceleration value is 0.30g, which indicates that the seismic activity level in the area is relatively high. The steep terrain and the high seismic activity level of the Mogangling landslide provide favorable conditions for the high landslide caused by the earthquake.
The numerical calculation was used to achieve the simulation and inversion analysis of the Mogangling landslide movement process.

2. Model theory

The model equation of landslide movement has the following conservation form [2-3]:

\[
\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} = S
\]  

(1)

where \( U \) is the conserved variable, \( F \) is the computational flux, and \( S \) is the source term, which can be expressed as:

\[
U = \begin{pmatrix} h \\ hu \end{pmatrix}, \quad F = \begin{pmatrix} hu \\ hu^2 + \frac{1}{2} gh^2 \end{pmatrix}, \quad S = \begin{pmatrix} 0 \\ S_t \end{pmatrix}
\]  

(2)

where \( h \) is the flow depth, \( u \) is the velocity of the landslide, and \( g \) is the acceleration of gravity.

The source term in the model equation can be decomposed into:

\[
S = \begin{pmatrix} 0 \\ S_t \end{pmatrix} = \begin{pmatrix} 0 \\ S_0 + S_i \end{pmatrix}
\]  

(3)

where \( S_0 \) is generated by topographic conditions, generally referred to as the source term of bottom slope, and \( S_i \) is generated by the bottom resistance, which becomes the source term of frictional resistance and can be selected according to the material composition and motion characteristics of the landslide. In this study, the water resistance and frictional resistance were considered in the form [2]:

\[
S_i = \frac{3c_f \mu u}{\rho h} \text{sgn}(u) gh \tan \varphi_b + \frac{c_f \mu h}{\rho} \frac{\partial^2 u}{\partial x^2}
\]  

(4)

where \( \text{sgn}(u) \) is the marking function indicating the direction of velocity, \( \varphi_b \) is the bottom friction angle, \( c_f \) is the fluid volume fraction, \( \mu \) is the pore fluid viscosity, and \( \rho \) is the density of the debris flow.

By integrating equation (1) into the control volume, the following can be obtained:

\[
\int_{V_j} \frac{\partial U_i}{\partial t} dV + \int_{\partial V_j} \nabla \cdot F_i dV = \int_{\partial V_j} S_i dV
\]  

(5)

Let \( U_i \) be the average of element variable, defined on the center of the element, then:

\[
U_i = \frac{1}{A_j} \int_{V_j} U dV
\]  

(6)

According to the Green’s theorem, the equation (5) was divided and discretized, and the following can be obtained:

\[
\Delta U_i = -\frac{\Delta t}{A_j} \sum_{j \neq i} \left( F_i \cdot n_j \right) \Delta l_j + \frac{\Delta t}{A_j} \int_{V_j} S_i dV
\]  

(7)
where \( \Delta U_i \) is the increment of the variable, \( F_{ij}^* \) is the flux of the \( j \)th boundary of the \( i \)th element, and \( n \) is the outer normal direction of the boundary. Let \( F_{ij} = F_{ij}^* n_i \), then \( F_{ij} \) represents the normal numerical flux through the \( j \)th boundary of the \( i \)th element. Let \( S_i = \int S_i dV/A_i \), then the final discrete equation is:

\[
\Delta U_i = -\frac{\Delta t}{A_i} \sum_{j=1}^{N_i} (F_{ij}^*) \Delta t_i + \Delta t_i S_i \tag{8}
\]

The HLL scheme proposed by Harten [4-5] was used in this study to calculate the numerical flux. The HLL approximate Riemann solution was used to calculate the interface flux of the control volume, as shown in the following equation:

\[
F' \cdot n = \begin{cases} 
(F_{L,i})_j \cdot n & s_L \geq 0 \\
(F_{R,i})_j \cdot n & s_R \leq 0 \\
s_L(F_{L,i})_j \cdot n - s_L(F_{R,i})_j \cdot n + s_L s_R [(U_{L,i})_j - (U_{R,i})_j] & s_L \leq 0 \leq s_R 
\end{cases} \tag{9}
\]

where the subscripts L and R respectively represent the physical quantities on both sides of the interface, \((U_{L,i})_j\) and \((U_{R,i})_j\) are respectively the variables on the left and right sides of the \( j \)th boundary of the \( i \)th element, and \( s_L \) and \( s_R \) represent the wave velocity on both sides, which can be expressed as:

\[
s_L = \min(u_i n_i - c_L, u'^* - c^*)
\]

\[
s_R = \max(u_i n_i + c_R, u'^* + c^*)
\]

where \( c = \sqrt{gh/2} \), and \( u'^* \) as well as \( c^* \) can be expressed respectively as:

\[
u'^* = 0.5[(u_{L,i} + u_{R,i})n_i] + c_L - c_R
\]

\[
c^* = 0.5(c_L + c_R) + 0.25[(u_{L,i} - u_{R,i})n_i]
\]

When the left side is a dry beach, \( s_L \) and \( s_R \) can be calculated as:

\[
s_L = u_i n_i - 2c_R, (h_L = 0)
\]

\[
s_R = u_i n_i + c_R
\]

When the right side is a dry beach, \( s_L \) and \( s_R \) can be calculated as:

\[
s_L = u_i n_i - c_L, (h_R = 0)
\]

\[
s_R = u_i n_i + 2c_L
\]

For finite volume methods, the variables in the control volume should be linear to obtain spatial second-order accuracy. In this study, based on the MUSCL (Monotonic Upwind Scheme for Conservation Laws) method [6-7], the adjacent states on both sides of the interface were determined by state extrapolation as the initial value of the Riemann problem. After the state interpolation, although the flux formula has only one order, the accuracy of the solution can reach the second order. In order to avoid the false vibration caused by too large slope gradient during interpolation, it is necessary to limit the interpolation variable [5]. At the same time, in order to obtain a time discrete scheme with high-order accuracy, the two-step Runge-Kutta method was used here and the time discrete scheme with second-order accuracy was obtained [8].

Based on the HLL approximate Riemann solution [4-5], the finite volume method was used to numerically discretize the landslide model equation [9-10], and the numerical solution to the model equation with second-order space and time accuracy was achieved by the MUSCL linear reconstruction and the two-step Runge-Kutta method.

3. Simulation and analysis of the Mogangling landslide movement process

The calculation model was established based on the investigation and research after the occurrence of the Mogangling landslide. According to the relevant literature [1], the geological section before the landslide occurred, the sliding surface when the landslide occurred, and the final depositional form after the occurrence of the landslide were obtained, as shown in Figure 2.
The Mogangling landslide body is mainly composed of highly and moderately weathered granite, diorite and diabase. According to the data in the reference [1] and combined with the actual situation of the Mogangling landslide, 1600 m in the horizontal direction was selected as the calculation area.

![Figure 2 Topography before and after the Mogangling landslide](image)

According to the final deposition of the landslide, the movement process was inversely analyzed, and a set of inversion parameters consistent with the actual deposition was obtained including the bottom friction angle $\phi_b=28^\circ$, the liquid phase volume fraction $c_f=0.4$, the saturation density $\rho=2000\,\text{kg/m}^3$, and the fluid viscosity coefficient $\mu=0.1\,\text{Pa}\cdot\text{s}$. The calculation results of the Mogangling landslide using these parameters are shown in Table 1 and Figure 3.

| Time interval (s) | Moving distance (m) | Average velocity (m/s) |
|------------------|---------------------|------------------------|
| 0-5              | 127                 | 25.4                   |
| 5-10             | 283                 | 54.6                   |
| 10-20            | 303                 | 30.3                   |
| 20-40            | 4                   | 0.4                    |
| 40-50            | 2                   | 0.2                    |

![Table 1 Calculation result of Mogangling landslide movement](image)

![Figure 3 Calculation results in 5s](image)
Figure 3 Calculation results of Mogangling Landslide Movement Process
It can be seen from the calculation results that the movement of the Mogangling landslide has mainly undergone several major stages. In the first stage, after the landslide failure, the front part of the landslide body first accelerated to slide forward, and the rear part slid relatively late. Since the landslide body had a high potential energy, a large starting velocity can be obtained at the moment of failure. When the moving time reached 5s, the horizontal position of the front part of the landslide body is 895m, and the sliding distance was 127m in 5s, which means, the average velocity of the front part reached 25.4m/s. The landslide body was in the accelerated sliding stage, showing high fluidity. When the moving time reached 10s, the horizontal position of the front part of the landslide body was 1178m, the sliding distance in the second 5s was 283m, and the average velocity of the front part reached 56.6m/s, which was relatively high. When the moving time reached 20s, the horizontal position of the front part of the landslide body is 1481m, which was quite close to the front part of the final deposition of the landslide. The sliding distance during 10s~20s was 303m, and the average velocity of the front part was reduced to 30.3m/s, at which time the rear part of the landslide entered a state of motion. After more than 20s of moving time, the landslide movement mainly manifested as the movement of the rear part. At this stage, the movement of the front part was basically finished, the horizontal movement was not significant, and the slow creep deformation was dominant. It can be seen from the calculation results of the final deposition that although several factors such as the theoretical assumptions and model simplification may cause a slight difference between the numerical calculation results of the rear part of the landslide and the actual situation, the calculated final moving distance of the landslide and deposition form are generally in good agreement with the actual situation, which fully indicates that the calculation in this study is correct and effective.

4. Discussion
The theoretical model of landslide selected in this study was obtained from the depth-averaged integral continuum equation. The model only applies to the simulation of the landslide dominated by the movement along the slope, without consideration for the momentum change in the vertical direction. Therefore, before deciding the model for calculation, it is necessary to demonstrate the feasibility of applying the model to the engineering case in combination with the actual situation. The Mogangling landslide is composed of loose geomaterials and had large deformation during the movement. There was no blocking structure during the landslide movement to force the landslide to undergo significant vertical motion. For this reason, it is feasible to use the depth integral theory model to analyze the Mogangling landslide.

Due to the lack of reference materials, more detailed information on the occurrence of the landslide cannot be obtained, which is one of the reasons for the difference between the calculation results and the actual situation. There may be some more complicated phenomena during the landslide movement, such as the rupture and decomposition of the landslide geomaterials, the change of the bottom resistance caused by the interaction between the landslide body and the sliding surface, and the grain-size sorting during the movement. Although these phenomena are not the main features of the Mogangling landslide, they have certain effects on the landslide movement. In some specific cases, they may even become the main factors controlling the landslide movement. Therefore, further research need to be carried out in this regard.

The numerical simulation of landslide movement can represent the occurrence and development of landslide disasters, and more importantly, it can realize the prediction of landslide disaster. Through numerical simulation, more details of the landslide movement can be obtained, which is a powerful means to study the landslide movement.

5. Conclusion
The landslide motion model and the finite volume method were used in this study to simulate the Mogangling landslide movement process. The calculation results show that the landslide has different movement characteristics at different time. According to these characteristics, the Mogangling landslide movement can be divided into several stages: “front part start, front part acceleration, front
part deposition / rear part start and rear part deposition”. At the same time, the calculation results were compared with the actual situation. It is found that the calculation results of the moving distance of the landslide and the deposition form are in good agreement with the actual situation, which also proves that the calculation in this study is correct and effective.

The numerical simulation of the Mogangling landslide movement not only reproduces the occurrence and development of the disaster, but also reveals the characteristics of the movement process. This study can provide reference for the simulation of similar landslide disasters as well as the prevention and mitigation work.

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