Numerical Simulation of Dynamic Analysis of Glacier Under Seismic Loading Based on Combined Finite-Discrete Method

Y. Su and E.I. Liu*

State Key Laboratory of Hydraulics and Mountain River Engineering College of Water Resource & Hydropower, Sichuan University, Chengdu, China

Abstract. The dynamic analysis of the Laohugou No.12 Glacier of Qilian Mountain under given seismic loading effect is analyzed by using combined finite-discrete element method (FDEM). The necessary ice parameters for FDEM simulation are calibrated by using numerical experiments of biaxial compression corresponding to the physico-mechanical parameters. The results indicated that the stress-strain curves are strain softening, and the peak value of deviatoric stress is consistent with the laboratory experiments. Under the dynamic load effect, the glacier slip along the slope direction, and the whipping effect of the speed is obvious. The feasibility of using FDEM method to study discontinuous problems such as ice avalanche is discussed.

Keywords: Glacier slip; dynamic analysis; the whipping effect

1. Instruction

According to statistics, China currently has 48,571 glaciers with a total area of \(5.18 \times 10^4\) km\(^2\), accounting for 0.54% of the country's land area, and glacial reserves of \(4.3 \sim 4.7 \times 10^3\) km\(^3\) (Liu 2015). The crust movement on the Qinghai-Tibet Plateau is active and strong earthquakes occur frequently. The natural disasters such as glacial lake outburst floods and ice avalanche have hindered the development of transportation and tourism and jeopardized the construction of mountainous industries. Therefore, it is important to study the stability of glaciers under seismic loading.

At present, research on glacial monitoring mainly focuses on changes in mass balance, advance and retreat at the end of glaciers, and climatic characteristics (Pu 2014, Chen 2014, Liu 2010, Shen 2013). In addition, Emmer (2013) studied the failure mechanism of the moraine-dammed lake failures. The effects of the dynamic causes such as earthquakes and heavy rainfall, as well as long-term causes such as the melting of buried ice and hydrostatic pressure had been observed. Schneider (2011) revealed the different paths and flow characteristics that cause ice avalanche. The experience in finding suitable ranges of friction parameters for numerical modeling and assessing risk is provided. Schaub et al. (2016) applied RAMMS and IBER for the coupled numerical simulation of the process chain of an impact wave triggered by an ice avalanche.

Since the continuity method based on the small deformation and continuity hypothesis is limited. Moreover, the discrete element method (DEM) is not intuitive enough to characterize cracks, stresses and strains, some scholars had begun to study solid problems that continuous and discontinuous coexist using combined finite-discrete element method (FDEM). Munjiza (1995) realized the contact and fracture simulation of the system and wrote a complete hybrid finite-discrete element coupling program Y. The process of cliff recession is well simulated by Mahabadi (2012) with the Y-Geo code. Lisjak (2013) used FDEM method to simulate the acoustic emission of brittle rock and carried out numerical analysis of tunnel excavation process. Zhou et al. (2016) researched the influence of joint
dip angle on the failure mode of the slope, the movement process and the accumulation pattern after the failure based on the FDEM method.

The introduction of joint elements in the continuous-discrete coupling analysis method can effectively capture the crack development during loading, simulate the progressive failure process, and realize the characteristics of the solid deformation from continuous to discontinuous. In this paper, the Laohugou No.12 Glacier of Qilian Mountain is selected as the research object. The stability of the Laohugou No.12 Glacier of Qilian Mountain under given loading effect is analyzed by using two-dimensional FDEM method. The feasibility of using FDEM method to study discontinuous problems such as ice avalanche is discussed.

2. Principles of FDEM
The continuous domain by the finite element method is described in the initial stage. A discontinuous zone produces as soon as a fracture occurs in the continuous domain under the load according to a series of fracture criterion. The implementation method is that inserting a zero-thickness joint element in each pair of elastic finite elements, which can enforce finite element discretization. The finite element method is used to simulate the continuous deformation of the material before the joint element fails. When the tensile or shear peak strength is reached, the material begins to yield, followed by stretching or shear slip damage. The joint element is destroyed and removed from the model after the fracture energy is released. As soon as contacting pairs of elements are detected by the contact detection algorithm, a potential function method is performed to calculate forces between discrete bodies. It should be noted that these cohesive joint elements are not real joints unless broken.

Stress and strain fields need to be modified due to microstructural defects and stress concentration, and strain-based cohesive cracking model has been implemented in FDEM codes.

3. Numerical Simulation of Model Test

3.1. Model Description
The two-dimensional plane model is used to carry out the biaxial compression experiments to calibrate the simulation parameters. The selected subjects are artificial polycrystalline ice samples at the temperatures of -15.0 ℃ (Xu 2011), with a diameter of 61.8 mm, a length of 125 mm and an average density of 870 kg/m³.

The grids are meshed by LS-PrePost, as shown in Figure 1. The computational domain consists of 5040 triangular elements with 2620 nodes. The minimum element size is 2 mm. The FDEM method uses explicit integral format for calculation. Usually, small time step size is required to ensure the stability of computational convergence. Therefore, Time step size is set to $5 \times 10^{-8}$ s, and the number of steps is 2,500,000 in total. The lower loading platen is fixed, while the loading rate of the upper loading platen is 0.1 m/s. Note that a friction coefficient of 0.1 (equivalent to 5.71°) is assumed between the ice sample and the loading platens. Five confining pressures are in the range of 0.5 ~ 2.5 MPa.

3.2. Calculation Parameters
Micro-properties describing the strength of the cohesive joint elements control the cracking behavior of the material, i.e. tensile strength $f_t$, cohesion strength $c$, fracture energy $G$. Munjiza (2004) found the critical value of viscous damping ($k_s$) as:

$$k_s = 2h\sqrt{\frac{E}{\rho}}$$

where $h$ is the element size, $\rho$ is the density, and $E$ is the Young’s modulus.

Meanwhile, the normal penalty is taken as ten times the Young’s modulus of ice and the shear penalty is equal to the Young’s modulus. The fracture penalty factor is taken as 5E. The final FDEM simulation parameters are shown in Table 1.
Table 1. Biaxial compression experiment parameters

| Parameter                              | Ice sample | Loading platens |
|----------------------------------------|------------|-----------------|
| Density (kg/m³)                        | 870ᵃ       | 7850            |
| Young’s modulus (GPa)                  | 1335ᵇ      | 200,000         |
| Poisson’s ratio (-)                    | 0.35ᶜ      | 0.29            |
| Viscous damping (kg/ms)                | 4,310,823  | 3,256,643,487   |
| Normal contact penalty (GPa)           | 13.35      | 200             |
| Tangential contact penalty (GPa)       | 1.355      | 20              |
| Tensile strength (MPa)                 | 0.549ᵇ     | /               |
| Cohesion (MPa)                         | 1.998ᵃ     | /               |
| Friction angle (°)                     | 15.4ᵃ      | /               |
| Fracture energy release rate (J/m²)    | 16.87ᵇ     | /               |
| Fracture penalty (GPa)                 | 6.675      | /               |

ᵃ Xu et al. (2011);ᵇ Zhang (2016);ᶜ Derradj-Aouat (1992).

Figure 1. The mesh of ice samples for computational model

Figure 2. Stress–strain curve
3.3. Calculation Results and Analysis

It can be seen from Figure 2 that the stress-strain curves obtained in this simulation experiment have similar morphology, all of which are characterized by strain softening. The deviatoric stress raises with the increase of the axial strain at first. However, after reaching the peak value, the curve shows a significant post-peak softening phenomenon. The entire process exhibits the characteristics of a brittle material. With confining pressure increasing, the maximum deviatoric stress of the ice sample gradually increases, as well as the residual strength. For example, the corresponding maximum deviatoric stress is 5.475 MPa when the confining pressure is 0.5 MPa, and 7.015 MPa when the confining pressure is 2.5 MPa.

The volume of the ice sample has a certain amount of shrinkage at the beginning of loading, but it has been stably expanded in the later stage. When the axial strain is 5%, the volumetric strain decreases from 1.39% to 0.70% when the confining pressure increases from 0.5 MPa to 2.5 MPa. The volume expansion becomes smaller and smaller as the confining pressure increases. In particular, the volumetric strain curve under 0.5 MPa is significantly higher than that under other confining pressure conditions. The reason is found to be that the appearance of the shear band caused the sample to break, and then some discrete elements flew out.

4. Glacier Numerical Simulation

4.1. Project Overview

The Laohugou No.12 Glacier of the Qilian Mountain is located in the northern part of the Qinghai-Tibet Plateau, on the northern slope of the Qilian Mountain, and in the Hexi corridor earthquake zone. It is the largest valley glacier in Qilian Mountain, with a length of 10.1 km and an area of 21.9 km². The terminal elevation is 4260 m, the highest elevation is 5481 m, and the slope is 3°–6°. The glacier is formed by the combination of eastern and western branches, which is typical polar continental glacier. Due to the rising temperature in the study area, the glacier is currently in a state of retreat and negative mass balance (Du 2008, Chen 2014, Sun 2014). In this paper, the middle streamline section of the eastern branch is selected for study. The maximum thickness is 261 m (2016).
4.2. Calculation Model and Parameters

The glacial computing model is shown in Figure 4. The computing domain consists of 5509 triangular elements with 2991 nodes. The minimum mesh size of the models is 30 m. As we can see, A, B and C are points on the upper part(ice), and D, E and F are points on the lower part(rock). The bottom was set as the fixed boundary while the lateral boundaries were fixed in the y-direction but free in the x-direction.

The FDEM simulation is carried out in two steps. First, the ground stress is balanced to obtain the initial stress field, and then the seismic load is applied for dynamic analysis. The seismic load is reduced by Lushan earthquake acceleration time history. As shown in Fig. 5, the maximum acceleration of the earthquake is 0.25g, which lasts for 40s. The calculation parameters are shown in Table 3 and Table 4.

Table 3. Elastic element parameters

| Parameter                      | Ice         | Rock       |
|--------------------------------|-------------|------------|
| Density (kg/m³)                | 870ᵃ        | 2420       |
| Young’s modulus (GPa)          | 1335ᵇ       | 51790      |
| Poisson’s ratio (-)            | 0.35ᶜ       | 0.23       |
| Viscous damping (kg/ms)        | 4,310,823   | 671,710,116|
| Normal contact penalty (GPa)   | 13.35       | 250        |
| Tangential contact penalty (GPa)| 1.355       | 20         |
Table 4. Cohesion joint element parameters

| Parameter                        | Ice-ice | Ice-rock | Rock-rock |
|----------------------------------|---------|---------|-----------|
| Tensile strength (MPa)           | 0.549   | 0.5     | 11.4      |
| Cohesion (MPa)                   | 1.998   | 2       | 34.77     |
| Friction angle (°)               | 15.4    | 16.7    | 23.7      |
| Fracture energy release rate (J/m²) | 16.87   | 15      | 80        |
| Fracture penalty (GPa)           | 6.675   | 7       | 25        |

4.3. Calculation Results and Analysis

The speed amplification factor is given by Figure 6. From the bottom of the bedrock to the shoulder, the amplification factor is gradually increased from 1 to 1.9. The magnification factor also increases continuously in the direction perpendicular to the slope, showing the magnifying effect of the surface. Under the action of seismic load and gravity, the glaciers creep and slide relative to the bedrock until the anti-sliding force is insufficient, resulting in complete instability. Since the X-directions of the two sides are fixed, the speed of the nodes on both sides is very low.

Figure 6. The amplification factor of horizontal velocity

Figure 7. Displacement time-history curve of monitoring points
The displacement of the X-direction node on the glacier is larger than that on the rock (Fig. 7), which indicates that the glacier has slipped, too. In the time history curve of the monitoring point on the line (Fig. 8), the peak concentration area appears near 5s, which is consistent with the input seismic loading. Point D and E reach the peak speed after the point F at the bottom of the bedrock, and the response is more delayed.

The formation and growth of the cracks can be represented by the break of the cohesive joint elements when the impulse generated through the collision becomes larger than the tensile strength and shear strength (Fig. 9). The process is well described and reproduced by numerical calculation using FDEM method.

5. Conclusions
(1) For the numerical simulation of triaxial compression test of polycrystalline ice samples with confining pressure of 0.5 MPa - 2.5 MPa, the stress-strain curves are strain softening, and the volume variation showed the trend of volume expansion after a little volume contraction. The calculated results are consistent with the test results.

(2) Under the action of seismic load, the glacier slip along the slope, and the whipping effect of the speed is obvious. Due to the propagation and time-consuming of the seismic wave, the farther away from the source, the more the response lags.

(3) According to the dynamic analysis results of glaciers under given earthquakes, the FDEM numerical method can well describe the generation and expansion of cracks, and it shows larger advantages and broad application prospects in the study of discontinuous problems.

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