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ORIGINAL ARTICLE

Does vertical seismic force play an important role for the failure mechanism of rock avalanches? A case study of rock avalanches triggered by the Wenchuan earthquake of May 12, 2008, Sichuan, China

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Abstract The Wenchuan earthquake triggered 15,000 rock avalanches, rockfalls and debris flows, causing a large number of causalities and widespread damage. Similar to many rock avalanches, field investigations showed that tensile failure often occurred at the back edge. Some soil and rock masses were moved so violently that material became airborne. The investigation indicates that this phenomenon was due to the effect of a large vertical seismic motion that occurred in the meizoseismal area during the earthquake. This paper analyses the effect of vertical earthquake force on the failure mechanism of a large rock avalanche using the Donghekou rock avalanche as an example. This deadly avalanche, which killed 780 people, initiated at an altitude of 1,300 m and had a total run-out distance of 2,400 m. The slide mass is mainly composed of Sinian limestone and dolomite limestone, together with Cambrian slate and phyllite. Static and dynamic stability analysis on the Donghekou rock avalanche has been performed using FLAC finite difference method software, under the actual seismic wave conditions as recorded on May 12, 2008. The results show that the combined horizontal and vertical peak acceleration caused a higher reduction in slope stability factor than horizontal peak acceleration alone. In addition, a larger area of tensile failure at the back edge of the avalanche was generated when horizontal and vertical peak acceleration were combined than when only horizontal acceleration was considered. The force of the large vertical component of acceleration was the main reason rock and soil masses became airborne during the earthquake.

Keywords Wenchuan earthquake · Rock avalanche · Vertical peak acceleration · Failure mechanism · Finite difference method

Introduction

On May 12, 2008, the Wenchuan earthquake (Ms = 8.0; Epicenter located at 31.0°N, 103.4°E) with a focal depth of 14.0 km occurred in the Longmenshan tectonic belt in Sichuan Province, China. It caused more than 15,000 landslides including rock avalanches, rock-falls and debris flows, resulting in approximately 20,000 deaths. Field investigations show that along the surface fracture of the earthquake fault, there were 13 great rock falls or rock avalanches, distributed from SW to NE. These events include, for example, the Niujuangou, the Xiejiadianzi, the Daguangbao, and the Donghekou rock avalanches (Fig. 1). During the investigation, we found that for many rock avalanches, tensile failure often occurred at the back edge, and some soil and rock masses moved with such high speed and force as to become airborne. Many experts have studied this phenomenon (Xu and Huang 2008; Yin et al. 2008, 2009; Wang 2009; Li and Siming 2009). This phenomenon

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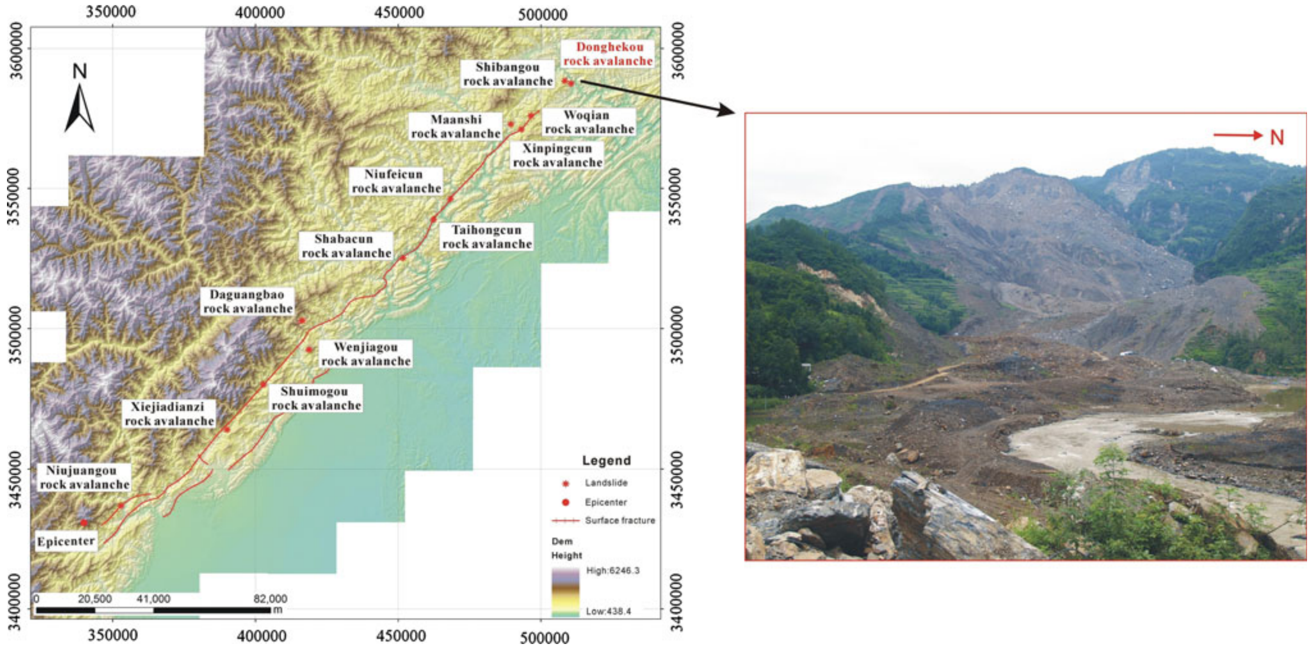


Fig. 1 The major rock avalanches in addition to the Donghekou rock avalanche triggered by the Wenchuan earthquake

indicates that the influence of vertical seismic force on rock avalanches was very pronounced in the failures that occurred in the Earthquake meizoseismal area. This conclusion supports the work of Qian (1983, 1988) who stated that “the traditional view that the horizontal seismic force plays an important role is wrong; but in fact, the vertical force plays a leading role”. Studies of the effect of vertical seismic waves have been published by experts using data from events found all over the world (Anderson and Bertero 1973; Qian 1983, 1988; Zhou et al. 2003; Liang et al. 2007).

The action of seismic acceleration is very complex, depending not only on the earthquake magnitude and distance from the epicenter, but also on the type of seismic fault, the propagation direction, topographic formations and geological structure, etc. This paper uses the Donghekou rock avalanche (Fig. 1) to analyze the effect of vertical seismic waves on the failure mechanism of rock avalanches triggered by the Wenchuan earthquake. A computational geological model of the Donghekou rock avalanche has been constructed using the real seismic waves characteristics derived from field investigations. The effect of vertical earthquake force on the model was analyzed using static and dynamics methods found in the software, FLAC.

A brief introduction of FLAC

Principle of FLAC

“FLAC” is an acronym for Fast Lagrangian Analysis of Continua. It is an explicit finite difference method (Morgenstern and Price 1965). Explicit finite difference method has the advantages of efficient storage capacity, fast calculation, as well as good convergence.

At present, the strength reduction has been proven to be an effective way to solve the slope stability factor, and the physical meaning is clear (Zheng et al. 2007). The basic principle is often presented in the following formulas:

$$c' = c/F \tag{1}$$

$$\tan\phi' = \tan\phi'/F \tag{2}$$

where c and ϕ are the original cohesion and friction angle of rock mass; F is the reduction coefficient; c' and ϕ' are the new cohesion and friction angle. When the slope rock mass is consistent with the given critical condition, the corresponding F is called the minimum safety factor of slope.

Slope failure condition

By taking into account the redistribution and co-deformation of the internal stress of a rock mass, the finite difference method can be used to compute the slope stability factor without making any assumption, and can accurately find the location of the corresponding slide surface.

For the integral failure of a slope, the classical limit equilibrium theory often assumed that each point on a sliding surface is in a limited equilibrium state, namely, a plastic zone slip that appears on a sliding surface. However, this is only the beginning of failure and is minimally necessary condition for failure, but not a sufficient one. Therefore, the strain of each point on a sliding surface must also be considered, that is to say, if the strain has reached the limit strain state, then it can be concluded that the integral failure has happened (Zhang et al. 2003).

The case study

Description of the Donghekou rock avalanche

The Donghekou rock avalanche, located in Donghekou village, Qingchuan County, Sichuan Province, is a typical rapid and long run-out rock avalanche with a height difference between the toe and main scarp of 700 m, a slide distance of 2,400 m, and a volume of 10 million m^3 (Fig. 1). The slide mass of the Donghekou rock avalanche is mainly composed of Sinian limestone and dolomite limestone, together with Cambrian carbonaceous slate and phyllite. After the long runout slide occurred, it then transformed into a debris flow, which scoured the banks of the Hongshihe River and the Xiasihe River successively, and formed two landslide dams consisting of loose debris and large rocks, which blocked the flows of the two rivers. In addition, this debris flow buried seven villages, including, Donghekou (notably, the Donghekou Elementary School), Houyuanli, and Honghaudi villages (and others) resulting in a total of 780 people killed. During the investigation, 17 field observation points were selected on the Donghekou rock avalanche (Fig. 2).

The simulation model

Field investigation indicates that the rock mass of the source area mainly consists of phyllite, as well as a small quantity of carbonaceous slate of the Cambrian system. The rock mass below the sliding surface is relatively intact, but the upper rock mass is strongly weathered and broken, with overlying Quaternary alluvium of varying thickness. To facilitate the modeling calculations for geometric mechanics, the geological model is generalized as the two materials, Rock 1 and Rock 2.

Based on the above-mentioned morphological character and geological setting of the Donghekou rock avalanche, the profile section and simulation model were constructed and are shown in Fig. 3.

To get the relevant parameters for a simulation model, typical samples of relatively intact rock mass (Rock 1) were collected for the indoor test, and both the microstructure and mechanical properties were analyzed (Sun et al. 2009).

By considering the above factors, combined with the local empirical value, the value of physico-mechanical parameters of Rock 1 was obtained. It is worth mentioning that it is difficult to collect samples for Rock 2, therefore, the related values for Rock 2 are approximate, based on the values of Rock 1. This is accomplished by taking the appropriate reduction factor into account, as shown in Table 1.

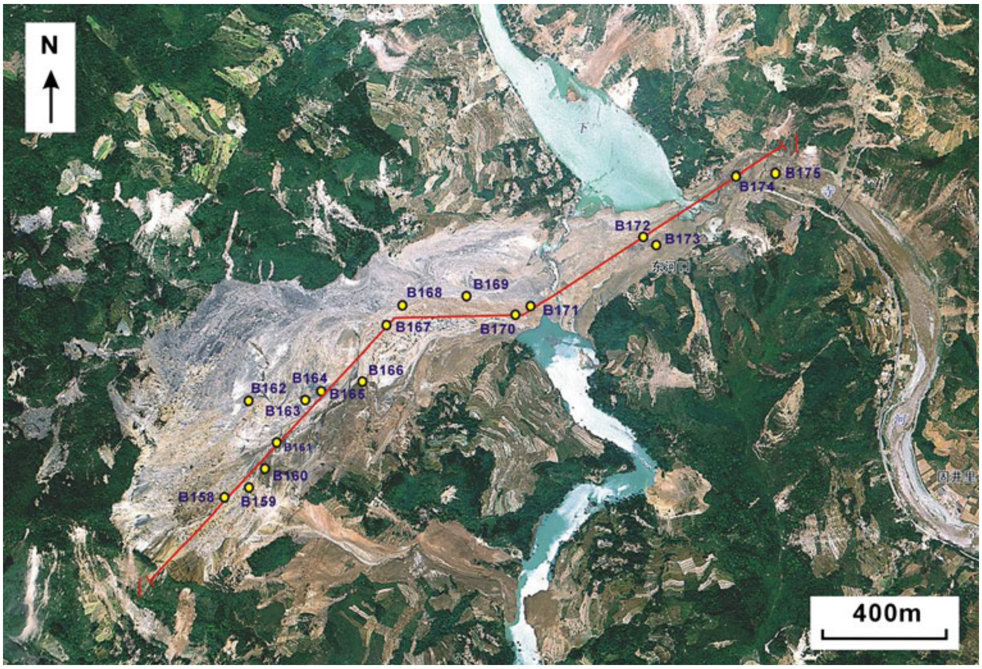


Fig. 2 Field observation points on the Donghekou rock avalanche

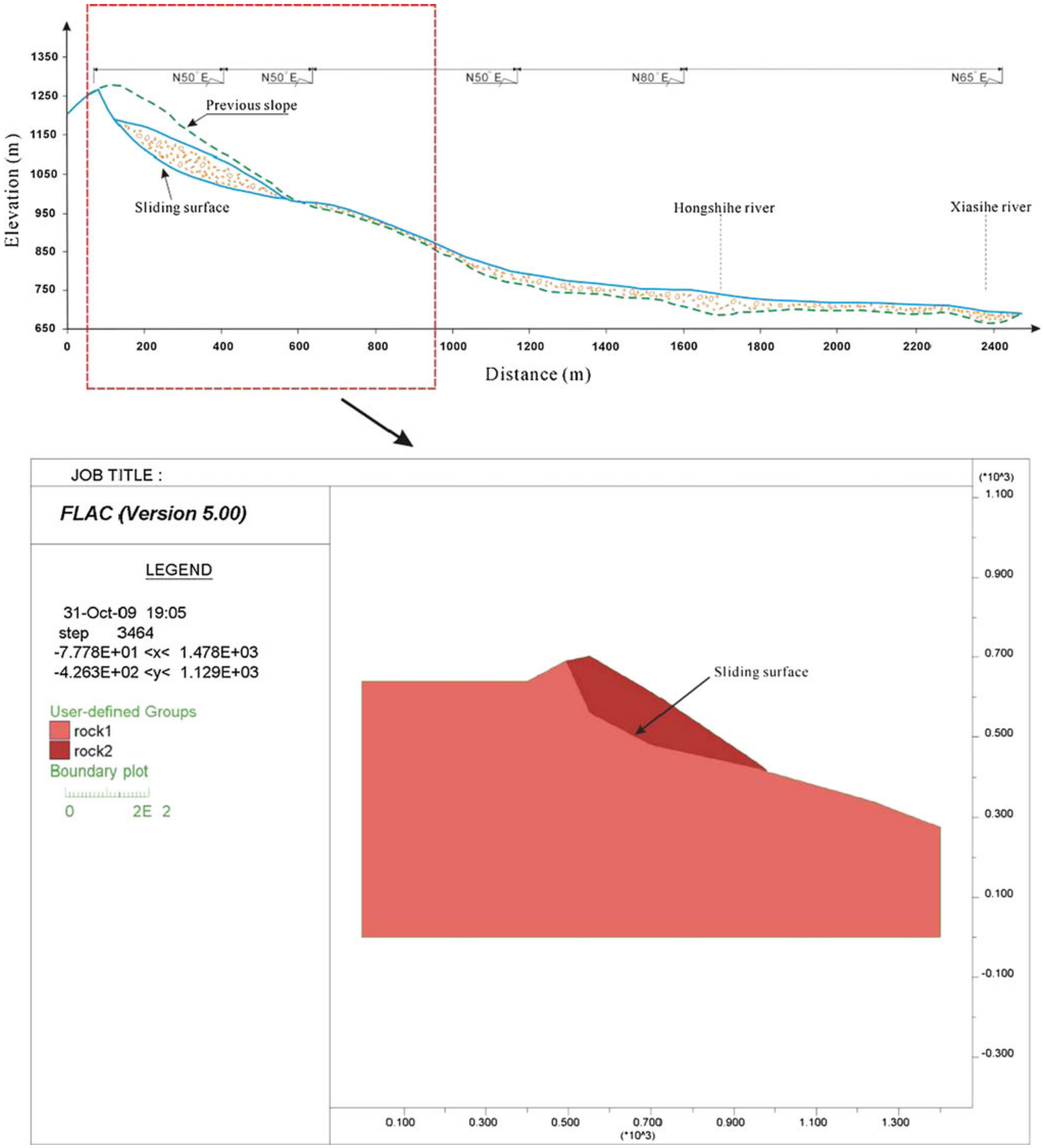


Fig. 3 Section of the diagrammatic sketch and simulation model of the Donghekou rock avalanche

Simulations and results

Static stability analysis

Before analyzing the influence of the Wenchuan earthquake on the Donghekou rock avalanche, the stability in its natural state should be analyzed first. By calculation, the factor of stability in the natural state of the Donghekou rock avalanche is 1.79, which indicates that the slope before the Wenchuan earthquake was stable.

In order to analyze the effect of the vertical seismic peak acceleration on the failure mechanism of the rock avalanche, two cases were considered. In case 1, only the horizontal earthquake force is taken into account; but in

Table 1 Physico-mechanical parameters of rock masses

Rock mass	Density (g/cm^3)	Young's modulus (GPa)	Poisson ratio	Shear strength		Tensile strength (MPa)
				Cohesion (MPa)	Friction angle (°)	
Rock1	2.2	15	0.25	1.0	42	0.8
Rock2	2.15	5.4	0.28	0.3	37	0.24

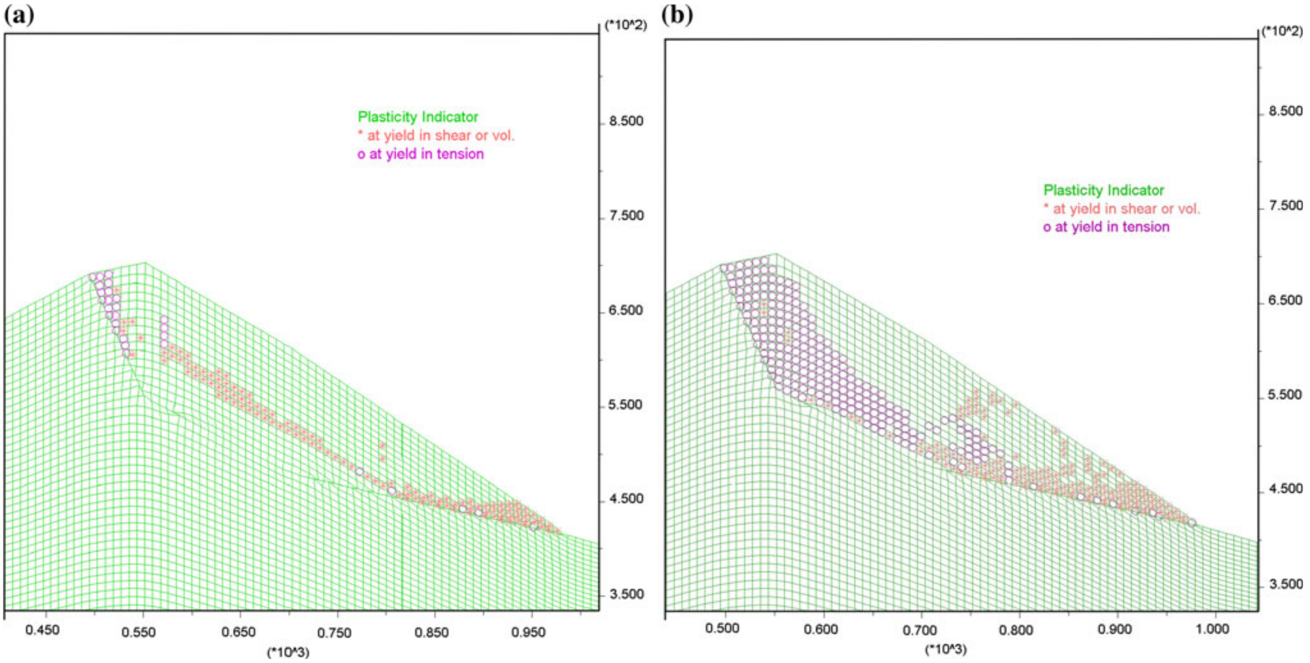


Fig. 4 Distribution map of the plastic zone in cases 1and 2 of static analysis **a** Only horizontal seismic force is considered; **b** Both vertical and horizontal seismic forces are considered

case 2, both the horizontal and vertical earthquake forces are considered.

The simulation result reveals that when the slope experiences earthquake force, failure will happen. The factor of stability (FOS) of the Donghekou rock avalanche in case 1 is 0.76 but 0.69 in case 2, which indicates that the vertical earthquake force can lead to great failure. Figure 4 shows the distribution map of the plastic zone in case 1 (Fig. 4a) and case 2 (Fig. 4b). It can be seen that when the vertical seismic force is considered, a high tensile failure number will occur at the head scarp.

Dynamic stability analysis

Boundary conditions

As for the dynamic analysis, the artificial boundary must be set up on the actual boundary, to make the fluctuations meet the radiation phenomena in the original continuous media. In this paper, the viscous boundary conditions in FLAC were used to ensure the precision of simulation results.

Studies show that the viscous boundary has first-order accuracy for simulating the wave propagation in an infinite medium, which can absorb the lay wave energy effectively and make the numerical solutions satisfactory (Liao and Liu 1992).

Mesh size and the input seismic wave

In order to simulate the wave propagation in the simulation model precisely, the appropriate mesh size must be chosen based on the following relationship (Kuhlemeyer and Lysmer 2005, see in FLAC, User's Guide):

$$\Delta l \leq \left(\frac{1}{8} \sim \frac{1}{10}\right)\lambda \tag{3}$$

where Δl is the maximum mesh size of simulation model, λ is the shortest wavelength of incident wave and it can be defined by

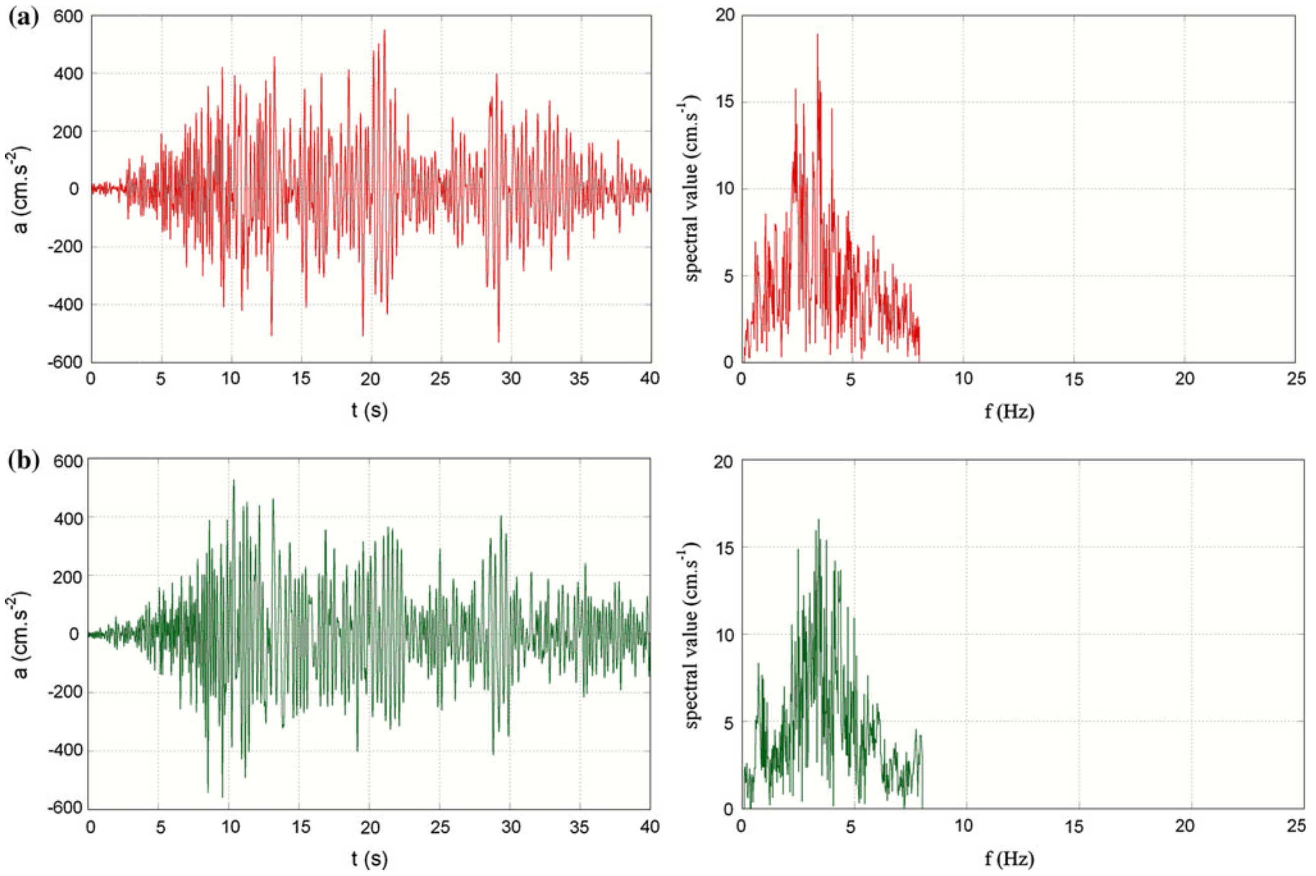


Fig. 5 Input seismic wave. **a** Input seismic wave along slope strike ($|A_{\max}| = 550.44$ cm s^{-2}) and its Fourier spectrum. **b** Input seismic wave perpendicular to the slope ($|A_{\max}| = 557.5$ cm s^{-2}) and its Fourier spectrum

$$\lambda = c_s / f \tag{4}$$

$$c_s = \sqrt{\frac{E}{2\rho(1+v)}} \tag{5}$$

where c_s is the minimum wave velocity of seismic wave; f is the maximum frequency of incident wave; E, ρ and v are the elastic modulus, density and Poisson's ratio, respectively.

It is known that for a seismic wave, it often contains a wide spectrum, but most of the energy is concentrated in the part with a frequency of less than 10 Hz. In fact, the high-frequency seismic wave does not play an important part of slope failure, so it can be filtrated through the filtering method.

For this case study, the original seismic wave is used as the simulated real wave of the Wenchuan earthquake monitored at Bajiao Town in Shifang City by the Seismic Monitoring Network, China Earthquake Administration. Based on the frequency component characteristics of the actual seismic wave recorded on May 12, 2008 and by transforming the three components of the seismic wave to two components along the slope strike and perpendicular to the slope, the input seismic wave with frequency components within 8 Hz were formed (Fig. 5).

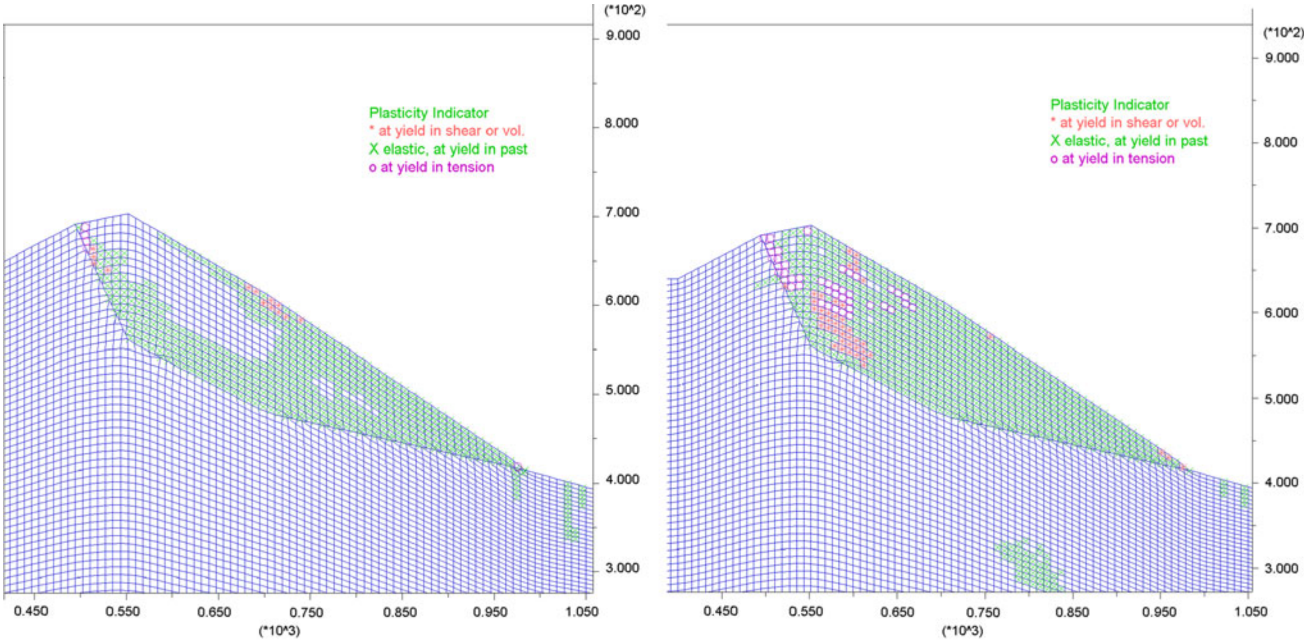
By considering the factors mentioned above, the length of mesh size is 8–10 m, which can attain the accuracy requirements.

Simulation results

Similarly, in order to analyze the effect of vertical earthquake motion on slope stability, two cases are simulated. In case 1, only the horizontal earthquake force is taken into account; but in case 2, both the horizontal and vertical earthquake forces are considered.

Figure 6 shows the distribution map of the plastic zone in case 1 (Fig. 6a) and case 2 (Fig. 6b), respectively. It also can be seen that when the vertical seismic force is considered, more tensile failure will occur at the head scarp. It can be seen that when the vertical seismic force is taken into account, the failure will happen earlier.

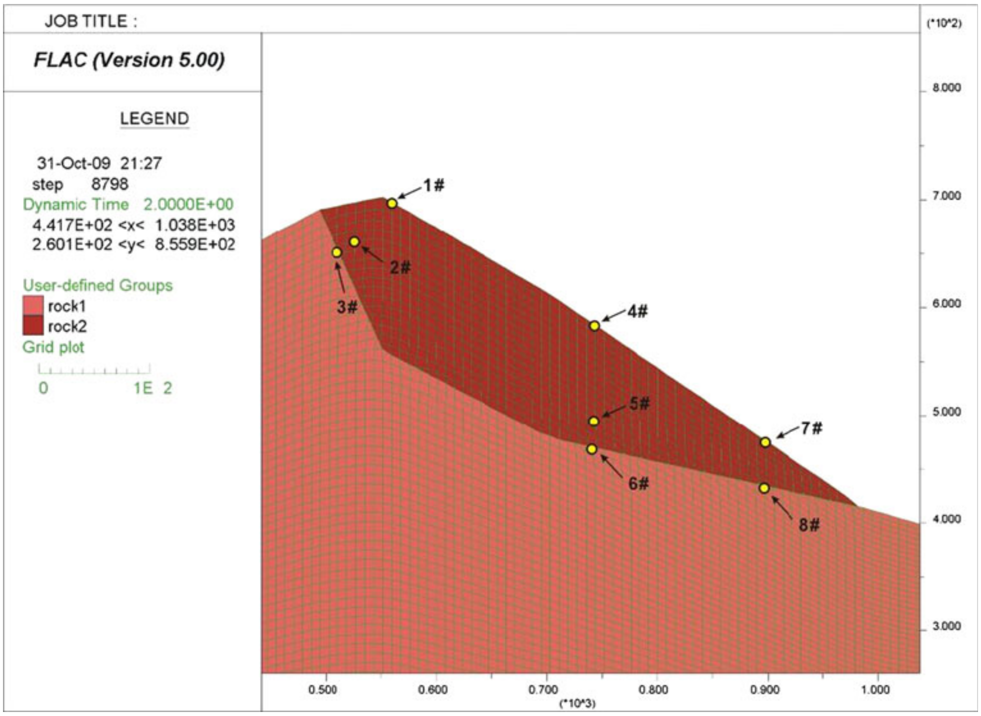
During simulation, the monitoring points on the simulation model were established and monitored (Fig. 7), so as to obtain the specific failure time and the residual



(a) t=12s **(b)** t=10s

Fig. 6 Distribution map of the plastic zone in cases 1and 2 of dynamic analysis. **a** Only horizontal seismic force is considered, **b** Both vertical and horizontal seismic forces are considered

Fig. 7 Distribution map of monitoring points on the simulation model



deformations of the Donghekou rock avalanche. Figure 8 shows that the time for the first airborne phenomenon at curves in case 1 (Fig. 8a) and case 2 (Fig. 8b) are 13.4 and 10 s, respectively. The specific failure time for Donghekou rock avalanche in case 1 and case 2 is 13.4 and 10 s, respectively.

Meanwhile, the values of the residual deformations in different cases are monitored (Table 2). From Table 2, it

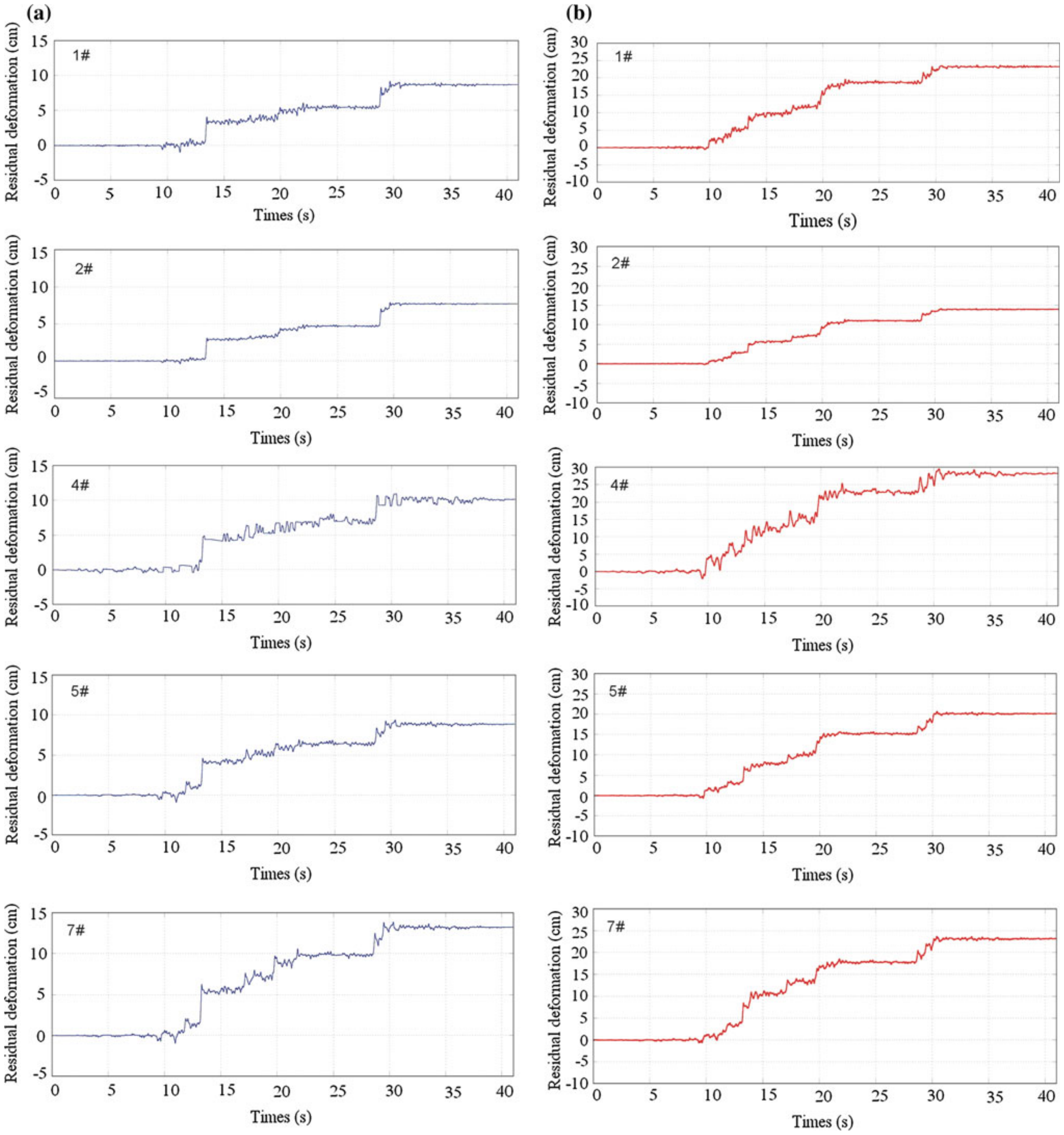


Fig. 8 Residual deformations of monitoring points above the sliding surface. **a** Only horizontal seismic force is considered, **b** Both vertical and horizontal seismic forces are considered

can be seen that the residual deformation in case 2 is larger than that in case 1.

Discussion and conclusions

This paper is a preliminary study of the effect of vertical seismic acceleration on the failure mechanism of rock avalanches triggered by the great 2008 Wenchuan earthquake. By using the Donghekou rock avalanche as a case study, the stability of the slope in a static state and a dynamic state are analyzed, respectively. The calculation results showed that the vertical peak acceleration led to distinct reduction of the slope stability factor, and played a significant role in the slope failure. In addition, large-scale tensile failure at the back edge of rock avalanches were

Table 2 Residual deformations for different cases (unit: cm)

Case	Monitoring points				
	1#	2#	4#	5#	7#
Case 1	7.9	6.9	7.8	6.5	10.6
Case 2	23.3	14.0	25.7	17.6	20.1

generated by the great vertical peak acceleration, which was the reason for the triggering of a large number of rock avalanches and rockfalls. The great vertical acceleration is also the apparent reason for soil and rock masses becoming airborne.

It is worthy to note that in most previous landslide or rock avalanche stability assessments, only the horizontal earthquake force is considered and the vertical force is neglected. However, the results of this study indicate that it is very necessary to consider the effect of vertical seismic forces for analyzing rock avalanche stability in meizoseismal areas.

Therefore, for rock avalanche stability analysis and engineering calculations in the future, the vertical seismic force must be emphasized, as well as the existing empirical equation for analyzing landslide stability. This indicates that some building and land-use codes of China should be re-evaluated.

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