Numerical analysis of Daguangbao slope failure in China induced by Wenchuan earthquake

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Abstract. The 2008 Wenchuan earthquake resulted in a large number of fatalities and caused significant economic losses, in China. Thousands of landslides, many of which are very large, were triggered by the earthquake. Most of these catastrophes were distributed along the Longmenshan fault system, on the edge of the Tibetan plate. Some of these landslides blocked rivers, causing flooding that in turn triggered secondary landslides. Among the most significant landslides, the Daguangbao landslide had the highest volume. To analyze the Daguangbao landslide, two-dimensional and three-dimensional numerical models based on the Material Point Method (MPM) were developed to simulate failure and post failure behavior of the slope, taking into account large deformations. The numerical results were compared with the post-earthquake profile and with the affected area by the event. As a consequence of the landslide, an almost vertical rockwall of more than 500m was generated. This situation is considered high risk, requiring ongoing monitoring and evaluation.

Keywords: Wenchuan earthquake; Landslides; Daguangbao landslide; Material Point Method (MPM).

1. Introduction

Earthquakes, particularly those with strong ground motion, can trigger thousands of landslides in mountainous regions with unfavorable geomorphic environments. The 2008 Wenchuan earthquake, which occurred in China is such an example. The earthquake occurred along a 240 km rupture zone with an estimated maximum slip of 9-12 m, and it resulted in a large number of fatalities and caused significant economic damage. More than 87,000 casualties and millions of displaced people were reported. The major landslides were distributed along the Longmenshan fault. The Daguangbao landslide was the largest in volume, about 7.4 x 10^{8} m^{3}, with a length of 4200 m, a width of 1160-3200 m, and a maximum thickness of 690 m. The landslide was characterized by high kinetic energy with intensive cracking and deformation (Cui et al. [1]; Zhang et al. [2]).

The main objective of the paper is to better understand the causes and the effect of the 2008 Wenchuan earthquake on the Daguangbao landslide using a numerical implementation of the Material Point Method (MPM). This method allows the simulation of large mass movements and is able to capture the complex mechanics associated with seismic slope failure, with which failure modes can be observed. A second objective of this paper is to propose a safety analysis methodology for the existing head scarp, generated by the earthquake-induced landslide. The head scarp is almost vertical and has a maximum height of about 700 m. The safety methodology proposed in this paper is a combined risk decision model based on dynamic Bayesian Networks (BNs) models and monitoring techniques, with the aim of assessing and reducing the risks associated with the rockwall.

The present paper presents four sections. Section 2 describes the geological characteristics of the Daguangbao landslide. Section 3 presents the numerical results of the 2D and 3D analysis regarding the failure mechanism and the affected area. Section 4 summarizes conclusions about the study.

2. 2008 Wenchuan earthquake

The Wenchuan earthquake (magnitude Ms=8.0) occurred on the Longmenshan fault system in a mountainous region to the northwest of Chengdu, at the eastern margin of the Tibetan Plateau, resulting from motion on a northeast-striking reverse fault along the northwestern margin of the Sichuan Basin, China (He et al. [3]). It was the most catastrophic earthquake in China after the M7.6 Tangshan earthquake in 1976. The aftershock distribution elongated over 250-270 km along Longmenshan fault zone. The epicenter of the earthquake was located near the southwestern end of the aftershock sequences, and the aftershocks had a magnitude from 4.0 to 6.5. The earthquake caused significant economic damage (Cui et al. [1]; Zhang et al. [2]).

The major landslides were distributed along Longmenshan fault. Table 1 shows the ranking of some of the major landslides by the estimated value. Among the most significant landslides, the Daguangbao landslide was the largest in volume (He et al. [3]). This landslide covered an area of about 7.3 km^2. The lithology of the area was classified into the geological formations indicated in Figs. 1 and 2.

Table 1. Ranking of the major landslide induced by the Wenchuan earthquake.

Landslide	Volume (m^3)	Area (m^2)	Run-out (km)	Height H(m)
Daguangbao debris avalanche	7.5x10^8	7,273,719	4.5	1,450
Wenjiagou debris avalanche	1.5x10^8	2,945,520	4.2	3,900
Shuimogou debris avalanche	3.6x10^7	915,608	2.1	700
Woqian debris avalanche	3.0x10^7	695,672	2.15	200
Tangjiashan landslide	2.8x10^7	572,009		2,780
Donghekou debris avalanche	2.3x10^7	1,283,627	2.4	300

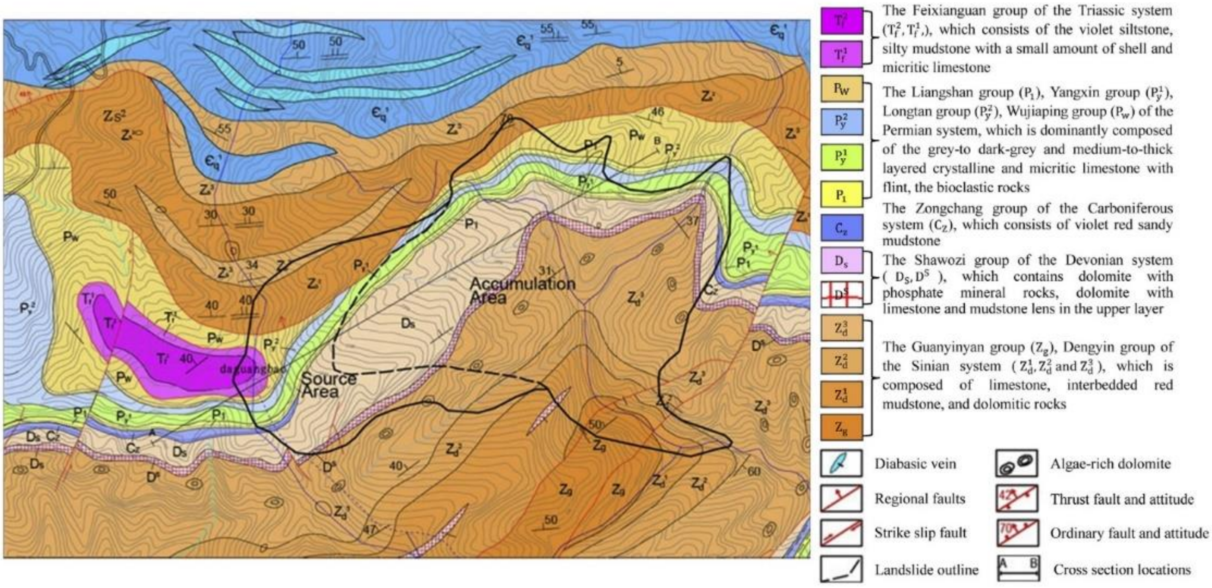


Fig. 1. Geology of the Daguangbao area (He et al. [3]).

The ground motion used in the simulation was recorded at Qingpin Station. It was a very strong shaking with a long duration. The main characteristics of the records are presented in Table 2. The record exhibits a high-frequency content. The predominant period is 0.04s for horizontal components and 0.08s for vertical ones (He et al. [3]).

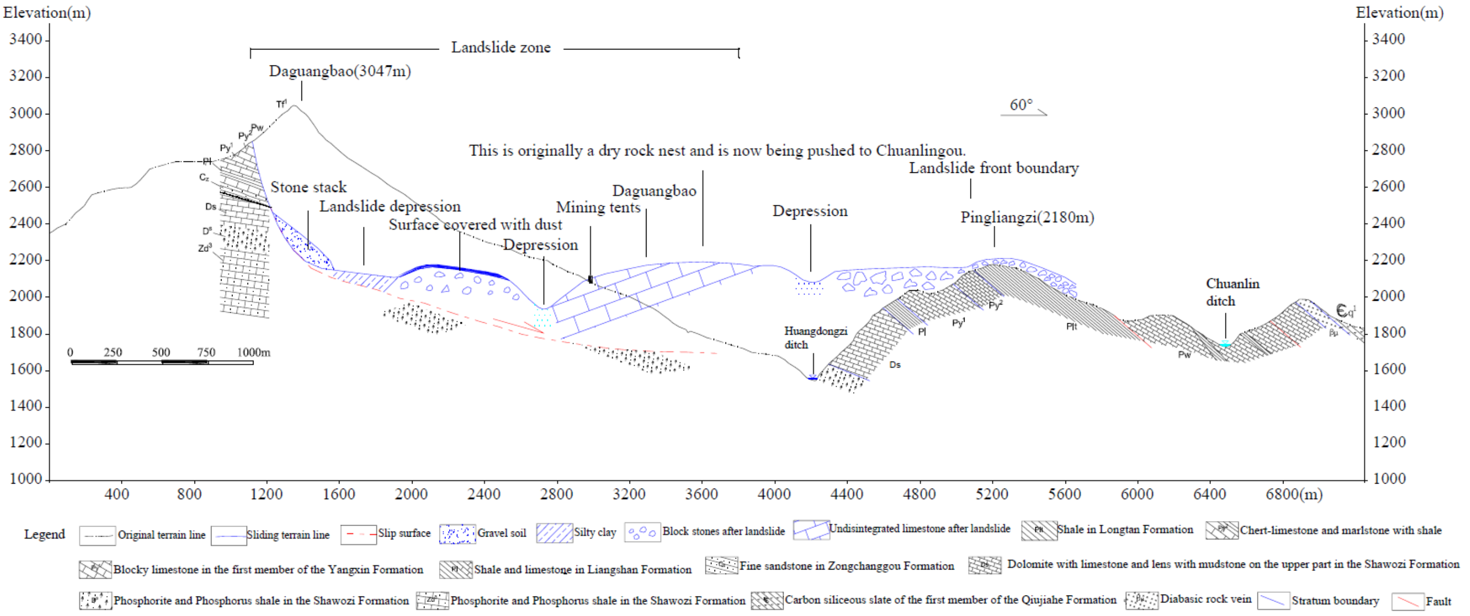


Fig. 2. Geologic profile of the Daguangbao area after the earthquake (He et al. [3]).

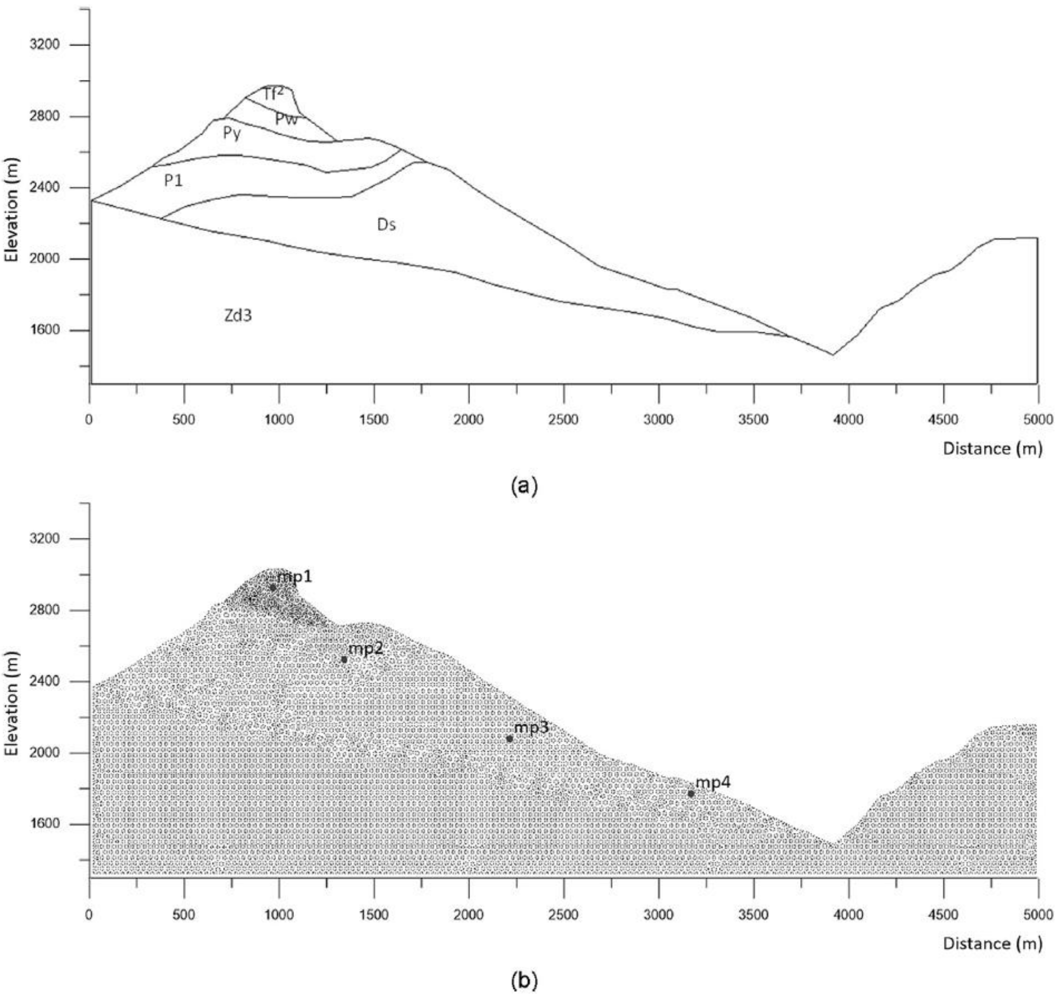
Table 2. Characteristics of the Wenchuan earthquake (Fernández et al. [4]).

	NS	EW	Vertical
Maximum acceleration (g)	0.80	0.82	0.62
Maximum acceleration time (s)	48.52	46.86	47.24
Maximum velocity (cm/s)	73.01	127.35	37.15
Maximum velocity time (s)	38.6	38.11	46.59
Maximum displacement (cm)	836.28	139.14	107.23
Maximum displacement time (s)	159.99	150.74	138.47
Predominant period (s)	0.04	0.04	0.08
Average period (s)	0.28	0.32	0.24

3. Numerical analysis of the Daguangbao landslide

The discrete MPM models for the simulation of the Daguangbao landslide were built using elevation data of the land and each material around the affected area, using 2D and 3D approaches (Muller and Vargas [5]; Fernández [6]). The discrete model was subjected to an earthquake at its base, and laterals and non-reflecting boundary conditions were applied to the model lateral sides. The initial condition was established through an elastoplastic analysis. The constitutive modeling of the materials was considered using an elastic material for the base rock and an elastoplastic constitutive model for the failed mass. The peak resistance and deformability parameters were taken from the work of He et al. [3], where laboratory test results of the materials existing at the site are reported. This work considered material softening through an exponential law variation from the peak to residual values. To capture the characteristics of the event, the softening parameters in the elastoplastic models were used to adjust the numerical model with the observed topography.

The conceptual model used to create the 2D MPM model is illustrated in Fig. 3, with the distribution of material points used in the model (He et al. [3]). The representation of the rock mass was assumed as a continuum and the geomechanical properties were obtained by penalizing the properties of the intact rocks. The earthquake effects were imposed by applying acceleration at the base of the model. Top and lateral surfaces were considered as free to move, and the simulation time relative to the earthquake and post-earthquake was set 190s. Fig. 4 shows the geometry evolution during the run-out of Daguangbao landslide.



(a)

(b)

Fig. 3. Geometrical definitions and material distribution (a) and distribution of the material points (b) used in the 2D MPM model (He et al. [3]).

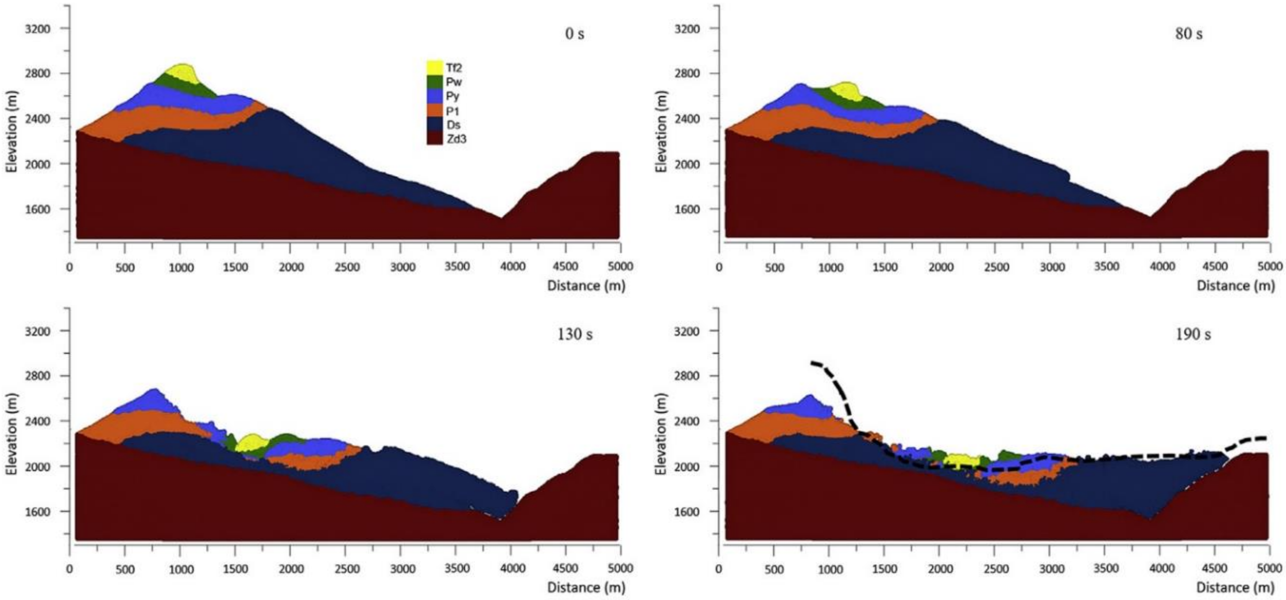


Fig. 4. Geometrical evolution during the run-out process obtained with the 2D MPM model (He et al. [3]).

Also, a 3D MPM model was created following the methodology developed by Fernández et al. [7]. The 3D model is created from the elevation data of the land and the elevation data of each material. Fig. 5 shows the 3D MPM model formed by 1.6e+6 material points, with a 3D view and showing the material distribution in two sections. These sections are presented in detail in the publication Fernández et al. [4]. Also, details about the models used and parameters are indicated in the same publication (Fernández et al. [4].

Numerical analysis in three dimensions using MPM allowed the quantification of the movement of the collapsing mass and the determination of the affected area due to its interaction with the surrounding topography. Fig. 6 compares the reported affected area and the numerically obtained one. Fig. 6.a displays the final deformed configuration of the numerical model in plane view, the definition of the control points, and the contour of the reported affected area. The color scale represents the magnitude of the displacements in meters. Fig. 6.b compares the contours of the affected areas, showing the numerical model in blue and the reported area in red.

A general consistency between the two areas indicates that the numerical model adequately reproduces the observed data. It is important to note that there is an underestimation of the affected area at the front of the mass movement in the direction of control point P2. However, this effect is reavaleated by overestimating the affected area in the lower region in the direction of control point P3, resulting in a total affected area with an error of approximately -0.4% relative to the observed area. The shape of the affected area also proved to be consistent, with a maximum error of 11% in the width of the affected area and an error of -9% in the length of the affected area. In summary, the numerical results demonstrate that the three-dimensional model consistently captured the area affected by the collapse (see Table 3).

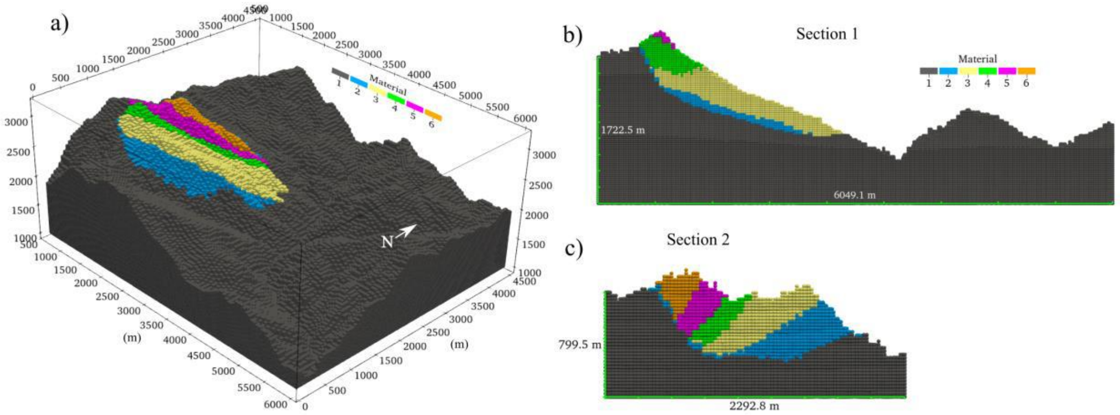


Fig. 5. MPM 3D model of the Daguangbao area showing material distribution: a) tridimensional view, b) Section 1, and c) Section 2

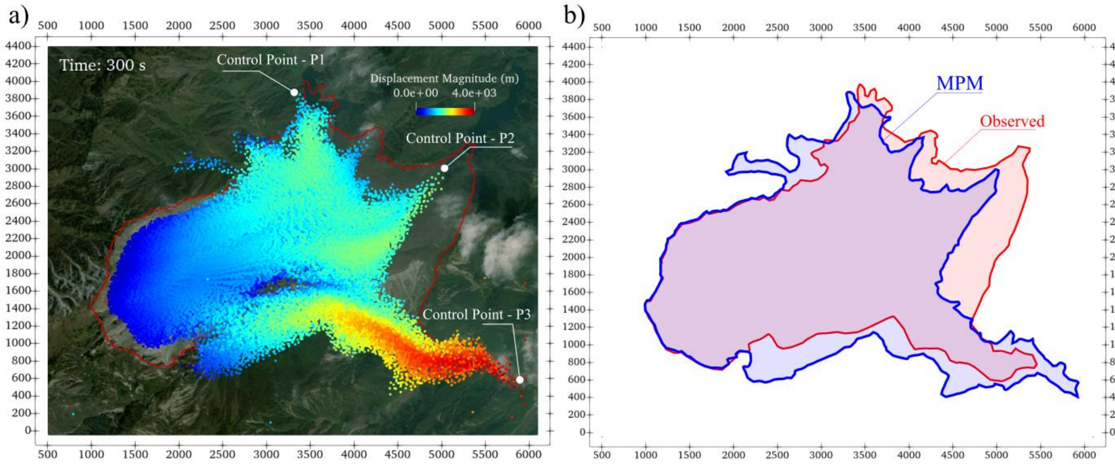


Fig. 6. Area affected by the Daguangbao landslide. a) Displacements magnitude in the post-earthquake condition. b) Observed and MPM determined affected areas

Table 3. Affected area comparison between numerical and reported values

	Reported	MPM	Relative error
Area (km^2)	7.49	7.46	-0.4%
Length (km)	4.85	4.39	-9%
Width (km)	3.90	4.33	11%

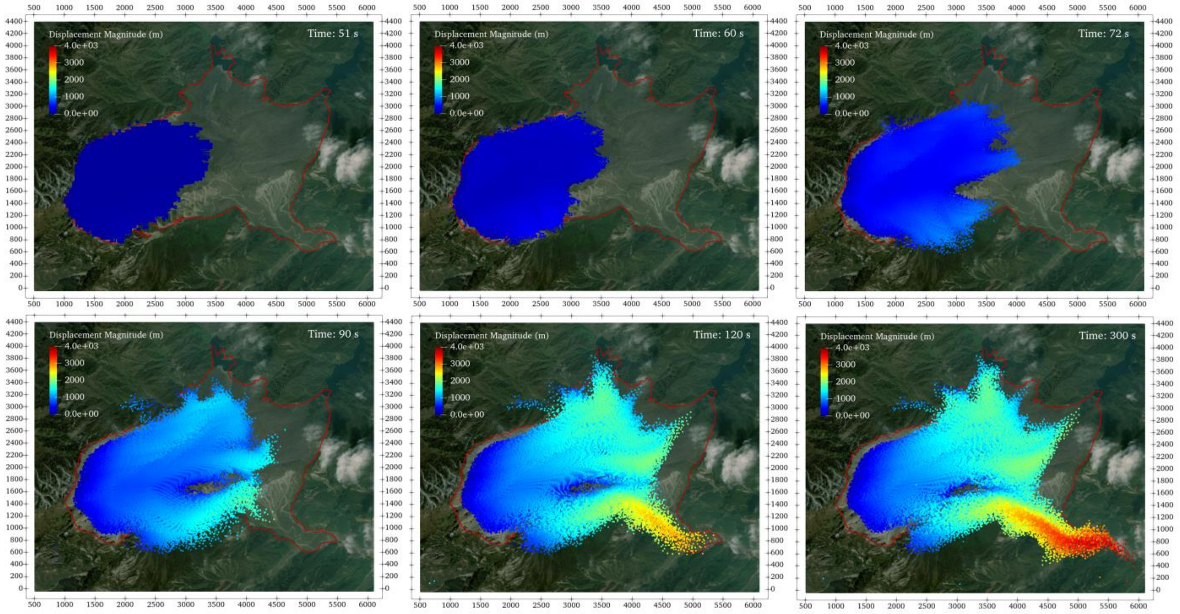


Fig. 7. Affected area evolution in terms of displacement magnitude.

Besides considering the affected area in the final configuration, another essential aspect of landslide modeling is the evolution of the mass movement during run-out after the failure. This type of analysis can predict the masses' interaction in rupture with existing structures. Fig. 7 shows the evolution of the mass movement during the run-out. At the beginning of the movement, between 51 and 60 seconds, the influence of the topography is perceived due to the presence of the Mankanshi valley, which generates a greater displacement towards the southeast direction. At 72 seconds, the movement of the mass continues in a frontal direction towards the axis of the Huangdongzi Valley. Between 90 and 120 seconds, the mass completely reaches the four central valleys (Menkanshi, Baiguolin, Chuanlin, and Huangdozi), and at 300 seconds, the mass stops in its deformed final configuration.

4. Conclusion

This study presents numerical and safety considerations about the Daguangbao landslide occurred in China. The main conclusions are as follows:

- A comprehensive investigation of the landslide mechanics was performed numerically. The study was carried out using 2D and 3D MPM models. These models permit the occurrence of large deformations and adequate non-linear processes.
- For the construction of the 3D model, a specific methodology of heterogeneous models for a large number of particles was used in conjunction with the software MPM-Particle-Generator (Fernàndez et al. [7]). The numerical analysis performed was dynamic, incorporating non-absorbent boundary conditions to minimize the radiating energy due to the boundaries. The earthquake used was the one recorded in stations near the event.
- There is an intrinsic risk associated with the present situation at the Daguangbao landslide site due to the existence of an almost vertical rockwall and an important landslide dam. For this reason, it is important to systematically assess and manage the associated risk.

Acknowledgments

The authors acknowledge Professor Runqiu Huang, from Chengdu University of Technology, Ru Zhang from Sichuan University and Dr. Liangjun Hao from SKLGDUE of China University of Mining and Technology for their help in the visit and the elaboration of a technical report.

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