Engineering Geology 174 (2014) 87–102

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Stability analysis of three-dimensional seismic landslides using the rigorous limit equilibrium method

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ARTICLE INFO

Article history:
Received 16 November 2013
Received in revised form 10 March 2014
Accepted 15 March 2014
Available online 25 March 2014

Keywords:
3D seismic landslide
The pseudo-dynamic method
The rigorous limit equilibrium method
Trust-region-reflective iterative algorithm
Neural network database

ABSTRACT

In this paper, a new method combining the rigorous limit equilibrium method and the pseudo-dynamic method is proposed to investigate stability of 3D seismic landslides, in which the force equilibrium conditions along three coordinate axes and the overall moment equilibrium conditions around three coordinate axes are all strictly satisfied. Moreover, sinusoidal–cosinusoidal wave is applied to simulate earthquake displacement and an amplification factor of peak seismic acceleration is referred to as the amplification of seismic wave when it propagates from the bottom to the top of landslides. The pseudo-dynamic factor of safety of 3D seismic landslides is determined using trust-region-reflective iterative algorithm. The effects of the parameters of the seismic landslides on the stability are analyzed by the BP neural network algorithm, in which a database to investigate the stability of 3D seismic landslides is established. In addition, the stability of Donghekou landslide is studied to verify the accuracy and precision of the present method.

1. Introduction

The landslides are the movement of a rock mass, debris or earth down a slope (Cruden, 1991), which can be triggered by a variety of external stimulus, such as earthquake shaking, intense rainfall, water level change, artificial disturbance or rapid stream erosion. Earthquake is one of the major triggers for instability of man-made and natural landslides (David, 2000; Mohammad et al., 2012). It has been strongly proved in lots of facts that failures and collapses of landslides lead to much more casualties and property losses than the earthquake itself (Hack et al., 2007). It is known that a devastating earthquake (Ms = 8.0) with an epicenter in Wenchuan County struck Sichuan Province, in southwestern China on May 12, 2008. Wenchuan earthquake and the extensive landslide triggered by it caused extensive damage of property and made many people lost their lives. For example, there were more than 15,000 landslide events which occurred around Longmenshan tectonic belt based on remote sensing images and field investigations. Landslide distributions of Longmenshan tectonic belt during Wenchuan earthquake were plotted in Fig. 1 (Yin et al., 2011).

The stability of seismic landslides has been considered as a vitally important issue in landslide engineering. Great progresses have been made in this problem in the past 100 years. Three main methods including the limit equilibrium method (Fellenius, 1936; Bishop, 1955; Spencer, 1967; Baker, 2003; Zhu and Qian, 2007; Zhou and Cheng, 2013), limit analysis method (Chen et al., 2001) and numerical analysis method (Duncan, 1996; Aringoli et al., 2008) were applied to investigate this problem. As a conventional method, the limit equilibrium method was proposed in the earliest and most universally applied to research the stability of slopes and landslides.

The limit equilibrium method has been used to analyze the stability of landslides, slopes and earth dams (Fellenius, 1936) for a long time. This method was firstly proposed by Fellenius (1927), in which the slip surface was approximated by a circular arc and the inter-slice forces were neglected. Then Fellenius' method was developed by researchers such as Janbu (1954), Bishop (1955), Morgenstern and Price (1965) and Spencer (1967). Recently, Hajiazizi and Tavana (2013) presented a new approach for finding three-dimensional non-spherical critical slip surface. All the above mentioned methods are belonging to quasi-rigorous limit equilibrium methods, which do not satisfy all six equilibrium conditions.

As far, studies of the rigorous limit equilibrium method for 3D slopes and landslides were few. For example, Zheng (2007), in the framework of rigorous limit equilibrium method, studied stability of 3D slopes based on non-column method. Moreover, Zheng (2009) improved his previous method by reducing the 3D limit equilibrium analysis to an algebraic eigenvalue problem. In this way, the divergence issue in solution was completely overcome. Besides, a methodology for extending 2D rigorous methods to the 3D versions was developed by Zheng (2012). Zhu and Qian (2007) given the solution of the safety factor slopes using the rigorous limit equilibrium method and discussed the difference between rigorous and quasi-rigorous limit equilibrium stability analysis for 3D slopes. Zhou and Cheng (2013) determined the factor

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http://dx.doi.org/10.1016/j.enggeo.2014.03.009
0013-7952/

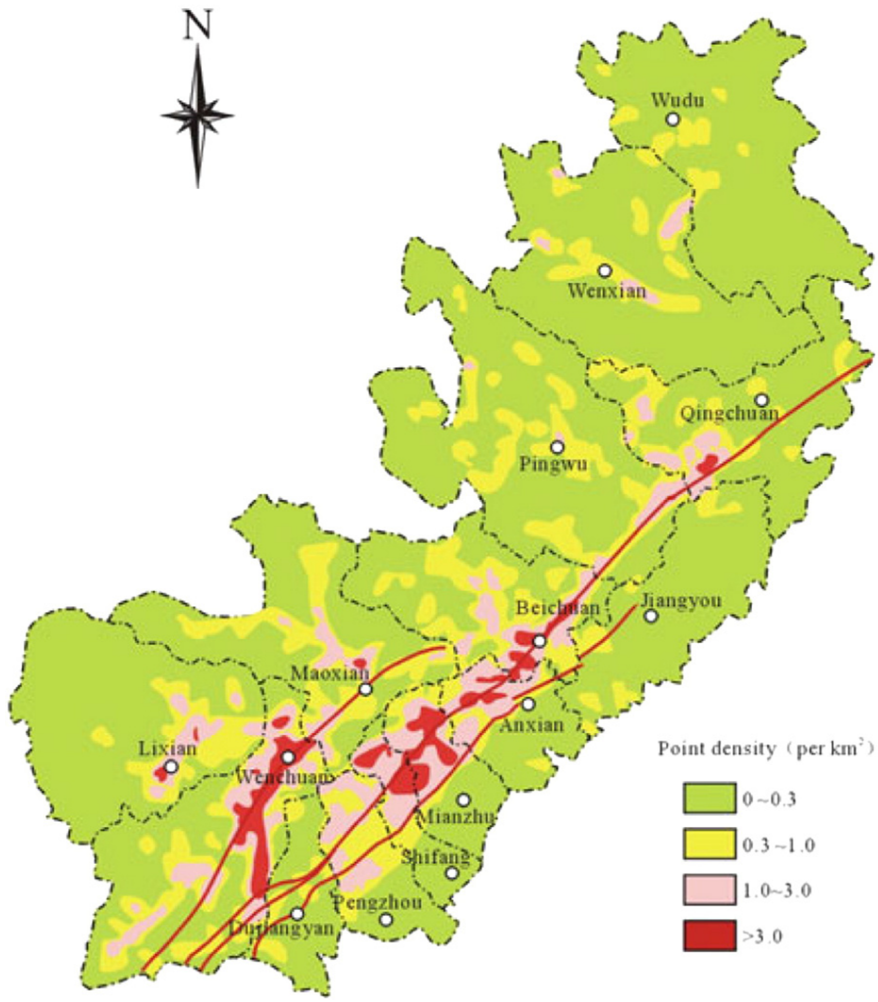

Fig. 1. Landslide distribution of the Longmenshan tectonic belt during Wenchuan earthquake (Yin et al., 2011).

of safety of 3D landslides based on column method in the framework of the rigorous limit equilibrium method. However, the rigorous limit equilibrium method for 3D seismic slopes and landslides has not yet been investigated.

In the past, the pseudo-static method was widely applied to analyze the stability of the two-dimensional seismic slopes and landslides. The pseudo-static method was first proposed by Terzaghi et al. (1951). In pseudo-static method, the effects of earthquake are equivalent to vertical and horizontal static forces acting on the center of gravity of the potential sliding body, and the directions of forces point to the outside and downside of sliding body, respectively (Baker, 2003; Robert and Rafael, 2008; Meehan and Vahedifard, 2013). Then, the pseudo-static factors of safety or earthquake-induced displacements of slopes and landslides are obtained using the limit equilibrium method. The merit of the pseudo-static methods is computationally simple. However, the major limitation of the pseudo-static method does not consider the most important nature of earthquake, such as cycle and oscillator characteristics of seismic loads (Grelle et al., 2011). For example, Seed studied several cases of slopes in his literatures (Seed, 1979), in which slopes were safe based on pseudo-static method, but they actually collapsed.

One merit of the pseudo-dynamic method is that the finite shear and primary wave propagating from the bottom to the top of landslides with time variation can be taken into account. Another merit of the pseudo-dynamic method is that it is simple and provides analytical solutions, which is convenient for engineers to analyze the stability of landslides. Recently, the acceleration-pseudo-dynamic approach was applied to analyze passive earth pressure behind a retaining wall in the framework of planar failure mechanism under seismic loads (Zeng and Steedman, 2000; Choudhury and Nimbalkar, 2005; Robert and Rafael, 2008; Basha and Babu, 2009). However, to our knowledge, the pseudo-dynamic approach was not applied to investigate the stability of seismic landslides.

In this paper, the pseudo-dynamic method is applied to analyze the stability of 3D seismic landslides in the framework of the rigorous limit equilibrium method. The horizontal and vertical sinusoidal–cosinusoidal displacements are used to simulate seismic wave, the major advantage of using the sinusoidal–cosinusoidal displacements as earthquake wave is that it possesses most of the representative characters of the earthquake wave. Another advantage is that calculations are easily performed when the sinusoidal–cosinusoidal displacements are adopted. Then, the pseudo-dynamic factor of safety of 3D landslides can be determined using trust-region-reflective iterative algorithm. The effects of parameters of landslides and earthquake waves on the stability of 3D landslides can be analyzed using the BP neural network algorithm. In addition, Donghekou landslide is investigated using the present method.

2. Principle of the rigorous limit equilibrium method for 3D landslides

2.1. Forces acting on the columns

The sliding body is divided into a number of columns with vertical interfaces, as shown in Fig. 2. The direction of movement of the sliding