Engineering Geology 226 (2017) 122–135

Contents lists available at ScienceDirect

Engineering Geology

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

The role of seismic triggering in a deep-seated mudstone landslide, China: Historical reconstruction and mechanism analysis

Zelin Zhang[a,b,*], Tao Wang[a], Shuren Wu[a], Huiming Tang[b], Changyu Liang[a]

[a] Institute of Geomechanics, Chinese Academy of Geological Sciences, 100081 Beijing, China
[b] China University of Geosciences, 430074 Wuhan, China

ARTICLE INFO

Keywords:
Zhengjiamo landslide
Discrete element simulation
Particle Flow Code (PFC)
Dynamic processes

ABSTRACT

Deep-seated mudstone landslides are widely distributed in northwest China. The Zhengjiamo landslide occurred in 734 CE near Taijing, Tianshui region. It was triggered by the main shock of the historical Ms = 7.0734 CE earthquake. The earthquake also induced a wide range of landslides in this area, with hundreds of fatalities and many houses destroyed by landslide debris. Based on a detailed field survey, borehole data, and mapping, a detailed geological reconstruction of the slope was achieved and the geo-mechanical features of the claystone involved in the landslide were obtained. Using the Particle Flow Code to simulate the mechanism of the Zhengjiamo landslide, the features of the landslide dynamics were obtained using a 5-stage model. During the landslide process, the slip mass at the front and upper edges exhibited higher mobility than at the rear and bottom edges. Furthermore, the contact bond strength of the sliding body gradually weakened. The model indicates that the particle bond strength has a larger influence on the maximum runout distance and landslide debris morphology than the type of weak intercalated layers. The slip mass presented a rotational slide pattern and remained on the slip plane throughout the sliding process. Finally, the earthquake uplifted the slope toe, which prevented the slip mass from gliding. The modelled scenario provided a reasonably good fit to the actual topography, verifying the modelling results. After the historical earthquake, with the clay minerals swelling and shrinking under rainfall and efflorescence conditions, the structure of the soft rock changed, contributing to the weakening of the sliding rock mass. The landslide gradually crept and evolved to its current topography.

1. Introduction

Landslides are among the most damaging events associated with earthquakes (Bozzano et al., 2008). Earthquake motion is considered one of the main causes of landslides, with the largest earthquakes capable of triggering thousands of landslides within an area of > 100,000 km^2 (Keefer, 2000; Tang et al., 2009). The damage from seismically induced landslides and other ground failures (i.e., cracks along faults, liquefaction, densification) can exceed the damage caused directly by the ground motion, as testified by a recent review of casualties and economic losses resulting from earthquakes (Bird and Bommer, 2004; Bozzano et al., 2008). A large database of landslides triggered by recent earthquakes in China is available in the literature, for example, landslides resulting from the 1999 Chi-Chi earthquake (Tang et al., 2009, 2013), 2008 Wenchuan earthquake (Yin et al., 2009; Chigira et al., 2010; R. Huang et al., 2012; Y. Huang et al., 2012), 2010 Yushu earthquake (Xu et al., 2014), and 2013 Lushan earthquake (Xu and Xu, 2014). However, because of the lack of data, there are far fewer studies of landslides induced by historical earthquakes.

China, with its complex geology, is one of the most seismically active countries in the world (Zhang et al., 2016a, 2016b; S. Zhang et al., 2016). Several historical earthquakes with $M_W > 6.0$ struck northwest China, inducing extensive deep-seated landslides, which resulted in severe damage to the highway system and residential houses (Wang et al., 2015). The slip clay layer is composed of interbedded mignonette and weathered red mudstone (WRM); it is prone to weathering and is impermeable. Therefore, the slip clay layer often undergoes high to complete weathering. The presence of the layer makes overlying slopes prone to sliding easily along the bedding plane during earthquakes. Deep-seated mudstone landslides are widely distributed throughout northwest China. Understanding the failure mechanisms and kinematic processes of these seismically induced landslides is very useful for hazard assessment and prediction; however, the dynamic behaviour and kinematic processes of these landslides in northwest China remain poorly understood.

When analysing earthquake-induced landslides, the initiation point of a landslide can be determined by two methods: acceleration of the sliding body or crack/displacement development. In the acceleration

* Corresponding author at: Institute of Geomechanics, Chinese Academy of Geological Sciences, 100081 Beijing, China.
E-mail address: 249133236@qq.com (Z. Zhang).

http://dx.doi.org/10.1016/j.enggeo.2017.06.001
Received 9 January 2017; Received in revised form 2 June 2017; Accepted 2 June 2017
Available online 03 June 2017
0013-7952/

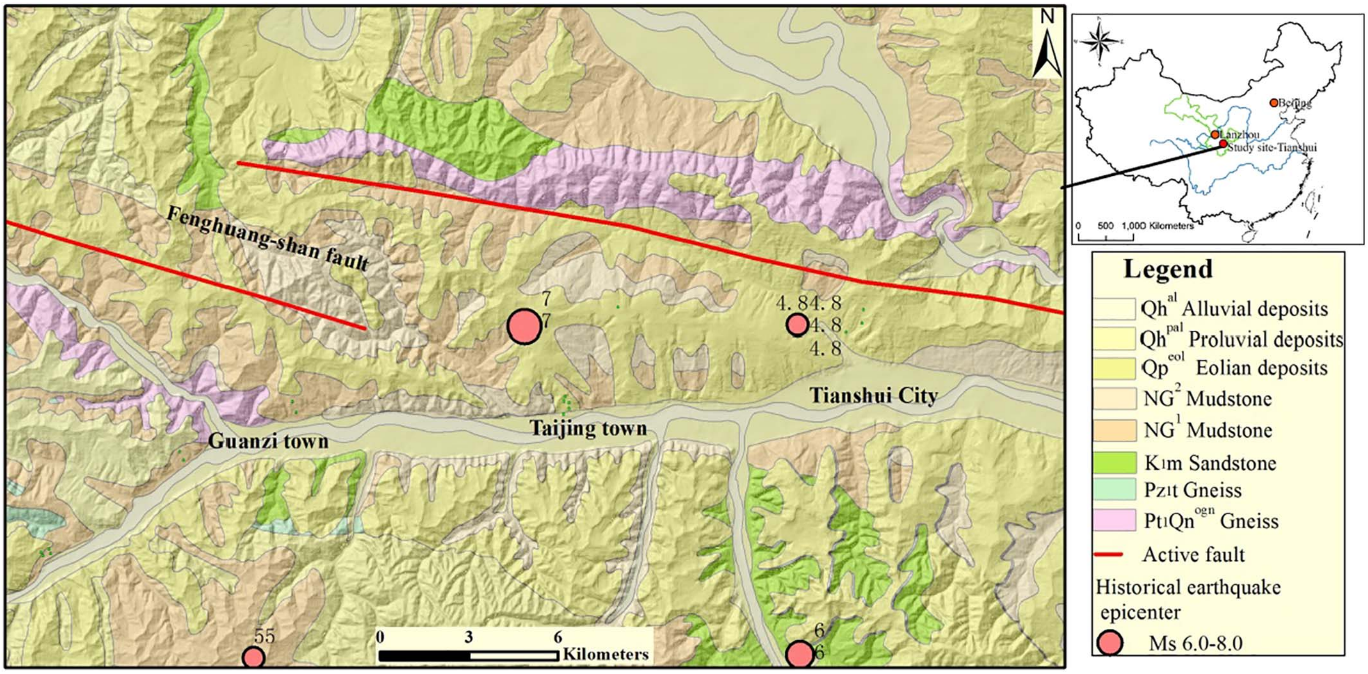

Fig. 1. Location, morphology, and geological setting of the Tianshui area.

method, landslide initiation is identified as the point when the acceleration of the sliding body changes from linear to non-linear (Lin and Wang, 2006). In the displacement method, permanent displacement is used as the index that determines landslide occurrence (Wang and Lin, 2011). Generally, three methods are used to analyse earthquake-induced landslides: site investigation, numerical simulation, and physical modelling tests (Wang and Lin, 2011; Huang et al., 2013; Luo et al., 2014; Rizzitano et al., 2014; Zhang et al., 2016a, 2016b; S. Zhang et al., 2016). Physical modelling tests are expensive to run and require advanced technology, while site investigations require a range of monitoring stations and field work. Numerical simulation, however, can be applied to a variety of cases and conditions and is thus an efficient method to study the landslide processes.

Many studies on the seismic amplification effect, failure mechanism, and motion of earthquake-induced landslides have been documented (Take et al., 2004; Mousavi et al., 2011; Li et al., 2012; Huang et al., 2013; Wang et al., 2014; Zhang et al., 2014, 2015; Gischig et al., 2015). These landslides usually showed very high mobility, with features typical of flow sliding (fluid-like motion of granular material; Bishop, 1973). The fluidized, rapid, long-distance movement of these landslides is of interest to geotechnical scholars and engineering geologists because the landslides were scattered in different areas, experienced little preceding precipitation, and displayed no evidence of occurrence beneath the groundwater table (Huang and Dai, 2014; Wang et al., 2014). When studying the dynamic processes of these landsides, discrete element methods can be used as a powerful tool for modelling rock slope susceptibility to earthquakes. The discrete element method provides explicit solutions in the time domain, and is therefore an ideal method for studying the time propagation of stress waves or ground vibrations. Because the landslide block behaves as a quasi-rigid body, the Particle Flow Code (PFC) model is frequently used in landslide models to analyse the granular assemblages, with purely frictional or bonded circular particles represented by discs (Tang et al., 2009). The PFC method can take into account mechanical discontinuities explicitly; the advantage lies in the technique being preferable to modelling approaches in terms of continuum mechanics. Refined numerical solutions and a Coulomb-like behaviour of earthquake-induced landslides were successfully modelled for two- and three-dimensional granular mass flow codes (Tang et al., 2009, 2013; R. Huang et al., 2012; Y. Huang et al., 2012; Li et al., 2012; Zhou et al., 2013; Dai et al., 2014; Havaej and Stead, 2016).

According to historical documents and our field investigations, most landslide failures in the Tianshui area, northwest China, occurred along the weak surface of the WRM layer, although no evidence of liquefaction has been found near the landslides in this region. Hence, we need to understand the kinetic process and failure mechanisms of these landslides to mitigate the damage from future coseismic slopes in the Tianshui area. In this paper we present a detailed reconstruction of the development of the Zhengjiamo landslide to determine its geophysical characteristics and state of activity in a historically documented highly seismic area (Tianshui, northwest China). We also investigate the complex geological background of the Tianshui area, and establish a reference geological model. The kinematical process and failure mechanism of the Zhengjiamo landslide is modelled using a 2D Particle Flow Code (PFC) based on the use of granular material. Finally, we discuss the possible mechanisms contributing to these rapid rotational-sliding mudstone landslides induced by historical earthquakes, thus shedding further light on the mechanism of the Zhengjiamo landslide.

2. Engineering geological background

Tianshui is located in the southwestern part of the Gansu loess plateau, with the West Qinling Mountain to the south and the Fenwei basin in the west. This region is part of the hilly geomorphic section of the loess plateau, with its terrain characterized by a high northeastern region and a low southwestern region (Peng et al., 2016). The elevation of the Tianshui basin ranges from 750 to 2700 m, with a mean value of 1329 m, and the slope gradient ranges from 0° to 35°, with a mean value of 26.5°. The main rivers in the region are the Weihe River and its tributaries. Generally, the terrain is high in the northwest and low in the southeast. The action of the river cutting into its banks and the tectonic movement in the region have created a landform with ravines with long, narrow river channels as well as numerous ridges and hills (Peng et al., 2015). In terms of the geology, the active WNW-ESE Qinling fault zone defines the northern edge of the Qinling Mountains in neighbouring Shaanxi Province and has a strong influence on most of the similarly-aligned faults in eastern Gansu (Derbyshire et al., 1995). The active Qinling fault lying WNW-ESE is called the Fenghuang-shan