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The mechanism of high-speed motion and damming of the Tangjiashan landslide

Wen-Jie Xu [a,*], Qiang Xu [b], Yu-Jie Wang [c]

[a] State Key Laboratory of Hydroscience and Hydraulic Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China
[b] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, 610059, China
[c] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, 100038, China

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ABSTRACT

Understanding the mechanisms of landslide failure and resulting damming processes is crucial for constraining the hazard chain associated with landslide damming events. On May 12, 2008, the Wenchuan earthquake caused a large number of secondary hazardous events such as landslides and collapses, most of which occurred in high mountain gorges. In these areas, the sliding distance of landsides is often very short, and the landslides are often characterized by high speed, short distance, and damming. Using the Tangjiashan landslide damming events induced by the Wenchuan Earthquake as a model, this paper reconstructs the three dimensional failure and associated damming caused by the landslide based on a detailed geological investigation of the landslide area and using the dynamic finite element technique. The study proposes a four-stage model for the failure and damming process of the Tangjiashan landslide: earthquake induction and progressive destruction of the slide body, destruction and high-speed sliding of the slide body, slide body impact, disintegration, and river blockage for the formation of a damming body, and vibration compression. The average speed of the Tangjiashan landslide reached a maximum value of 22 m/s about 30 s after the earthquake, and the landslide reached stability about 60 s later.

1. Introduction

A large number of investigations have indicated that earthquakes are an important factor in the triggering of geological hazards such as landslides. Occasionally, an earthquake of higher magnitude may even lead to thousands or tens of thousands of landslides within an area as large as 100,000 km^2 (Keefer, 2000; Keefer and Larsen, 2000). For example, the 1994 M6.5 Northridge earthquake in the United States triggered 11,000 landslides over an area of about 10,000 km^2, causing more than 30 billion US dollars in economic losses (Parise and Jibson, 2000). The 1973 M7.9 earthquake that hit Luhuo, Sichuan, China triggered 137 landslides of different scales, resulting in a death toll of 2175 (Quanzhong, 2002). China is a mountainous country, with mountain-covered land accounting for two-thirds of its total area. Furthermore, China lies between the two most active seismic belts in the world, the Pacific seismic belt in the east and the Himalaya–Mediterranean seismic belt in the south. Strong earthquakes, many of them destructive, are widespread in China, especially in the west where they are strong and frequent (Zhenliang et al., 1995). Landslides caused by earthquakes are widely distributed, and most occur at high speeds. Hence, in earthquake-prone areas (especially those in mountainous areas), landslides as a secondary geological hazard cannot be ignored and have drawn the attention of scholars worldwide.

In landslide modeling, Kuo et al. (2009) applied continuum modeling of hydraulic flow to simulate numerically the dynamics of a landslide based on a pseudo three-dimensional (3D) model. The impact of the earthquake in this model was determined by reducing the joint friction angle. Mousavi et al. (2011) used the two dimensional (2D) finite element software (Geostudio) to study the stability of the slope under both static and dynamic conditions, and a quantitative probabilistic approach was developed for determining the frequency and magnitude of earthquake processes. Wu and Chen (2011) used seismic DDA to simulate the kinematic behavior of sliding blocks of rock in an earthquake-induced landslide. The distinct element method in 2D (PFC^{2D}) and 3D (PFC^{3D}) was used by Tang et al. (2009) and Lo et al. (2011) respectively, to model the kinematic processes of the landslide. At present, continuum models (e.g., FEM) and discrete models (e.g., DEM and DDA) are used to study the failure process of landslides; however, most of these techniques focus on the 2D simulation of landslide processes. Because landslide instability is a 3D problem, such 2D analyses cannot consider 3D spatial effects without resulting in large errors.

Most landslide studies focus on the failure mechanism of high-speed and long-distance landslides (Qiangong, 1999; Wang et al., 2002; Aiguo, 2003; Tang et al., 2009; Lo et al., 2011; Wu and Chen, 2011). However, landslides induced by strong earthquakes in mountainous regions are known to occur mainly in gorges where they are blocked by the opposite mountain once they reach the bottom of the valley. In such case, the slide distance is often short and cannot reach the “flight phase.” Moreover, such landslides can block the valley, forming a damming

* Corresponding author. Tel.: +86 10 62782301.
E-mail addresses: wenjiexu@tsinghua.edu.cn (W.-J. Xu), xq@cdut.edu.cn (Q. Xu), wangyj@iwhr.com (Y.-J. Wang).

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body (also called a landslide dam). Therefore, great differences exist between the mechanisms and effects of high-speed short-distance landslides and high-speed long-distance landslides.

The M8.0 Wenchuan earthquake that occurred on May 12, 2008 induced a large number of secondary geological events such as landslides and collapses, most of which took place in gorges, resulting in the formation of hundreds of damming bodies. Most landslides occurred at high speeds and covered only short distances. The Tangjiashan landslide, one of the largest river-blocking landslides triggered by the Wenchuan earthquake, blocked the Tongkou River, and formed the most dangerous barrier lake after an earthquake (HydroChina Chengdu Engineering Corporation, 2008a, 2008b; Liu et al., 2010). Taking the Tangjiashan river-blocking landslide as an example, this paper studies the earthquake-induced instability, slide motion, and river-blocking mechanisms of high-speed short-distance landslides. The findings from this study will serve as a theoretical basis and technical support for the prevention of similar landslides and the reduction of secondary geological hazards.

2. Introduction to the Tangjiashan landslide area

2.1. Topographic and geomorphologic characteristics

The Tangjiashan landslide lies on the right bank of the Tongkou River (also called Jianjiang) in Sichuan Province, China, 6.5 km upstream of Beichuan County (104° 25′56.93″ E, 31°50′40.60″ N). The Tongkou River meanders through the landslide area in a S70°E to N40°E direction (Figure 1). Prior to the landslide, the water level in the Tongkou River at the study location during the dry season was about 664.8 m above sea level, the water surface was 100 m to 130 m in width, and the water depth was 0.5 m to 2 m. The valley of the landslide had an asymmetric "V" shape.

The top elevation of the Tangjiashan landslide is 1580 m with a slope height of about 900 m. The lower terrain is steep (40° to 60°) with the bedrock exposed, whereas the upper terrain gently slopes at an angle of about 30°, with diluvial gravel soil (about 5 to 15 m in thickness) covering the surface. The landslide area has two gullies: Xiaoshuiwan, which lies upstream of the landside, and Dashuiwan, which lies downstream (Figure 2). The distance between the two gullies is about 500 m.

2.2. Stratum lithology

Chronologically, the strata of the Tangjiashan landslide area comprises the upper Qingping Formation of the lower Cambrian, a residual–diluvial layer of Quaternary sediments, and an alluvial layer of Quaternary sediments.

2.2.1. Upper Qingping Formation of the lower Cambrian ($\in_{1c}$)

This stratum is composed of thin to moderately-thick bedded siltstone, silicalite, marlite, and mudstone. The mechanical strengths of the former two are higher than those of the latter two, and they are alternately distributed. These strata compose the main part of the landslide, dipping outward (N60°E/NW∠60°) and forming a typically steep bedding slope. In contrast, the left bank of the valley forms a reverse slope.

2.2.2. Residual–diluvial layer of Quaternary sediments

This stratum is distributed on the top slope of two banks. It is 5 to 20 m thick, and its soil-rock mixture consists of silt, debris, and block stones. The upper part is dominated by silt (60%), with several block stones scattered in the area. The lower part contains mores and rock blocks.

2.2.3. Alluvial layer of Quaternary sediment

This stratum is the alluvium of the Tongkou River, and it is distributed on the riverbed. This alluvial layer is mainly composed of grayish-black, fine sand with a silt content of about 35%. The layer also contains a small amount of small gravel.

2.3. Geological structure

The Tangjiashan landslide is near the core of a Qinglinkou overturned anticline, the axial strike direction of which is NE45°. The axial surface of the landslide area is inclined to the NW with a dip angle of about 70°. The landslide area lies in the south of the block formed by the northern

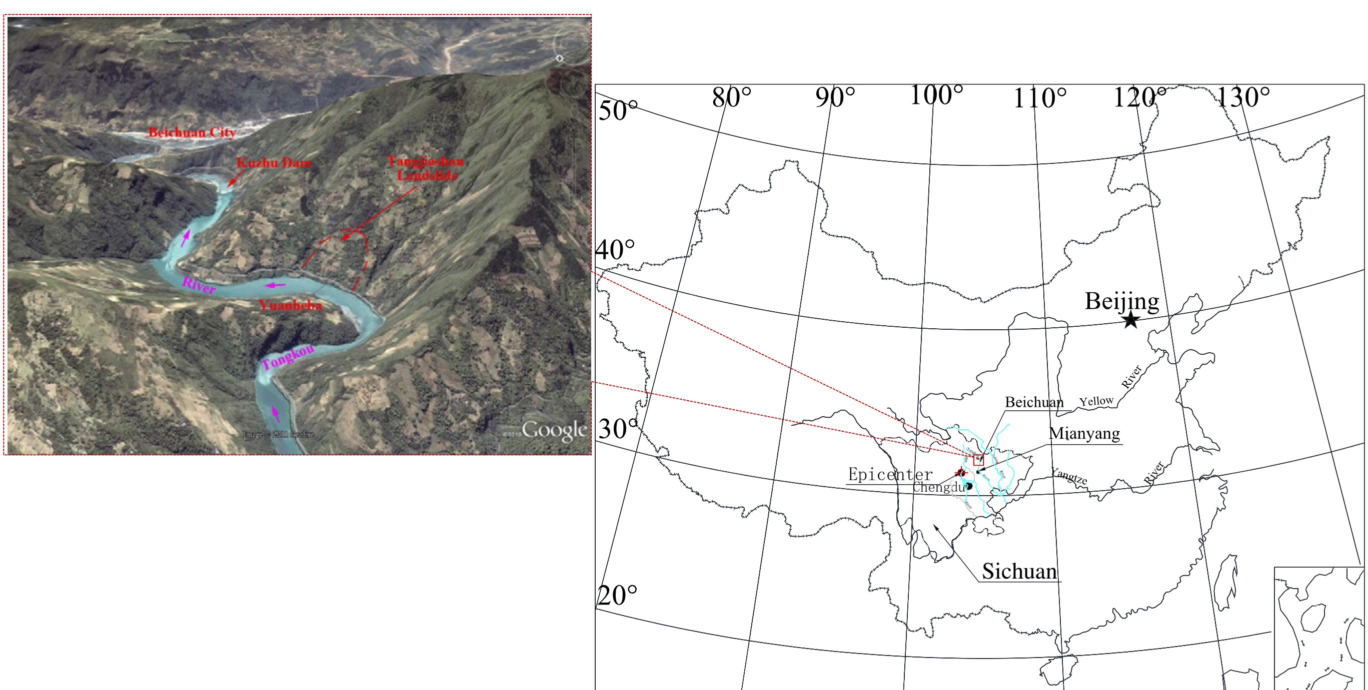

Fig. 1. Location of the Tangjiashan landslide.