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Genetic Types of Large-Scale Landslides Induced by the Wenchuan Earthquake

Q. Xu, S. Zhang and X. J. Dong

Abstract

The 5.12 Wenchuan earthquake had induced thousands of large-scale landslides. Through the field investigations and surveys on deformation and destroy characteristics of 20 landslides induced by the Wenchuan earthquake, and combined with the shaking table test and numerical simulation, we found that the deformation and mechanical mechanism of these large-scale landslides are different from those landsides induced by routine gravity. On the condition of strong shock, the most essential deformation and destroy element of the slope rock mass are tension-cracks and shearing slide, and mainly based on tension-cracks. According to the geological and topographical change, the large-scale landslides induced by the Wenchuan earthquake can be classified into five genetic types, i.e. tension-strike slip, crack-bedding slip, tension-horizontal slip, tension-scattering slip, and tension-shearing slip.

Keywords

Wenchuan earthquake · Large-scale landslide · Genetic types · Tension-cracking deformation · Shearing sliding

1 Introduction

For the type and genetic model of geological disasters induced by earthquake, a number of relevant researches have been conducted. In which, the representative is the Seismic Landslide Classification System established by Keefer (1984). Taking into account of the material composition, the motion characteristics, the internal damage and the ground water content, the earthquake-induced rock landslides are classified into the five categories (Keefer (1984)) rock falls, rock slides, rock avalanches, rock slumps and the

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Fig. 54.1 Steep scarp with coarse cracks from Donghekou landslide, Qingchuan

rock block slides. The earthquake-induced soil landslides are classified as soil falls, disrupted soil slides, soil avalanches, soil slumps, soil block slides, slow earth flows, soil lateral spreads, rapid soil flows and subaqueous landslides. Huang (2009) classified the Wenchuan earthquake-induced geological disasters as five major categories and 14 subclasses according to the slope instability process and slope geological structure, respectively. The five major types are sliding, falling, projecting, stripping, and shattering.

After Wenchuan earthquake, by investigating more than 20 earthquake-induced large-scale landslides, Xu et al. (2009a, b) found that there have significant differences between the earthquake-induced landslides and the regular landslides, mainly reflect the differences of deformation failure mode and sliding mechanisms. The earthquake-induced landslides have steep scarp with tension coarse cracks at the trailing edge (Fig. 54.1). In order to identify the slope instability mechanisms, shaking table test was conducted for simulating earthquake-induced landslides under varieties of working conditions (Xu et al. 2009a, b), which revealed the typical deformation and failure mode of the slope rock mass under strong shock are mainly of the tensile failure. Five genetic models of earthquake-induced landslides were established after investigating the deformation characteristics of more than 20 large-scale landslides in Wenchuan earthquake zone.

2 Dynamic Instability Mechanism of Earthquake Induced Landslide

Zheng et al. (2009) adopted the numerical simulation to explore the failure mechanism of seismic slopes and the mechanical properties of failure surface. The results show that the slope failure can be contributed to the tensile failure in the upper part combined with the shear failure in the lower part of slope. Both the tensile cracking surface and shear sliding surface composed of the landslide failure surface.

Under normal gravity conditions, the stress state in the superficial part can be described as followed: the maximum principal stress is parallel to the slope surface; the minimum principal stress is vertical to the slope surface; the intermediate principal stress is parallel to the strike direction of slope. Therefore, the shear stress concentration occurred at weak surface and slope toe part, which resulted in shear deformation and failure following Morh-Coulomb criterion along the weak plane, i.e. weak structural plane or the ancient sliding surface. With shear deformation developed, an apparent tensile stress concentrated at the trailing edge of the slope, and resulted in many tensile cracks (Fig. 54.2). During the earthquake, the minimum principal stress of the slopes is performed as a repeated pull-compressive stress state on the influence of seismic waves. Due to the elevation amplification effect, the horizontal acceleration in the upper part of the slopes is always larger than 1 g. Thus, the seismic horizontal inertia force is far more than the tensile strength of rock mass itself. Griffith proposed a criterion of crack propagation, i.e. $\sigma_3 > \sigma_\tau$, which illustrated that the rock mass of slope are prone to generate the crack surface parallel to the free surface under seismic conditions. Sustained shaking will contribute to widen and deepen the crack surface during the earthquake, then a deep tension crack parallel to the strike direction formed at the top of the slope. Subsequently, crack-shear slip surface will develop at the bottom of the slope and landslide happened eventually (Fig. 54.3).

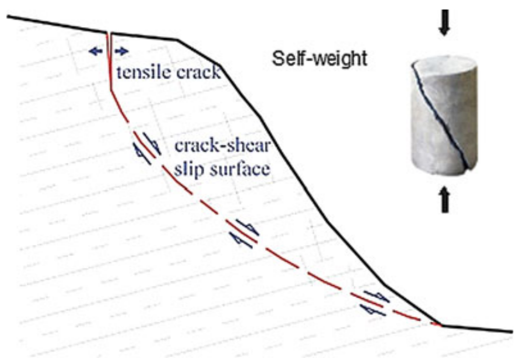

Fig. 54.2 Typical deformation and failure mode of the slope rock under self-weight operative force

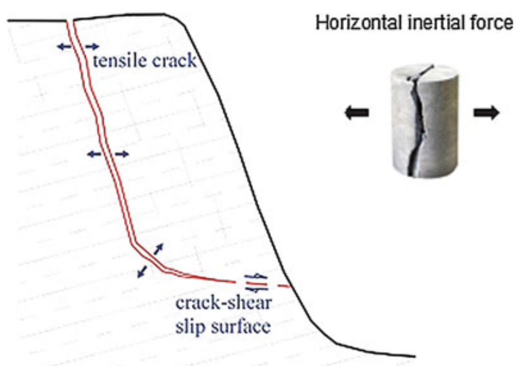

Fig. 54.3 Typical deformation and failure mode of the slope rock mass under strong shock

The above results of shaking table test are consistent with the results of numerical simulation conducted by Zheng (2009). By making a comparison between Figs. 54.2 and 54.3, a large difference either exists in the slopes as described above, or has a significant difference in other ways. For example, under normal gravity, a typical sliding is always occurred along the weak plane followed by tensile cracks in the trailing edge, while under earthquake conditions, a deep tension crack is developed in the trailing edge firstly, and then shear slip appeared along the bottom of the slope. Regarding to the landslides during the earthquake, the tension crack is deep, steep, roughly in the part of trailing edge. The shear slip surface at the bottom surface is relatively short, which is dominant by cracking in trailing edge. However, the sliding surface of landslide happened under normal conditions is longer with shear characteristics. The cracking surface is generally shallow and small, which is dominant by shear sliding at the bottom of slope.

3 Failure Modes of the Earthquake-Induced Landslides

By the knowable, tension and shearing slip are the basic failure mode of earthquake-induced landslide. The bottom shearing slip would occur along the different structure surface which is decided by the rock structure.

3.1 Tension-Strike Slip

Three conditions can contribute to the tension-strike slip. (1) The slope is mainly composed of gently, dipping (range from 20° to 40°) and stratified rock, such as limestone; (2) the structural surface is normally parallel to the bedding plate, meanwhile, in addition to the frontal surface, a free face should exist on one side of the slope; (3) On the influence of dynamic loading caused by earthquake, a cracking surface will be developed by tracking the structural surface along the dip direction, a tension-strike landslide will occur along the weak surface.

In the Wenchuan earthquake zone, Daguangbao landslide is a typical tension-strike slip. As long as the topography and slope structure are eligible, the tension-strike landslide can also occur under normal gravity condition. The Daguangbao landslide is the largest one happened during the Wenchuan earthquake, which is located in Gaochuan, with a volume of approximately 750 million m^3 (Huang et al. 2008, 2009). The source area is mainly composed of a higher weathering argillaceous limestone in Sinian (Z_d), with partially phosphate and its associated minerals formed in Devonian (D_s). The SE side of landslide is steep which caused by the cutting of Menkanshi Gulley (Fig. 54.4). Two groups of large structure surfaces which parallel to the strike and dip direction are developed in the slope, with the attitude of N40° W/NE ∠80–85° and N 55–60° E/SE ∠ 60°.

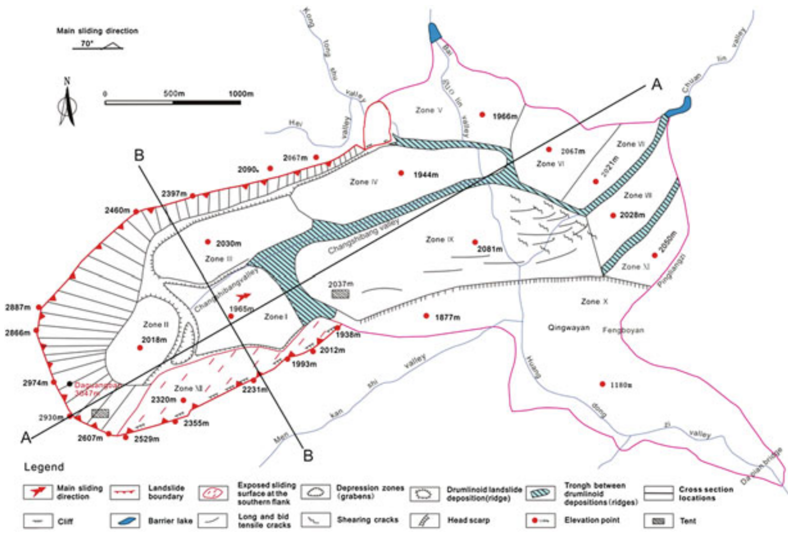

Fig. 54.4 The engineering geological condition of Daguangbao landslide

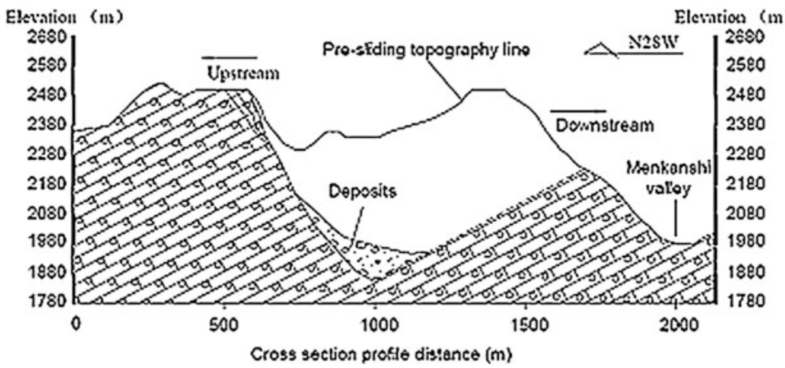

Fig. 54.5 Cross section B-B' showing source area of Daguangbao landslide

The two structural surfaces combined with the free surface at E and S side can cut the rock mass into blocks (Huang et al. 2009). Under the dynamic role of the earthquake, the sliding mass is firstly depart from structure surface in the trailing edge of landslide in NW direction, then the landslide happened by taking the NE steep dip structure as the lateral crack surface and the sand soft layers as the slip surface (Figs. 54.5 and 54.6).

Based on the slickenside in bottom slip surface, it can be speculated that the slip mass cannot completely slide along the strike direction. As shown in the Fig. 54.4, a cross angle can be observed between the sliding and strike direction in the initial stage of the slope sliding. However, the sliding deformation along this direction can be blocked by the mountain nearby, the slip mass had to gradually shift to the other direction in order to slide out smoothly (Fig. 54.4).

Fig. 54.6 Aerial view of Daguangbao landslide with main sliding direction of NE

3.2 Crack-Bedding Slip

In the bedrock area with steep dip angle, the slope failure will occur along the bedding weak plane, i.e.

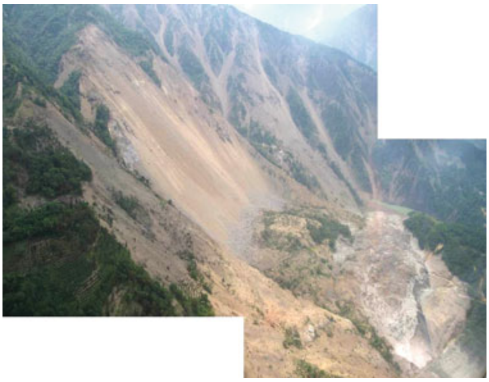

Fig. 54.7 Overview of the Tangjiashan landslide, Beichuan

the interface between soft and hard rock, intra-formational weak plane. Such tension failure accompanied by loss of cohesion is caused by the dynamic loading during earthquake. Subsequently, a high-speed sliding happened along the failure surface under the constant dynamics role of earthquake, which named as crack-bedding slip. The Tangjiashan landslide in Beichuan County is a crack-bedding and high speed slip triggered by Wenchuan earthquake. The run-out distance of the landslide is approximately 0.9 km with a velocity of 30 m/s. A 20 million m^3 landslide dam formed in the Jian River with length of 803.4 m, width of 611.8 m, thickness of 124 m. As shown in Fig. 54.7, the capacity of the barrier lake is 300 million m^3 (Hu et al. 2009a, b). About 100 people were killed during this disaster. Immediately sluice dug in the landslide dam make the flood discharged and the potential danger relief timely.

Before the Wenchuan earthquake, the average slope gradient of Tangjiashan landslide is 40°, the elevation of Tangjiashan catchment is ranged from 665 to 1500 m, with a relative relief of 835 m. The landslide area is mainly underlain by mudstones and siliceous consisting the Qingping group, Cambrian. The outward bedding rock layer has the dip angle range from 50° to 85°. Weak layers of mudstone exist in the slope consist of the potential sliding surface. If the potential sliding surface was invisible, a cutting-bed surface will appear under the dynamic role of earthquake. Such phenomenon is more prone to happen in the soft rock slopes (Fig. 54.8), like Tangjiashan landslide and Zhengjiashan landslide in Pingwu County. If the potential sliding surface is visible at the front of the slope, landslide will happen along the direct linear sliding surface. Such phenomenon is prone to happen in hard rock slope. The occurrence of bedding slip is very common in the earthquake zone.

3.3 Tension-Horizontal Slip

When the outward rock slope stratum is nearly horizontal, with influence of strong horizontal seismic inertia force, there will appear steep pull-apart plane at the trailing edge. Affected by seismic force continuously, the rock mass outside the pull-apart plane will slide along stratum and form a tension-horizontal sliding landslide. With the elevation amplification effect of seismic wave and the terrain amplification effect of cuesta, tension-horizontal sliding landslide is concentrated in some special terrain, such as long ridge and mountain projection. Steep scarp is always locating at the downstream of slippery source area, so that the slip mass could fly over the scarp with a larger initial velocity than normal landslide, which also lead to the slip mass throw out from mountain and move longer distance. A typical representative of tension-horizontal sliding landslide is Donghekou landslide, which locates in the Donghekou Village, Hongguang County, Qingchuan. The landslide stratum consists of Upper Sinian Yuanji Group (Z_y), Lower Cambrian Qiujiahe Group ($€_q$,) and Youfang Group ($€_y$), which is nearly horizontal with dip angle of 12°. The slope has a sandwich (i.e. hard-soft-hard) structure (see Fig. 54.9). Controlled by a fault at right boundary and a fracture zone at left boundary, a steep pull-apart plane appeared at the trailing edge of slope under strong horizontal seismic load. Afterwards, the rock mass outside the pull-apart plane slide along soft stratum and left a large groove in the source area (Fig. 54.10). After being thrown out, the rock mass flied over a steep scarp with high speed and then crashed to the ground. The rock mass fragment moved forward about

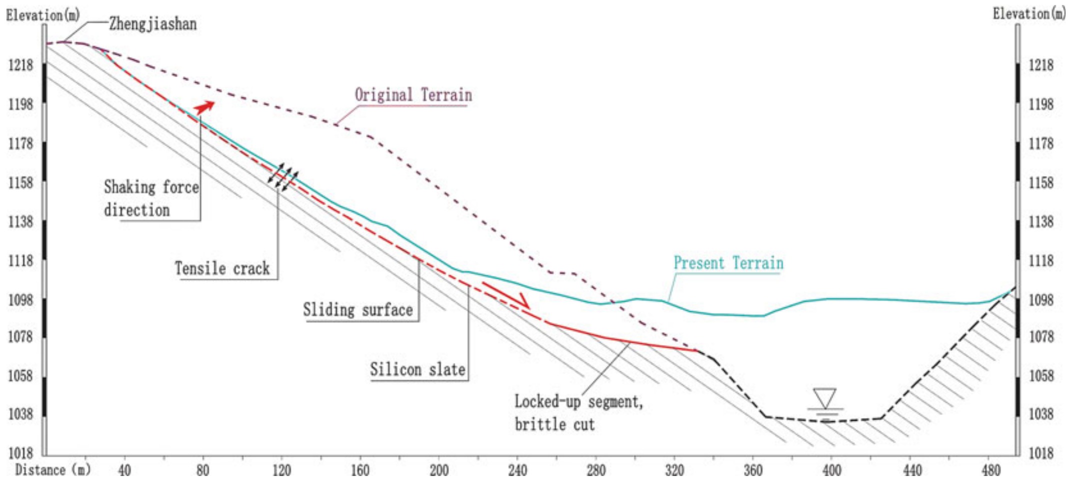

Fig. 54.8 Typical longitudinal section and genetic mode of No.1 landslide, Zhengjiashan

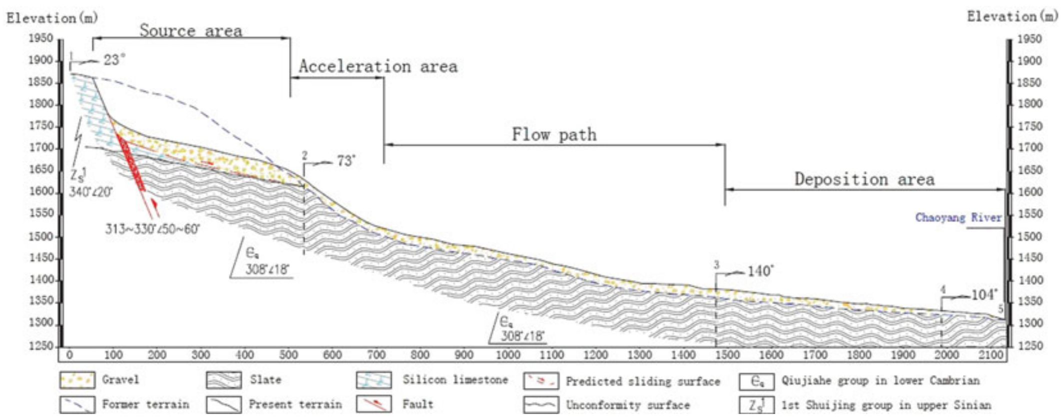

Fig. 54.9 Geological section of Donghekou landslide, Qingchuan

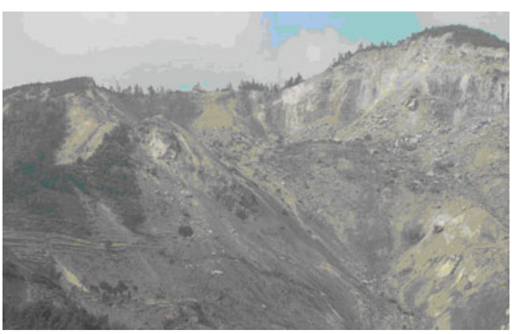

Fig. 54.10 Large scar left in the source area after Donghekou landslide

2 km along the valley as a debris flow (Sun et al. 2009).

3.4 Tension-Scattering Slip

The slope rock mass composed of limestone, dolomite, granite and other hard rock will develop a multi-group structural plane under geological structure force, which is always tension due to weathering and unloading (especially the steep vertical structure plane). Strong

Fig. 54.11 Large blocks in the deposition zone of Beichuan new middle school landslide

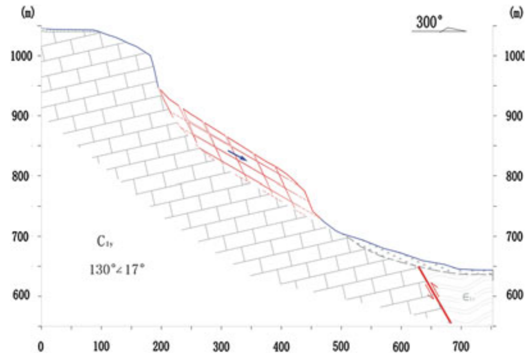

Fig. 54.12 Shattering-cracking

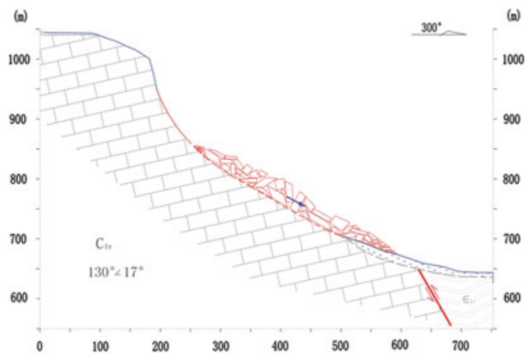

Fig. 54.13 Scattering-sliding

earthquake force loosen the superficial rock mass and then a number of vertical tension crack was formed. Afterwards, the loose rock mass disintegrated and formatted so called tension-scattering sliding with the help of reciprocate earthquake load.

A typical representative of tension-scattering sliding is Beichuan new middle school landslide (Fig. 54.11). This landslide located in the back of mountain of new district, Beichuan. Limestone of Carboniferous Yanguan group (C_{1y}) consists of the slope rock mass in the source area. Multi-group structural plane cut the slope rock into blocks. Therefore, numerous landslides or rock falls occurred in this area before. During the Wenchuan earthquake, the superficial rock mass of slope disintegrated and slip along one group of structural plane finally (Fig. 54.12). The accumulation zone of this type of landslide is mainly composed of granular boulder (Fig. 54.13).

3.5 Tension-Shearing Slip

In the counter-inclined bedding slopes, a deep crack surface developed outward formed at the posterior edge on the influence of the horizontal inertial force caused by earthquake. Subsequently, the separated slope slide along the bottom of the deep crack surface with the sustained earthquake dynamics forces. Ultimately a tension-shearing slip is developed. The failure process can be summarized into four stages as shown in Fig. 54.14.

In the earthquake area, the counter-inclined bedding slopes as well as the massive rock slope are widely distributed, especially concentrated along the hanging wall of Yingxiu-Beichuan fault. Therefore, the tension-shearing slip is very common, e.g. Wangjiayan landslide in Beichuan Town, Guershan landslide in Beichuan Town, Zhengjiashan landslide in Pingwu County, Guantan landslide in Anxian County, Dongjia landslide in Qingchuan County. From the longitudinal section and deformation and failure mode of Zhengjiashan landslide (see Fig. 54.15), the large-scale landslides have the failure conditions of tension-shear slip. Most importantly, the bottom slip surface of tension-

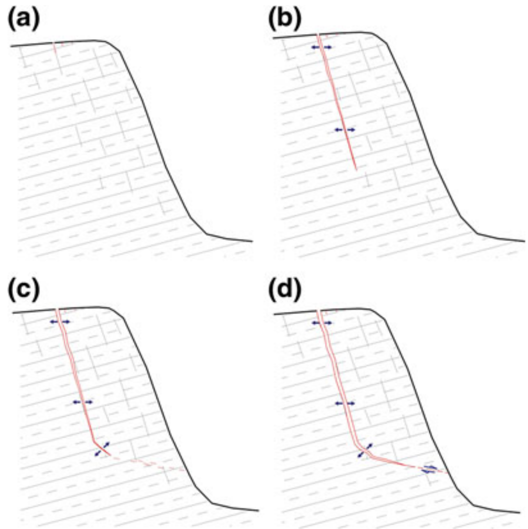

Fig. 54.14 Failure process of typical landslide with tension-cracking and shearing. **a** The shallow of the top of the slope was shattered and cracked in a large scale; **b** a deep and large pull-apart plane, along the sub-vertical discontinuities, was induced from the top; **c** tension-shearing and shear failure was appeared on the pull-apart plane; **d** in sequent sliding plane was formed on the bottom and the whole slope commerce to slide

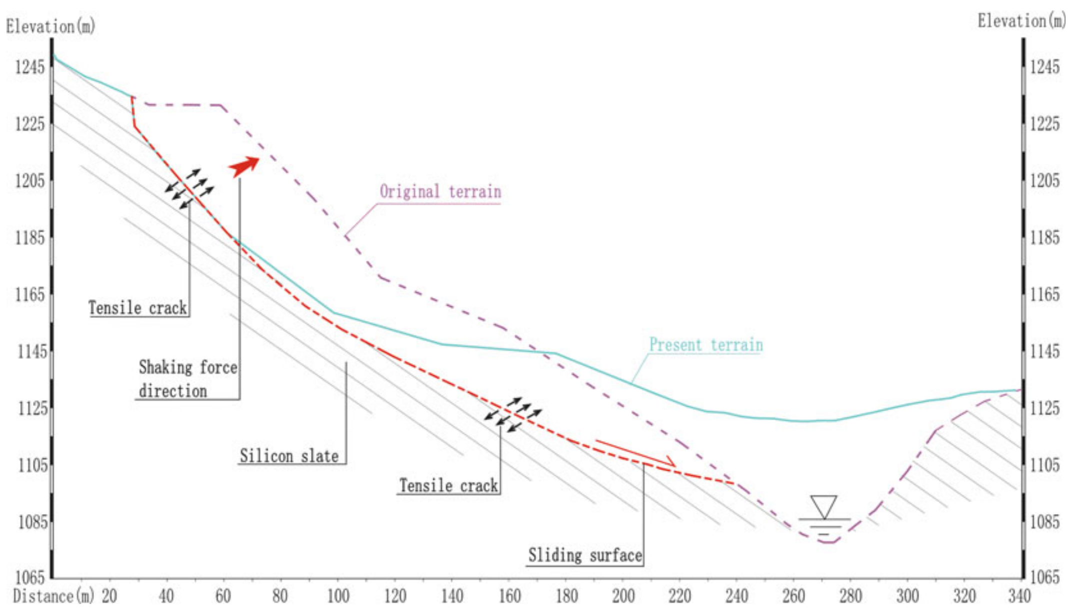

Fig. 54.15 Longitudinal section and deformation and failure mode of No. 2 landslide, Zhengjiashan

shear landslide is developed by cutting the rock mass, while the bottom slip surfaces of the other types of landslides are basically developed by tracking the existing structure surface. Therefore, the tension-shearing slip is relatively difficult to develop a slip surface at the bottom. The landslides happened shortly after the earthquake is mostly belong to the tension-shearing slip, among which the most typical one is Wangjiayan landslide, in Beichuan County.

According to the eyewitness descriptions, the Wangjiayan landslides happened 10 min later after the Wenchuan earthquake. The main reason of this laggard phenomenon can be concluded as a partial crack surface in trailing edge had developed during the earthquake, the locked segment was remained stable until the shake stopped. After the earthquake, the separated slip mass was only supported by the rock beneath. Finally, under the effect of stress caused by weight, the left locked section was completely cutted and shear slip surface formed then the tension-shear slip occurred.

4 Conclusions

From the study on earthquake-induced landslides in this paper, the following conclusions can be drawn,

1. The deformation and failure mode of earthquake-induced landslides is significantly different from the landslides under normal conditions. On the condition of strong earthquake, the horizontal acceleration on the middle-top of the declivity can exceed 1 g, and its earthquake horizontal inertia enormously exceeds the tension strength of the rock mass. A vertical crack surface will easy to develop at the trailing edge of the slope. With the continuous influence of earthquake, a tension-shear slip surface developed at the bottom and the earthquake triggered landslides happened at the same time. Therefore, a deep, vertical and rough crack surface is developed in the earthquake-induced landslides.

2. On the condition of strong shock, the most essential deformation and destroy element of the slope rock mass are tension-cracks and shearing slide, and mainly based on tension-cracks. As far as different slope structures, the bottom shearing slide will occur with different discontinuities. According to the geological environment of the landslide source region as well as the characteristics of the slope form and lithological association, the large-scale landslides induced by earthquake can be divided into five genetic types, i.e. tension-strike slip, crack-bedding slip, tension-horizontal slip, tension-scattering slip, and tension-shearing slip.

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