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ORIGINAL ARTICLE

Classification of large-scale landslides induced by the 2008 Wenchuan earthquake, China

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Abstract Over 30,000 landslides were triggered by the 2008 Wenchuan earthquake. The deformation and failure mechanisms of these landslides have been found distinct from those of general landslides self-weight induced. Under gravity, typical sliding in rock slope commonly occurs along a gentle tension crack in some depth at the rear part, which connects to a shear plane at the lower part of the slope to form a complete failure surface. However, due to seismic shaking, a much deeper and steeper tension crack tends to develop at the rear part, which promotes the shearing at the far lower part of the slope. In this paper, the failure modes of earthquake-induced landslides have been classified into four scenarios, in terms of failure mechanisms, characteristics of geological structures, and development of the sliding surface, i.e., tension-strike slipping, tension-dip layering, tension-shattering, and tension-shearing failures. This is evidenced by field investigations. Detailed field investigations were performed on the deformation and failure characteristics of large-scale and deep-seated landslides induced by the Wenchuan earthquake, among which five typical landslides are introduced in this paper in order to illustrate the classification.

Keywords Landslide · Slope · Failure mechanism · Tension-shearing failure · The Wenchuan earthquake

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Introduction

Landslides are extreme events and the resulting rock avalanches can have disastrous consequences to people and infrastructure (Buske 2013). The shaking force of an earthquake can cause deep-seated landslides in earthquake regions (Crozier et al. 1995). On May 12, 2008, the Ms 8.0 Wenchuan earthquake occurred in the Longmen Mountain region at the eastern margin of the Qinghai-Tibet Plateau, adjacent to the Sichuan Basin (Fig. 1). Over 30,000 landslides were triggered during the earthquake (Huang and Li 2009). The deformation and failure mechanisms of these landslides have been found distinct from those of general landslides by self-weight.

Relevant researches have been conducted on the earthquake-induced landslides (e.g., Sassa et al. 1996; Baum et al. 2001; Keefer 2002; Wright and Rathje 2003; Bijan and Nicholas 2003; Fukuoka et al. 2004; Sassa et al. 2005; Xu et al. 2009a; Huang et al. 2012a, b; Zhang et al. 2012, 2014a, b; Kojima et al. 2014). Seismic Landslide Classification System proposed by Keefer (1984) categorized earthquake-induced rock landslides into five categories, i.e., rockfall, rock slide, rock avalanche, rock slump, and rock block slide. This system takes the material composition, motion characteristics, internal damage, and the groundwater condition as criteria to perform the classification. Huang (2009) classified the landslides triggered by the Wenchuan earthquake into five major classes (i.e.,

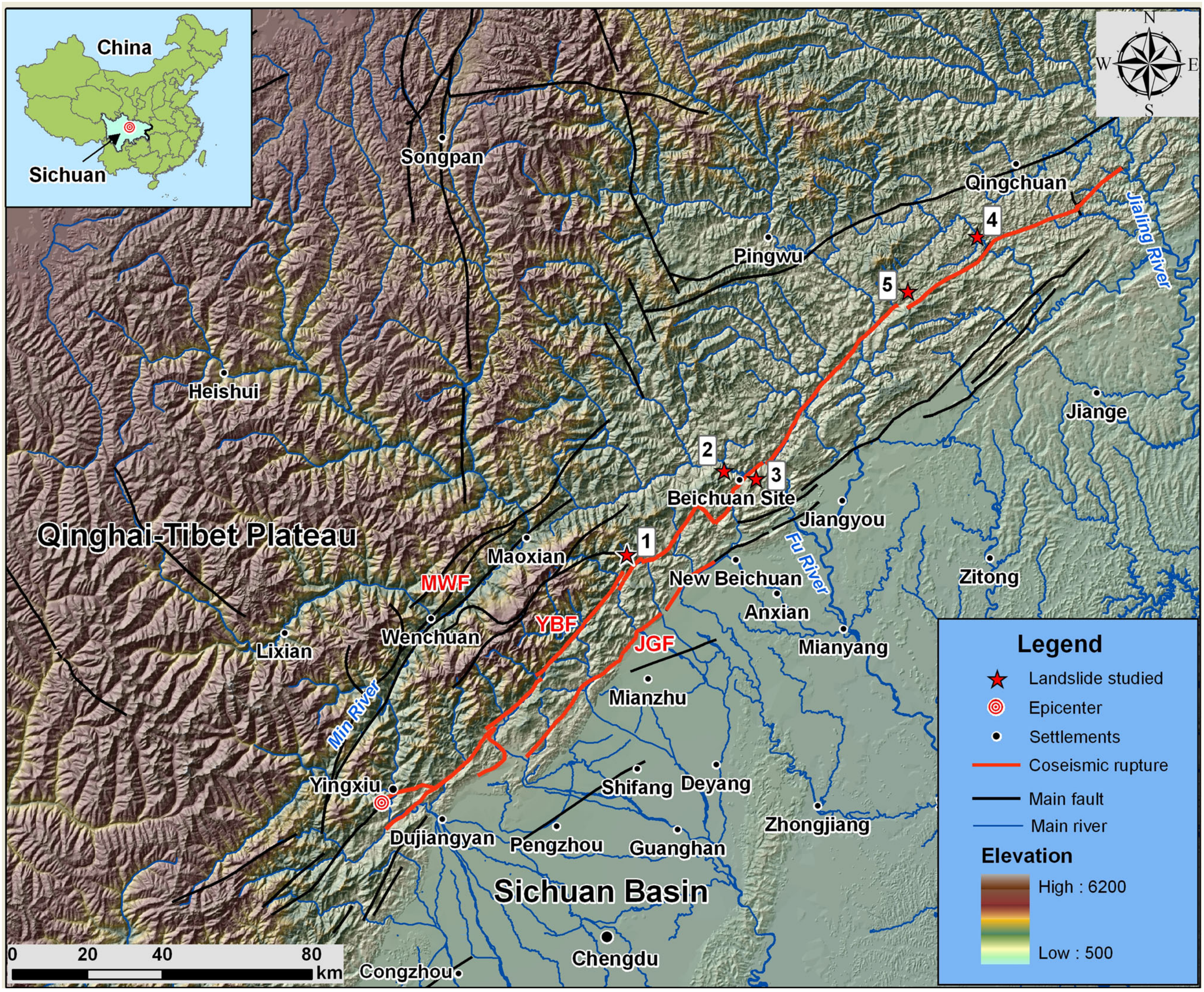

Fig. 1 The 2008 Wenchuan earthquake area (*MWF* Maoxian-Wenchuan Fault, *YBF* Yingxiu-Beichuan Fault, *JGF* Jiangyou-Guanxian Fault. *1* Daguangbao landslide, *2* Tangjiashan landslide, *3* Beichuan New Middle School landslide, *4*: Donghekou landslide, *5* Zhengjiashan landslide)

sliding, falling, projecting, stripping, and shattering), which is further divided into 14 subclasses, as per the failure process and geological structure. Bommer and Rodriguez (2002) compiled a database of earthquake-triggered landslides in Central America and compared their characteristics with global relationships between the landsliding area and the earthquake magnitude. An important conclusion drawn from the data and correlations explored is that there are important differences in the nature of earthquake-induced landslides between the countries of northern and southern Central America. In order to identify the earthquake-induced large-scale landslides, Nonomura and Hasegawa (2013) proposed and tested a simple algorithm for extracting surface geomorphology of flexural-toppling in sedimentary rock areas from 10-m resolution DEM by windows of two sizes. Much has been learned about the failure mechanisms of large-scale rock landslides (e.g., Broadbent and Ko 1971; Lo and Wai 1978; Huang 2012; Yin 2014; Yang et al. 2014), and the generic mechanisms were identified as sliding, tension cracking and shearing. Zhang and Wang (2007) clarified the failure mechanisms of the landslides induced by the Haiyuan earthquake in 1920, based on the field survey and a series of ring shear tests, which revealed that pore water pressure was built-up gradually before the failure, and subsequently, large excess pore pressure was quickly generated due to the failure of loess soil structure. Yin et al. (2009) analyzed the distribution of landslides induced by the Wenchuan earthquake and the characteristics and mechanisms of typical landslides, and assessed the hazards caused by some of the landslide dams. Zheng et al. (2009) conducted a study on the failure mechanisms of earthquake-induced landslides and the mechanical properties of the sliding surfaces using numerical simulation, and indicated that the earthquake-induced landslides were mainly caused by tensile failure at the upper part combined with shear failure at the lower part of the slope. Both the tensile and shear cracks promote each other and facilitate a complete failure surface.

Due to the extremely high magnitude, long duration of vibration and the complicated geo-environment in the Wenchuan earthquake area, the disaster produces not only a huge number of landslides and rockfalls, but also a series of complicated dynamic processes involved in their occurrence, such as widely distributed loosing and cracking mountains, unique shattering-sliding, extremely powerful dynamic process of large-scale or individual rock block ejection, long distance motion, etc. (Huang 2009). They are quite different from the characteristics of landslides and rockfalls under general gravity force. Current study on the classification of earthquake-induced landslides is still very limit in this field. Even though a classification based on the dynamic process of the landslides triggered by the Wenchuan earthquake has been discussed (Huang 2009; Huang et al. 2012a, b), a specific classification is required to differentiate the failure types of earthquake-induced landslide based on the typical geological characteristics of landslides. This paper aims to investigate the failure mechanisms for the typical earthquake-induced rock slides, to classify the failure modes of the earthquake-induced rock slides in the Wenchuan earthquake area. Four failure modes of earthquake-induced landslides were proposed in terms of the geologic structures and deformation characteristics of large-scale landslides investigated in the Wenchuan earthquake zone.

General geology of the study area

The Wenchuan earthquake area is situated in mountainous terrain with an elevation ranging from 500 to 6200 m. As shown in Fig. 1, the NE–SW striking Longmenshan fault zone is composed of three sub-parallel faults, i.e., the Maoxian-Wenchuan, Yingxiu-Beichuan, and Jiangyou-Guanxian faults. The landslides triggered by the Wenchuan earthquake are identified by both field investigations and interpretation of satellite images, and the landslides are found mainly distributed along the Yingxiu-Beichuan fault (Sato and Harp 2009; Xu et al. 2012).

The study area is underlain by granitic rock, Sinian pyroclastic rock, Carboniferous limestone, and Triassic sandstone. These hard rocks account for the steep terrain in this area. Loose Quaternary deposits are distributed in forms of terraces and alluvial fans. The Min River and the Fu River run over this region, which are tributaries of the Yangtze River. The local climate is typical of subtropical monsoon climate characterized by high precipitation. The annual rainfall is 800–1600 mm on average over a period of 30 years, which is concentrated in the rainy season from June to September.

Comparison of failure mechanisms between landslides subject to self-weight and earthquake shaking

Normally, the major principal stress performed at the superficial layer of a slope appears parallel to the slope surface; the minor principal stress is perpendicular to it; and the intermediate principal stress is parallel to the strike direction of slope under self-weight conditions. Thus, both the shear stress and shear deformation are concentrated within weak zones and/or around the slope toe. The shear deformation at the lower part is generally followed by development of tension crack at the rear part of the slope, which followed the criteria of Mohr–Coulomb. As shown in Fig. 2a, an apparent tensile stress is concentrated at the trailing edge of the slope with the enlargement of shear

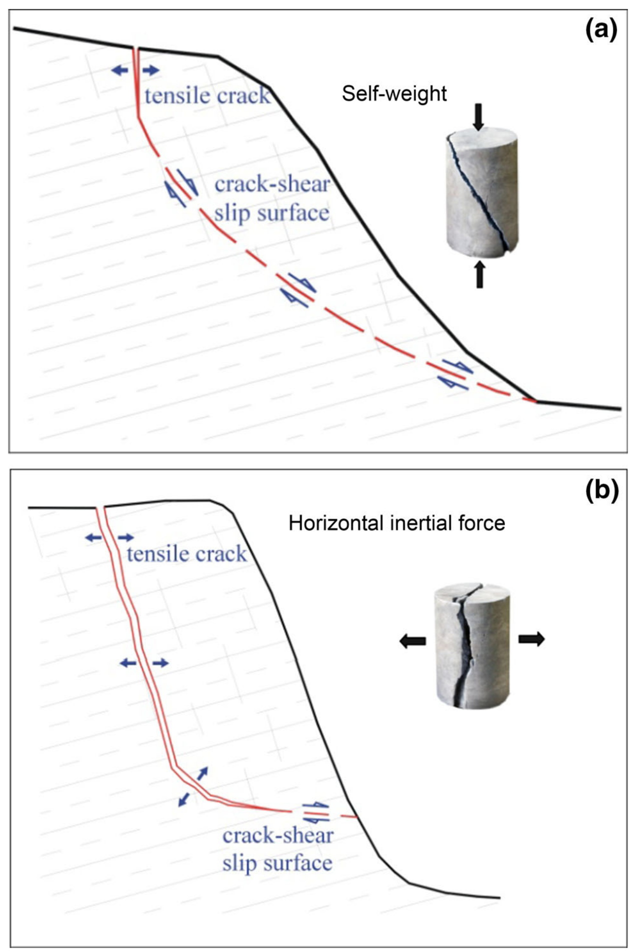

Fig. 2 Deformation and development of sliding surface of rock slope: **a** under self-weight, **b** under earthquake shaking effect

deformation and, finally, tensile cracks will be formed at the trailing edge.

Shaking table tests conducted by the authors (Xu et al. 2010) revealed that the stress state and deformation mechanism of an earthquake-induced landslide are different with those of an ordinary slope failure subject to self-weight. Under the shaking effect of earthquake, the minor principal stress turns into a cyclic state of tensile stress alternating with compressive stress, whereas the minor principal stress of a general slope is of compressive stress, with exceptions for local minimal tensile stress due to unloading. In addition, the horizontal acceleration of the upper part of a slope subject to earthquake may be greater than 1.0 g due to the amplification effect of elevation (Xu et al. 2009b). This would lead to a horizontal inertial force greater than the tensile strength of the rock mass. Based on the Griffith criterion of crack propagation (i.e., minor principal stress $\sigma_3 >$ tensile strength σ_τ), sustained shaking by earthquake would contribute to the development of cracks. It results in a tension crack developed from the top of the slope to a great depth, and promotes the development of shear crack within the far lower part of the slope (Fig. 2b).

By making a comparison between Fig. 2a, b, large difference not only exists in the stress state as described above, but also can be found in the slope failure profile. Deformation of a self-weight-induced landslide normally occurs first at the lower part, followed by tension crack at the rear part. However, under earthquake, deep and steep tension cracks develop first at the rear part, followed by shearing at the lower part. In other words, the self-weight-induced landslide is generally shallow, small-scale failure and normally dominated by shear resistance at the lower part. The development of tension cracks at the rear part is the key for an earthquake-induced landslide, which is normally deep-seated (Crozier et al. 1995; Zheng et al. 2009; Xu et al. 2010).

Failure modes of earthquake-induced landslides

Based on the comparisons of earthquake-induced and conventional gravity landslides, tension deformation initiated at the rear part combined with the shearing deformation at lower part of the slope is the basic failure mode. Shearing slip tends to occur along different structure surfaces due to the variation of slope structures. According to geological structure, lithology of landslides, and development of the sliding surface, this paper classifies the earthquake-induced landslides into four categories, which are tension-strike sliding, tension-dip layering, tension-shattering, and tension-shearing failures. More than 20 catastrophic earthquake-induced landslides were investigated, and the detailed information on these landslides can be found in Xu et al. (2009b). Five typical deep-seated landslides among these landslides are presented as the representatives of the each category in this paper, i.e., Daguangbao landslide in Anxian; Tangjiashan and Beichuan New Middle School landslides in Beichuan; Donghekou landslide in Qingchuan; and Zhengjiashan landslide in Pingwu (Table 1; Fig. 1). Representative failure of each category is presented with brief but essential information (Table 2).

Tension-strike slipping

Tension-strike slipping failure is defined as a massive rock block to be separated from the tension crack at rear part of landslide and to slide along the strike direction of the rock layer, by connecting the joints under earthquake shocking when a free face is available along the sliding direction (Fig. 3a). Such failure tends to occur in mountain ridges of gently anti-dipping rock layers with bedded structures (dip angle of 20°–40°). The orthogonally developed joints (e.g., a set of the joint contours are parallel to the strike lines of the rock layer and the other set parallel to the dip direction of the rock layer). Another precondition is that the dip direction of the slope is near to the strike direction of rock layers.

The Daguangbao landslide is a typical event with the mode of tension-strike failure in the Wenchuan earthquake area (Fig. 4). The Daguangbao landslide is located in Gaochun, Anxian County (Fig. 1) and is the largest landslide triggered by the Wenchuan earthquake, with a volume of approximately 712 million m^3 (Huang et al. 2008; Huang 2012). As shown in Fig. 4, the source material of Daguangbao landslide is mainly composed of highly weathered argillaceous limestone of Sinian (Z_d), with partial phosphate and associated minerals formed in Devonian (D_s). The covering area of the depositional material is measured as 7.12 km^2. The travel distance of runout materials is 4500 m with an elevation difference of 1500 m (Table 1). When the landslide happened, the runout debris struck two buildings located within the deposition zone, caused 38 deaths, blocked the river, and formed a debris dam.

The rock layer of the Daguangbao landslide strikes at N80-88°E and dips at NW with dip angle of 34°–38°. As shown in Figs. 5 and 6, the slope is dipping at the same direction as the rock layer's strike. The SE side of the mountain ridge is steep, caused by the cutting of Menkanshi Gully. Contours of two sets of well-developed joints (N40°W/NE∠80°–85° and N55-60°E/SE∠60°) are parallel to the strike and dip direction, respectively (Fig. 5). The two sets of joints together with the free surfaces at E and S sides tend to divide the rock mass into

Table 1 Characteristics of large-scale landslides induced by the Wenchuan earthquake

No	Name	Location	Volume (10^6 m^3)	Travel distance (m)	Elevation difference (m)	Covering area (km^2)	Deposition width (m)	Lithology	Attitude	Landslide lake	Fatality
1	Daguangbao	Gaochun, Anxian	712	4500	1500	7.12	2200	Carbonatite; attitude	N80-88° E/NW/35-38°	Yes	38
2	Tangjiashan	Beichuan	20.37	1020	540	0.57	611.8	Sandstone, mudstone;	N70-80° E/NW/50-85°	Yes	>100
3	Donghekou	Qingchuan	20	1477	700	1.08	600	Limestone, shale and phyllite	–	Yes	780
4	Beichuan New Middle School	Beichuan	2.4	500	450	0.12	290	Limestone	–	No	700
5	Zhengjiashan 2#	Pingwu	1.1	340	145	0.08	220	Quaternary alluvium	N50-66° E/NW/40-70°	No	33

blocks (Huang et al. 2012a, b). Based on the slickenside at the slip surface, it can be speculated that the sliding mass cannot completely slid along the strike direction since the rock layer is dip to inner-slope. As shown in Fig. 5, a cross-angle can be observed between the sliding and strike direction at the initial stage of the slope failure. However, the sliding deformation along this direction can be blocked by the mountain nearby, and the sliding mass had to gradually shift to the other direction in order to slide out smoothly (Fig. 5). Under earthquake shaking, the sliding mass was detached, along the NW joints, from the trailing edge, and slid along the NE joints and the bedding plane beneath (Fig. 6).

Tension-dip layering

Tension-dip layering failure is defined as a rock mass with layer dipping outwards that slides downslope (Fig. 3b). Due to the earthquake shaking force, the upper part separates from the bedrock by tension along the existing soft bedding plane. As a result, the self-weight of the separated mass forces the lower part to be sheared to complete the failure plane. Landslides in the type of tension-dip normally exhibit a high-speed sliding process due to the low shear strength of failure surface. Particularly, the major differences between the types of tension-strike slipping and tension-dip layering are the former one tends to be initiated at the rear part of a landslide in the sliding direction of 'strike,' while the latter one tends to be initiated along the existing soft rock layer in the direction of 'dip' (Figs. 3a, b).

The Tangjiashan landslide triggered by the Wenchuan earthquake was located in Beichuan County, which is typical of high-speed tension-dip failure with sliding velocity of 30 m/s (Fig. 7). Before the earthquake, the average slope gradient of Tangjiashan landslide is 40°, elevation of the slope ranges from 665 to 1500 m, with a relative relief of 835 m. The covering area of this landslide is estimated as 0.57 km^2. The Tangjiashan landslide originated in weathered metamorphic slate, sandstone, and pelite. The sliding surface of this landslide was identified along the bedding planes. A volume of 20.37 million m^3 formed a blockage of 803 m in length along the channel, 611 m in width across the channel, and 83–124 m in thickness (Cui et al. 2012). Since the travel distance of the landslide is approximately 1020 m and the duration of sliding is around 30 s (according to the eyewitness's description), the sliding velocity was estimated as 30 m/s (Table 1). A 20 million m^3 landslide dam formed in the Jian River with length of 803.4 m, width of 611.8 m, and thickness of 124 m. As shown in Fig. 7, the capacity of the landslide lake was 300 million m^3 (Hu et al. 2009). Approximately 100 people were killed during this disaster.

Table 2 Typical failure modes of large-scale landslides induced by the Wenchuan earthquake

Failure modes	General conditions	Basic characteristics	Typical landslides
Tension-strike slipping	Mountain ridges of gently anti-dipping rock layers, with orthogonally developed joints. A set of joints parallels to the strike direction of the rock layer, and the other set parallels to the dip direction of the rock layer. The dip direction of the slope is near to the strike direction of rock layers	A massive rock mass to be separated from the mountain ridge and to slide along the strike direction of the rock layers	Daguangbao Woqian (Xu et al. 2009b)
Tension-dip layering	Discontinuities (joint and/or bedding plane) dipping outwards, consequent slope	Shearing takes place along the existing bedding planes and joints dipping outwards. It connects the deep tension cracks at the rear part of the slope to form a complete sliding surface. The sliding velocity is high due to the low shear strength of failure surface. Parts of the activated rock mass may fly over a long distance under certain conditions of geomorphology and topography	Tangjiashan Wenjiagou No. 1 Zhengjiashan Laoyinyan Niumiangou Donghekou Dayanqiao (Xu et al. 2009a, b)
Tension-shattering	Fractured hard rocks	Scattering of the fractured rocks lead to structure collapse, like an avalanche or debris flow	Beichuan New Middle School Shibangou Xiejiadianzi K24-SR303 (Xu et al. 2009b)
Tension-shearing	Anti-dip slope	Shearing takes place in the far lower part of the slope by cutting the anti-dip rock layers. It connects the tension cracks at the rear part to form a complete failure surface	No. 2 Zhengjiashan Wangjiayan Guershan Dongjia Guantan Pingxicun (Xu et al. 2009b)

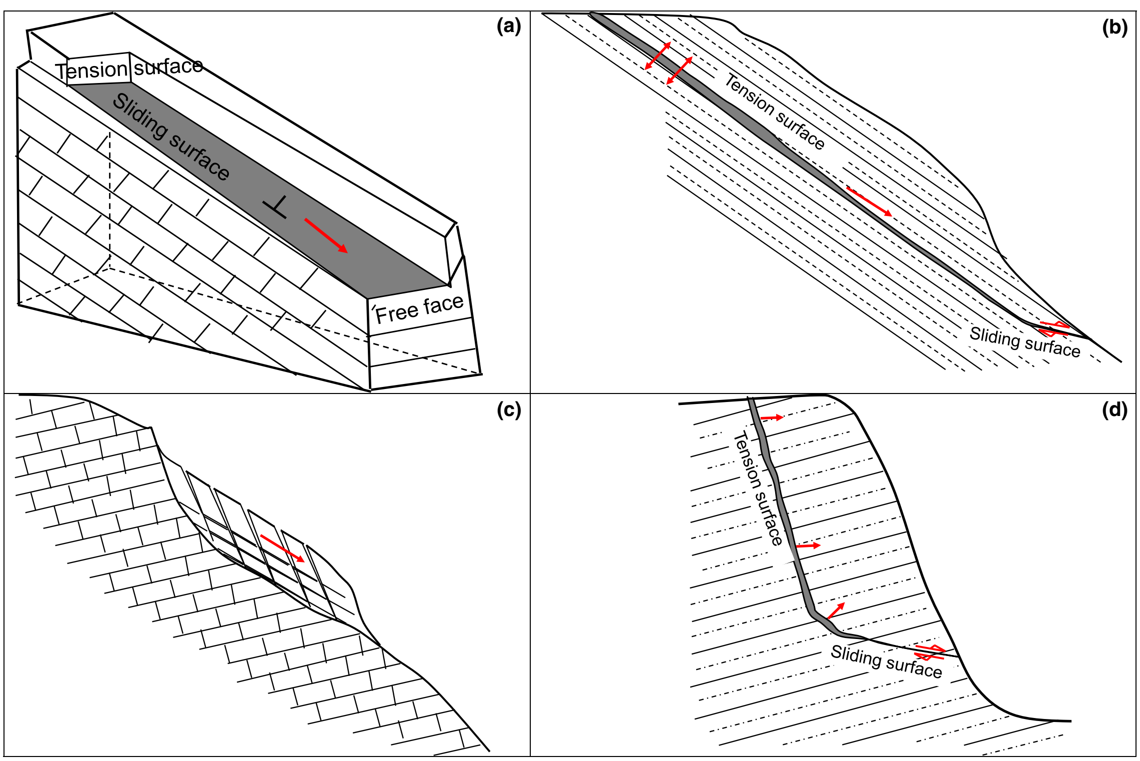

Fig. 3 Failure modes of rock slope: **a** tension-strike slipping, **b** tension-dip layering, **c** tension-shattering, **d** tension-shearing

Fig. 4 Aerial view of the Daguangbao landslide (sliding direction of NE, Huang et al. 2012a, b)

In order to discharge the flood to relief the potential danger, immediately sluices were dug in the landslide dam.

Due to the typical layering geological structure, the Tangjiashan landslide is classified as tension-dip layering landslide with inclination of 50–85°. The major lithology is Cambrian silicalite with mudstone. The mudstone is distributed randomly within the slope with a thickness of 5–20 cm, which is prone to mudding and softening in water. Weak mudstone layers are considered as the potential sliding surface, along which the rock mass was separated by earthquake shocking. When the layer of the rock slope is gently inclined outwards, under the influence of the strong horizontal seismic inertia force, a steep pull-apart plane can be developed at the rear part, and the rock mass would slide along the bedding plane in the lower part.

Another typical representative is the Donghekou landslide (Fig. 8). The Donghekou landslide is triggered by the Wenchuan earthquake, occurred in Donghekou Village, Qingchuan Country, Sichuan, with a distance of approximately 3 km to the north of the Yingxiu-Beichuan-Qingchuan fault (Fig. 1). The source materials are mainly composed of dolomitic limestone, dark gray siliceous shale, and carbonaceous quartz phyllite. The landslide dammed two confluent rivers (i.e., the Qingzhu River and the Hongshi River) and formed a massive landslide lake. When the landslide occurred, the debris of the landslide inundated four villages and a bus station, two large tourist buses, one car, and 780 villagers were buried. This typical

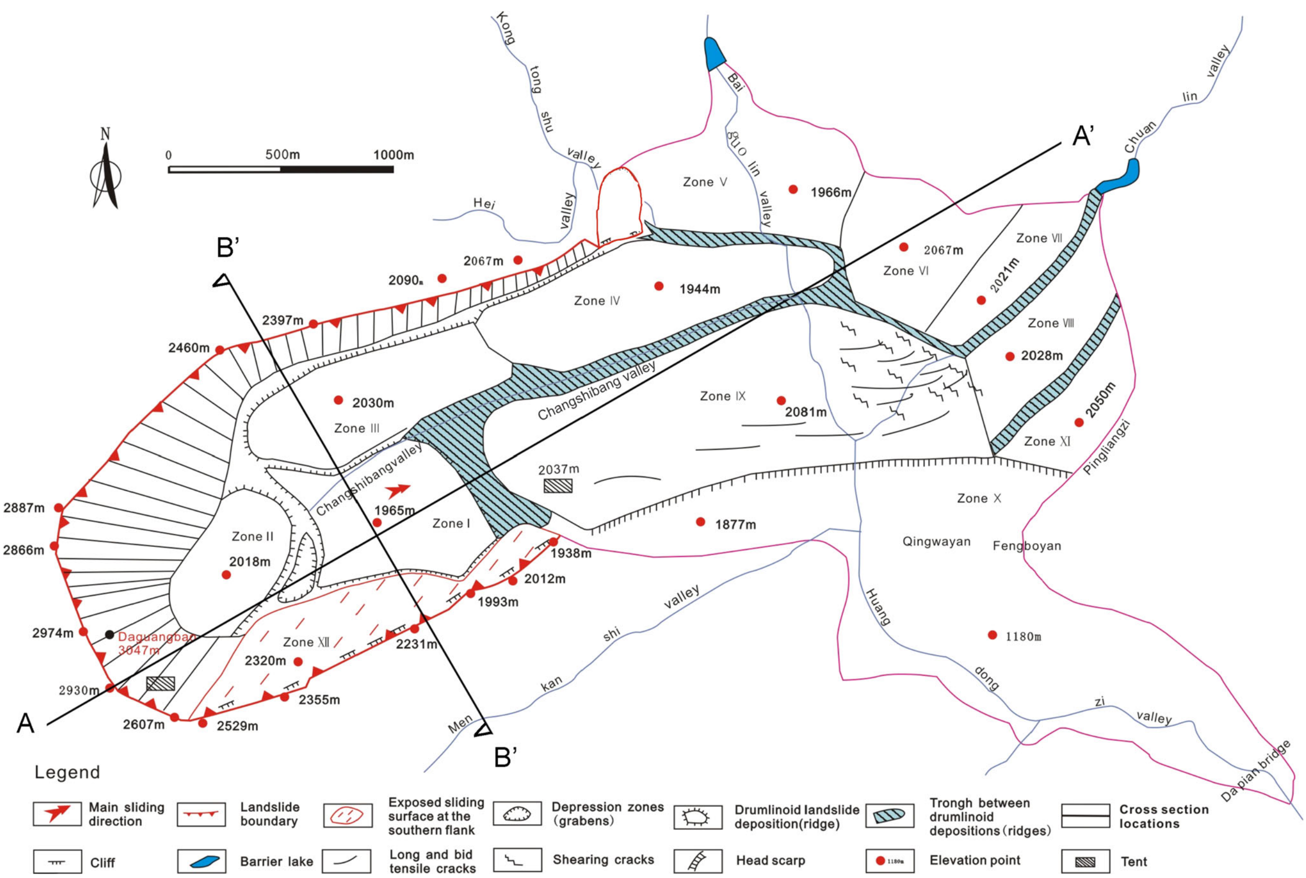

Fig. 5 Engineering geological map of the Daguangbao landslide (Huang et al. 2012a, b), zones I–III are source area, zones IV and IX are transit area, zones V–VIII, X, XI, are deposition area

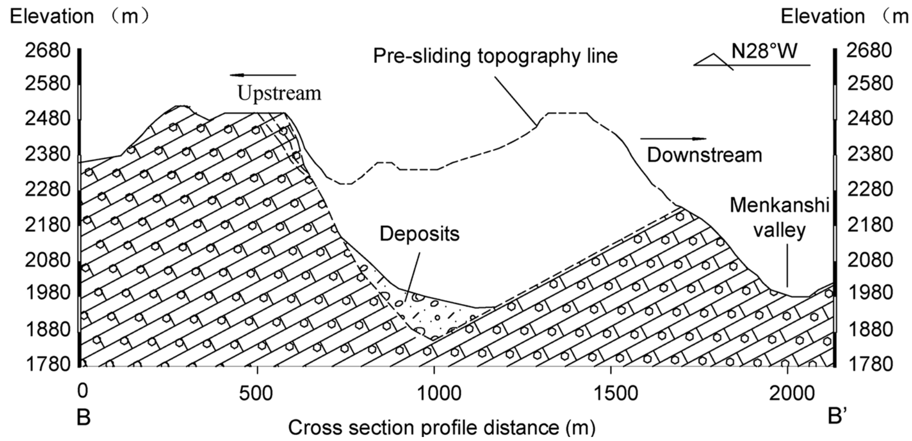

Fig. 6 Cross section (B-B′) showing source area of the Daguangbao landslide (Huang et al. 2012a, b)

Fig. 7 Overview of the Tangjiashan landslide in Beichuan

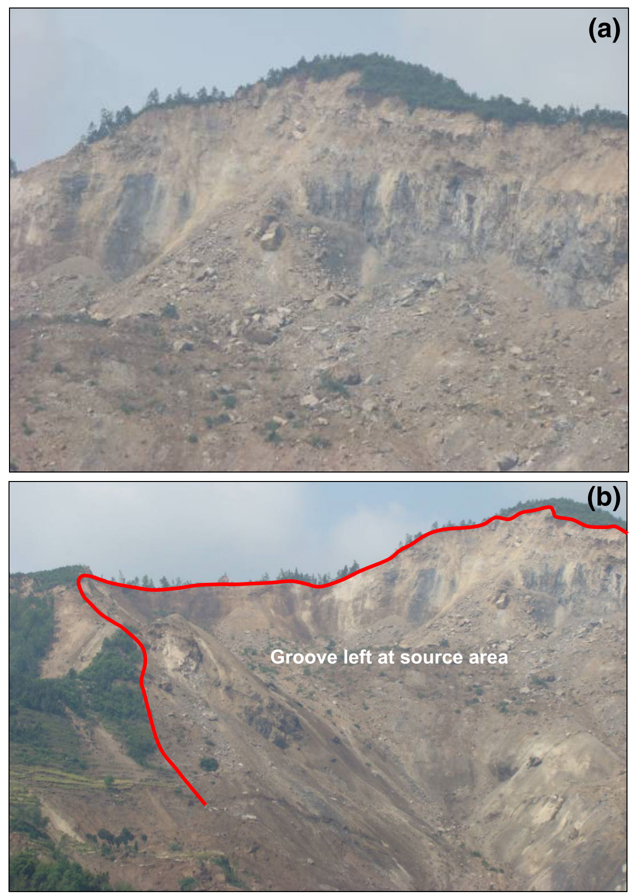

Fig. 8 Donghekou landslide in Qingchuan: **a** steep scarp, **b** a huge groove left at the source area

rapid landslide had a volume of 20 million m^3, a height between the scar and toe of 660 m, a length of 2700 m, a width of 150–600 m, and a covering area of 1.09 km^2. The thickness of the landslide deposits varied greatly, from several meters to dozens of meters (Zhang et al. 2011). Due to the scraping effect of the high-speed mass movement, the original loose deposits were detached from the slope as shown in Fig. 8a. The debris then ran down the hill and was deposited over a travel distance of 1477 m.

Donghekou landslide is characterized by a typical sandwich structure, as shown in Fig. 9, and the rock layer of Cambrian overlies the Sinian due to the total formation overturned. Tensile structure surfaces are widely distributed, especially concentrated at the rear and lateral parts of the slope. The rock layer of Donghekou landslide is gently inclined outwards at a dip angle of about 12°. A steep pull-apart plane appeared at the trailing edge under a strong horizontal seismic load. Afterwards, the rock mass slid along the weak plane beneath, and a large groove was left in the source area as shown in Fig. 8b.

Tension-shattering

A tension-shattering failure is defined as a form of mass movement in which a preexisting fractured rock mass mobilize as an avalanche that slides downslope (Fig. 3c). Discontinuities are generally well developed in hard rocks, e.g., limestone, dolomite, and granite, due to tectonic

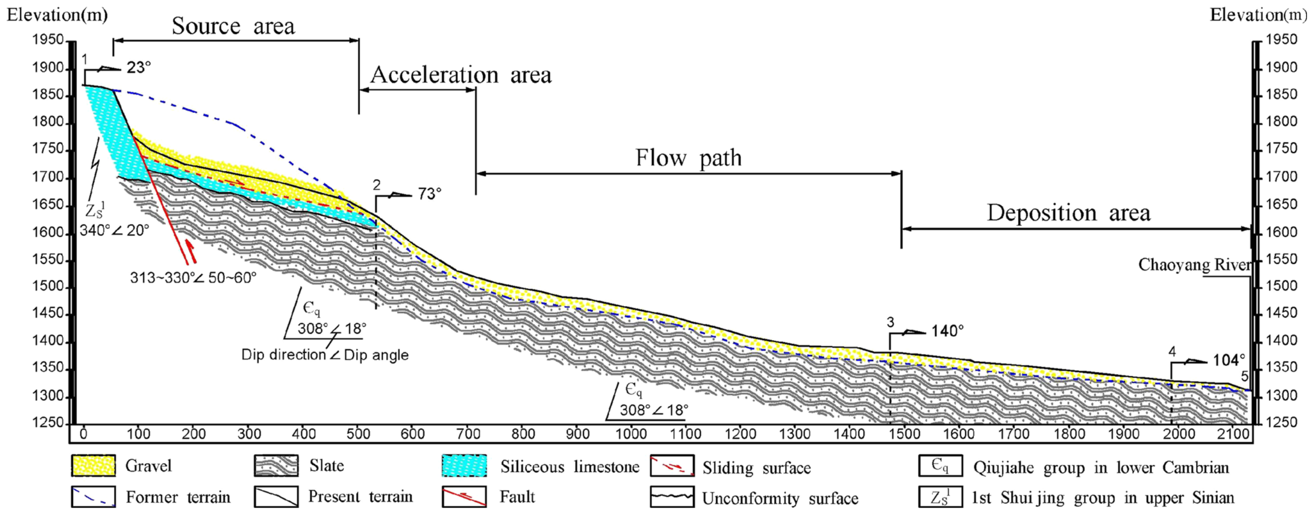

Fig. 9 Cross section of the Donghekou landslide in Qingchuan

compressions. The discontinuities in superficial layer of such a rock mass are of tensile feature due to the weathering and the unloading effect. Vertical or sub-vertical cracks are developed under the effect of earthquake shocking. They work together with the original discontinuities to make the rock mass more scattering. The slope finally fails as a loose mass flow.

A representative of tension-shattering failure is the Beichuan New Middle School landslide (Fig. 10). The Beichuan New Middle School landslide is an ancient landslide with a covering area of 0.12 km^2 (Table 1). The volume of the deposition material is approximately 2.4 million m^3 with an average thickness of 20 m. This landslide was mainly composed of blocks and stones. The travel distance of the runout debris was estimated as 500 m with an elevation difference of 450 m. When the landslide happened, the impulsive force totally destroyed a three-storied building in the New Middle School and took the lives of nearly 500 people (see Fig. 10).

Fig. 10 Overview of the Beichuan New Middle School landslide

The source materials of the landslide are mainly composed of limestone in Carboniferous Yanguan group (C_y^1). The rock mass was divided into blocks by sets of discontinuity. As shown in Fig. 11a, the Wenchuan earthquake loosened the shallow layer of the rock mass, and subsequently a tension-shattering failure occurred along one preferential plane (Fig. 11b). The accumulation zone of this type of landslide is mainly composed of rock blocks of different sizes (Fig. 11c).

Tension-shearing

Tension-shearing failure is a mode that a rock mass vertically separated from the bedrock due to the development of vertical tension surface (Fig. 3d). It occurs mostly in slopes with anti-dip structure. Under horizontal inertial force by earthquake, deep tension cracks develop at the rear part by connecting the existing joints dipping outwards the slope. Shear deformation starts at the lower end of the tension crack to form a complete failure surface (Fig. 12).

Since the anti-dip slopes are widely distributed in the earthquake area, the tension-shearing failure is the most popular failure modes of landslides triggered by the Wenchuan earthquake. Representatives include Wangjiayan and Guershan landslides in Beichuan County, Zhengjiashan landslide in Pingwu, Guantan landslide in Anxian, Dongjia landslide in Qingchuan (Xu et al. 2009b).

The Zhengjiashan landslide occurred in Pingwu County (Fig. 1). During the Wenchuan earthquake, the 3.2 million m^3 runout materials slid down and blocked the Ziku River. These depositional materials directly buried the residents' buildings and caused 33 deaths. The

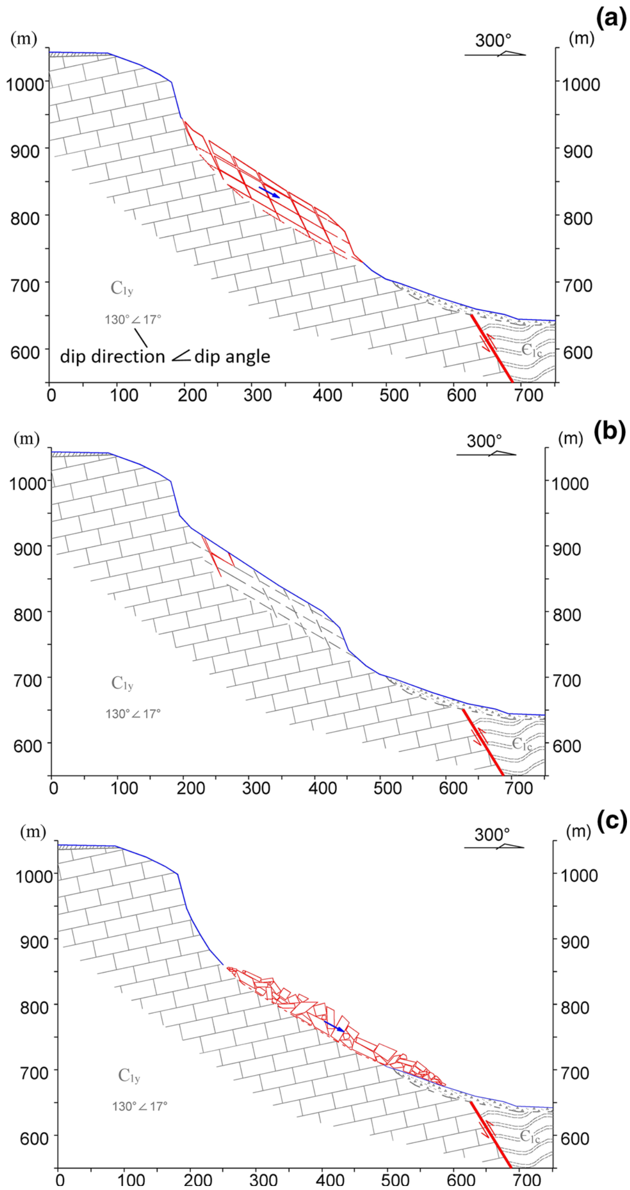

Fig. 11 Failure mechanisms of tensile cracking-scattering slip: **a** initial state, **b** shattering-cracking, **c** scattering-sliding

Zhengjiashan landslide mainly consisted of two parts with different sliding directions and failure mechanisms, i.e., Zhengjiashan $1^{\#}$ and Zhengjiashan $2^{\#}$. As shown in Table 1, the volume of $1^{\#}$ landslide is approximately 2.1 million m^3 with a travel distance of 480 m; $2^{\#}$ has a volume of 1.1 million m^3 with a travel distance of 340 m.

Figure 13 shows the longitudinal section of the Zhengjiashan $2^{\#}$ landslide, which illustrates the tension-shearing failure mode. It is worth noting that the failure surface of a tension-shearing failure is completed caused through shearing the rock at the lower part, while the failure plane in other failure modes mentioned above is basically developed by tracking/connecting the existing structure planes/joints. This somehow delays the occurrence of tension-shear failure. According to the eye-witness's descriptions, the Wangjiayan landslides happened 10 min after the major shock of the Wenchuan earthquake. This period is through to be taken for the development of shear plane in the locking segment, which is sheared by the overlying self-weight.

Conclusions

A huge number of large-scale landslides were triggered by the Wenchuan earthquake in 2008. Due to the extremely high magnitude, long duration of vibration, and the complicated geo-environment in the Wenchuan earthquake area, these landslides are quite different from the characteristics of landslides and rockfalls under general gravity force, and current study is very limit in this field. Our sustained investigations in the past 5 years indicate that the deformation and failure mechanisms of landslides triggered by this event are distinct from the common landslides driven by self-weight. In order to figure out the failure modes and sliding mechanisms, field investigations of earthquake-induced landslides were undertaken. The following conclusions can be drawn:

1. Significant differences exist between earthquake-induced rock landslides and conventional rock landslides, which are mainly reflected as deformation failure modes and sliding mechanisms. Deformation of a self-weight induced landslide normally occurs first at the lower part, followed by tension crack at the rear part. Deep and vertical cracking is one of the evidences to admit the contribution of earthquake to the occurrence of landslides. The horizontal acceleration by seismic wave at the upper part of a slope may exceed 1.0 g, and the horizontal inertia force may enormously exceed the tensile strength of the bedrock. Under such a condition, a vertical, deep, tensile crack would be easily developed at the rear part of the slope firstly. This in turn promotes that the development of the shear cracks at the far lower part of the slope.
2. Four failure modes of landslides induced by the Wenchuan earthquake are derived, i.e., tension-strike slipping, tension-dip layering, tension-shattering, and tension-shearing failures. Particularly, tension-strike slipping failure tends to occur in mountain ridges of gently anti-dipping rock layers, with orthogonally developed joints; tension-dip failure generally happens in slopes with rock layers dipping outwards and initiates along the existing soft rock layer; Tension-shattering failure is concentrated in fractured hard rocks; tension-shearing failure occurs mostly in slopes with anti-dip structure.

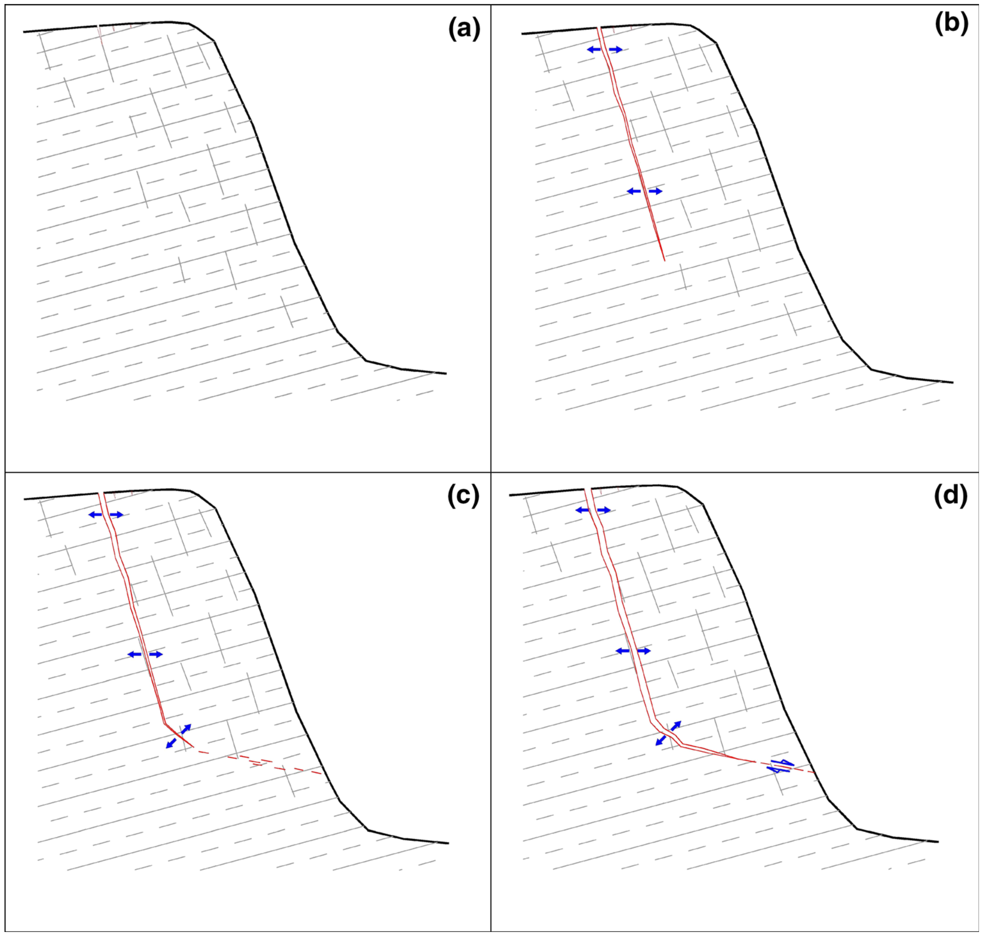

Fig. 12 Process of tension-shearing failure: **a** tension crack in shallow top, **b** deep tension crack along the sub-vertical discontinuities, **c** tension or tension-shear development, and **d** shearing at the far low part to form the complete failure surface

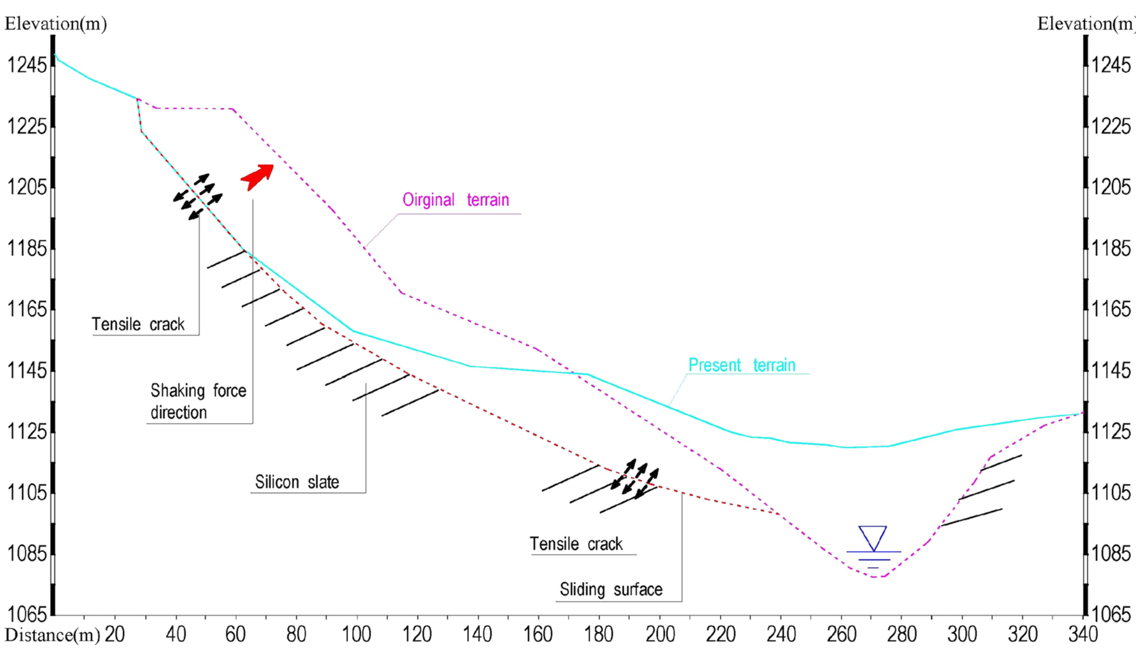

Fig. 13 Longitudinal section and failure mode of the Zhengjiashan 2# landslide

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