Failure modes of loose landslide deposits in the 2008 Wenchuan earthquake area in China

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Abstract: In this study, a geological investigation and statistical analysis of the postearthquake slope deposit failures in a meizoseismal area were presented with a selected example from the 2008 Ms 8.0 Wenchuan earthquake that occurred in Sichuan Province in China. The typical slope deposit failures were surveyed in three meizoseismal areas, namely, Qingchuan County in Guangyuan city, Beichuan County in Mianyang city, and the epicenter area, Wenchuan County, in Aba Tibetan Autonomous Prefecture. According to the movement, materials and deformation mechanisms of the rock or soil, the failures of the postearthquake landslide deposits could be subdivided into four categories: slide, rockfall, erosion and flow. This classification of the failure modes of landslide deposits considers topography and failure after an earthquake. Other important factors, such as topography, lithology and hydrogeology, are also considered. The above-mentioned four failure categories are further split into 12 subclassifications. The complicated deformation mechanisms and different failure patterns of the slope deposits are analyzed for typical deposits. This classification provides a good reference for the prediction of geological hazards, and the mitigation of the landslides and debris flows caused by loose deposits in meizoseismal areas is still a difficult task.

1. Introduction

The failure types of postearthquake deposits have been examined in several studies, and classification (1938) is primarily based on the materials (earth and rock), movement (flow and slip) and velocity (slow or very rapid) without considering the effects of the topography, landform, volume and inducing mechanism. Based on the material and type of movement, Varnes (1954, 1978) classified the slope failure into five types, including fall, topple, slide, spread and flow, and this has been the most widely used classification for landslides in the world. According to the seismic parameters, materials and geological environment, Keefer (1984) divided landslides into 14 types. Considering the landslide shape and geotechnical parameters, Hutchinson (1988) divided the slope deformation failure modes into a creep, frozen ground phenomena, and landslides but did not consider the trigger mechanisms and the effects of the volume. Hungr (2001) classified landslides into ten types based on genetic and morphological characteristics and introduced a new category in combination with unsorted material and sorted material. However, the deformation failure modes and the particularity of the loose postearthquake main body have not been extensively researched in previous studies, and further studies should be conducted based on these landslide classifications.

The purpose of the new classification proposed in this paper is to effectively split landslide deposits into common categories according to deformation mechanisms, which retains the established concept and reveals the deformation and failure trends of landslide events. This approach is easy to implement with a statistical analysis of field surveys, without resorting to more complex taxonomic methods. Moreover, understanding the deformation and failure modes can help to mitigate and prevent similar geological disasters. Some authors have made good attempts and achieved significant results. For instance, the "locking section" was used by Huang (2011) in one study of the mechanisms of large-scale landslides that occurred in China to identify a three-section model that includes sliding, tension cracking and shearing. Using the same apparatus, Yang (2015) also evaluated the postearthquake rainfall-triggered deposit failure that occurred in the Lushan area, Sichuan Province, China.

The discussion in this paper focuses on the deformation and failure mechanism of loose deposits after an earthquake. Although the deformation and damage mechanisms of the accumulation body have been preliminarily considered, the classification and specifics of the landslide deposits have not been well developed. Wang (1981) found that aftershocks caused cyclic shear to induce a decrease in the strength of the sliding surface shear on unstable rock slopes. Some researchers have used inertia, damping, weakening, and liquefied instability to interpret the instability of a deposit. Seed and Martin (1966) used a regular soil deposit for a laboratory test with a limited focus on the large deformation of the inclined slope caused by material liquefaction. Kramer (1997) suggested that postearthquake instability can be spilt into weakened instability and inertial instability. Based on indoor experiments and field tests, a few researchers have studied the liquefaction mechanism and shear deformation of loose deposits after earthquakes in China, Japan, and New Zealand. It was confirmed that liquefaction or shear forces established slope deformation. However, empirical models of the deformation and failure of loose deposits after such earthquakes have not been proposed.

According to the survey in 2010 by the China Geological Survey, nearly 45,000 loose deposits were induced by the 2008 Wenchuan Ms 8.0 earthquake in China, extending to 51 disaster areas across 130,000 km^2. These loose deposits included 13,229 landslide deposits, 5,180 rockfall deposits, and 2,400 debris-flow deposits in Sichuan Province, according to the postearthquake survey (Huang, 2009). Many loose deposits in the Sichuan postearthquake areas are susceptible to rainfall or landslides induced by aftershocks. From 30 May 2008 to 30 December 2010, more than 12,000 potential geological hazards triggered by rainfall and killed hundreds of people (Fig. 1) (Kirschbaum, 2010; Liao, 2011).

A clear classification system of the deformation mode of the accumulation body is beneficial to the evaluation of the stability of A geohazards. In particular, the geological hazard classification system in strong earthquake areas should consider the effects of multiple factors, such as the topography, stratum lithology, material, motion velocity, deformation, and failure mechanism. A practical type of classification based on selected attributes is a good classification and a quick way to solve practical engineering problems. According to the material and sedimentological characteristics, Fan (2017) divided the dam landslides caused by the 2008 Wenchuan earthquake into three categories, which will help the prevention and control of landslide dams in strong earthquake areas; however, there is no classification for loose deposits such as debris flows and rockfall deposits.

In this study, the geological conditions and the type of geohazards induced by the 2008 Wenchuan earthquake are first introduced. Subsequently, the classification method and the typical failure mode of the loose deposits that occurred since 2008 are discussed. A new classification method for the deformation and failure modes of deposits considering various factors, such as the topography, material, motion velocity, volume, and particle composition, is proposed. The formation mechanism and failure modes of the geological disasters induced by 12 loose deposits are analyzed. The proposed classification scheme of the failure modes for loose deposits could also be easily applied for the classification of geological hazards that occur in other strong earthquake zones.

2. Site Study

2.1 Geological conditions

Detailed analyses of the landslide deposits show that the slope deposit failures in postearthquake regions in Wenchuan, China, are complex. It is important to study the geological conditions to recognize potential geological hazards. The specific failure mode is related to the specific topography, deformation, and structure of the rock (soil). This study area crosses various geomorphic units covering the Qinghai-Tibet Plateau, Longmen Mountain and the Sichuan Basin and valley from north to south. The elevation is high in the north and west but low in the south and east. Due to well-developed faults, complicated topography, various types of rock-soil mass structures and climate change in this area, many postearthquake loose deposit slopes accumulated in the potential geohazard regions, and it is important to study the failure modes and evolutionary process in the Wenchuan earthquake area.

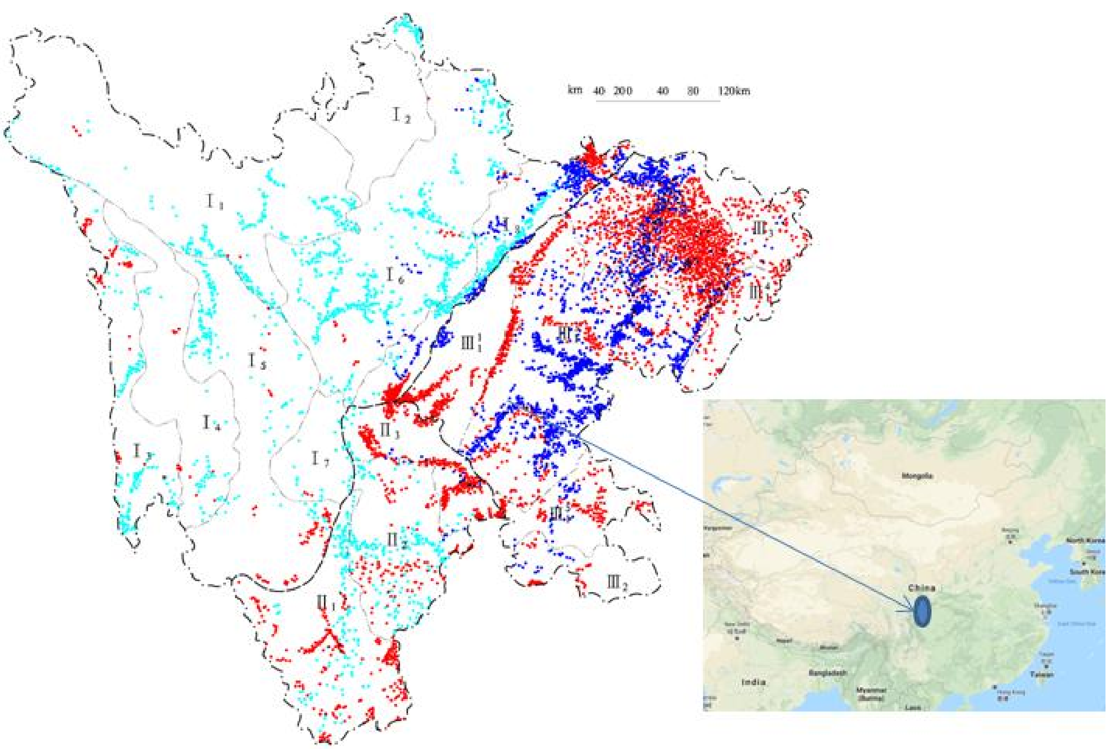


Fig. 1 Statistical distribution of Loose deposits postearthquake in Sichuan Province, China. (Landslide deposits are shown in red; rockfall deposits are shown in blue; debris flow deposits are shown in green. A geological survey in 2010 documented 13,229 landslides, 5,180 rockfalls, and 2,400 debris flows in the study area.)

Legend: landslide deposit; rockfall deposit; debris flow deposit

I: High mountain plateau region of western Sichuan; I1: Shiqu Seda structure denuded hilly plateau area; I2: Hongyuan Ruoergai tectonic denuded swampy plains; I3: East bank of Jinsha River tectonic erosion mountain canyon area; I4: Shapuli Mountain erosion or denudation hilly plateau area; I5: Yalong River structure erodes the deep valley mountain area; I6: Qionlai Mountain to Minshan Mountain tectonic erosion ridge mountains; I7: Gongga Mountain structure erodes extremely high mountains; I8: Longmen Mountain fault erosion slope in the mountain area.

II Mountain area of southwest Sichuan II1: Emei Mountain to Wuzhi Mountain tectonic erosion block mountain area; II2: Xichang Yanyuan tectonics erodes middle mountainous area of wide valley basin; II3: Liangshan tectonic erosion middle mount area.

III: Mountain area in eastern basin in Sichuan; III1: Tectonic erosion low mountain hilly in Sichuan Basin; III_1^1: Inclined plain subregion in the front of western fault depression basin; III_1^2: Mono-clinic low mountain subregion north of tectonic erosion basin; III_1^3: Table low hilly subregion south of erosion tectonic basin; III_1^4: Parallelism (low mountain) valley (hilly) subregion in eastern of erosion tectonic basin; III2: Michang Mountain to Dab Mountain tectonic corrosion bedded middle area; III3: Wu Mountain to Dalou Mountain strong karst valley middle mountain area.

2.2 Seismicity and rainfall

Several high-magnitude earthquakes have been recorded in the Longmen Mountain tectonic zone along the eastern margin of the Tibetan Plateau (China) in the last few decades. The Ms 7.5 Diexi earthquake on August 25 1933, caused a catastrophic landslide that blocked the Minjiang River and formed three famous "quake lakes". The rockslide depositions had slipped into a channel and formed a landslide dam and caused deformation and failure. Subsequently, the water in this lake poured down and, as a result, 2,500 people were killed and more than 6,800 houses were destroyed (Ren, 2017). The Wenchuan earthquake on May 12, 2008, and the Lushan earthquake on April 20, 2013, had magnitudes of Ms 8.0 and Ms 7.0, respectively. These epicenters were located on the Longmen Mountain fault, SW-NE of Chengdu city, and the epicenter was located 5 to 20 km deep within the Eurasian plate of the Yangtze plate (Fig. 2).

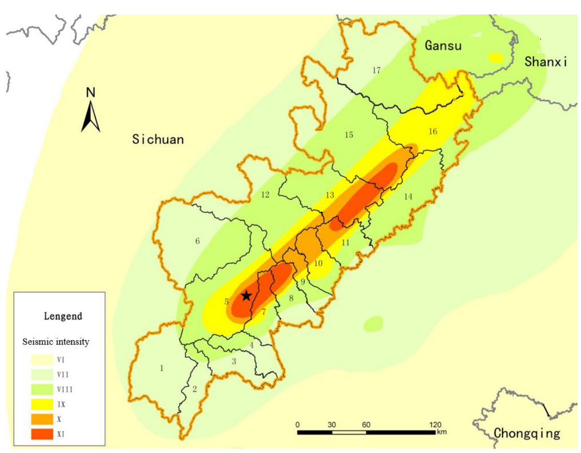


Fig. 2 Map of the seismic intensity of the Wenchuan earthquake on May 12, 2008

The abovementioned earthquakes occurred in the Longmenshan fault zone, indicating that strong earthquakes in this area are frequent and that the geological environment is very fragile, which is the source of power for loose accumulations. These recurring earthquakes are the result of the relative uplift of the Tibetan Plateau and the relative decline of the Sichuan Basin. The relative movement of the Qinghai-Tibet Plateau and the Sichuan Basin resulted in the uplift of the Longmen Mountains and formed a large seismic zone parallel to the eastern margin of the Qinghai-Tibet Plateau. The Longmenshan fault zone includes three major fractures, namely, the Maoxian-Wenchuan fault, the Yingxiu-Beichuan fault and the Pengxian-Guanxian fault, which are widely distributed on the two largest anticlinoria: the Pengguan anticlinorium and the Baoxing anticlinorium. Due to the violent new tectonic movement in the area, the rock mass was broken, and earthquakes are frequent, causing a large number of loose deposits (Fig. 3). As shown in Fig. 3, three major faults were formed, i.e., the fault located at the junction of the Longmenshan fault zone and the Sichuan Basin; the piedmont fault, also known as the Pengxian-Guanxian fault, which is approximately parallel to the Longmen Mountains and the 240 km main central fault, which is also known as the Yingxiu-Beichuan fault; and the Maoxian-Wenchuan fault, also known as the Maoxian-Wenchuan fault.

Most typical loose deposits triggered by the earthquake occurred in Longmen Mountain of Wenchuan, which is approximately 60 km from Chengdu city, Sichuan Province, near the eastern fringe of the Tibetan Plateau, China (Fig. 1). Based on the multisource remote sensing data and field survey data from 2009 to 2018 provided by the China Geological Survey (CGS), rainfall is the main cause of the landslides, rock avalanches, and rotations caused by loose debris deformation. Among them, the period of 2010-2014 is the peak of the development of rainfall and geohazards, and hundreds of geological disasters were caused by the failure of loose deposits after the 2008 Wenchuan earthquake.

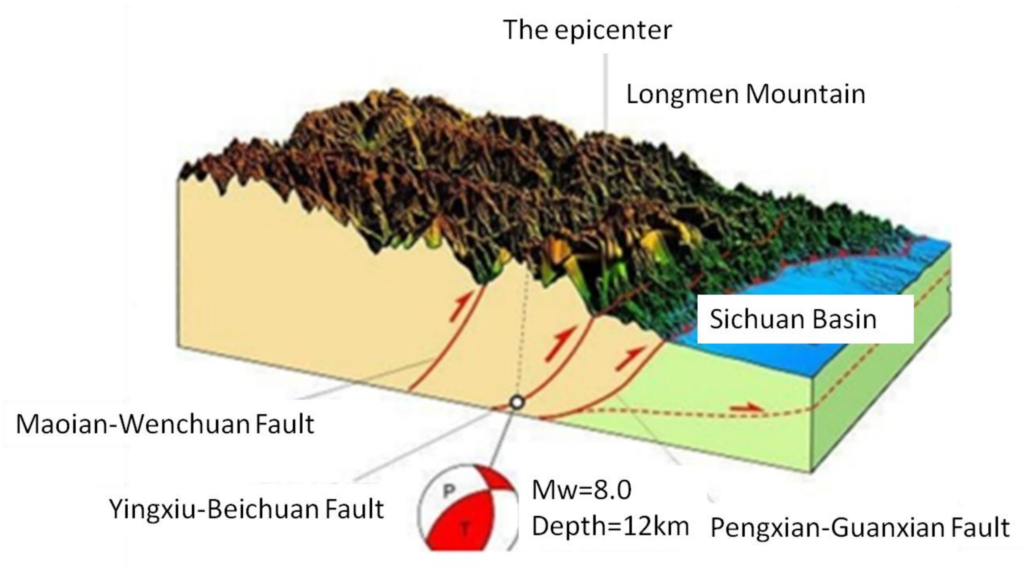


Fig. 3 Three main faults along the Longmen Mountain tectonic.

It is suspected that rainfall and aftershocks have triggered landslides or debris flows. Rainfall has played an important role in the conversion of loose accumulations into landslides and has also attracted the attention of many research interests. The study area has a subtropical humid climate that usually brings heavy rainfall between June and September. The average annual precipitation in the study area is 4.87×10^{12} m^3, and the annual average rainfall is 1003.1 mm. The Longmen mount fault zone is in an area of concentrated rainfall distribution with a maximum rainfall of 160 mm in 24 hours, which provides sufficient external dynamic conditions for the failure of loose accumulations. Besides, there are more than 1,400 rivers in the study area, and the water flow rate reaches 1.59×10^{4} m^3 per second, which is also an important factor for the deformation and failure of loose deposits (Fig. 4). Under the combined action of seismic activity and hydrogeological conditions, the slopes with loose accumulations in this area have a high risk of failure during earthquakes. These factors must be taken into consideration in the failure mode classification of loose deposits.

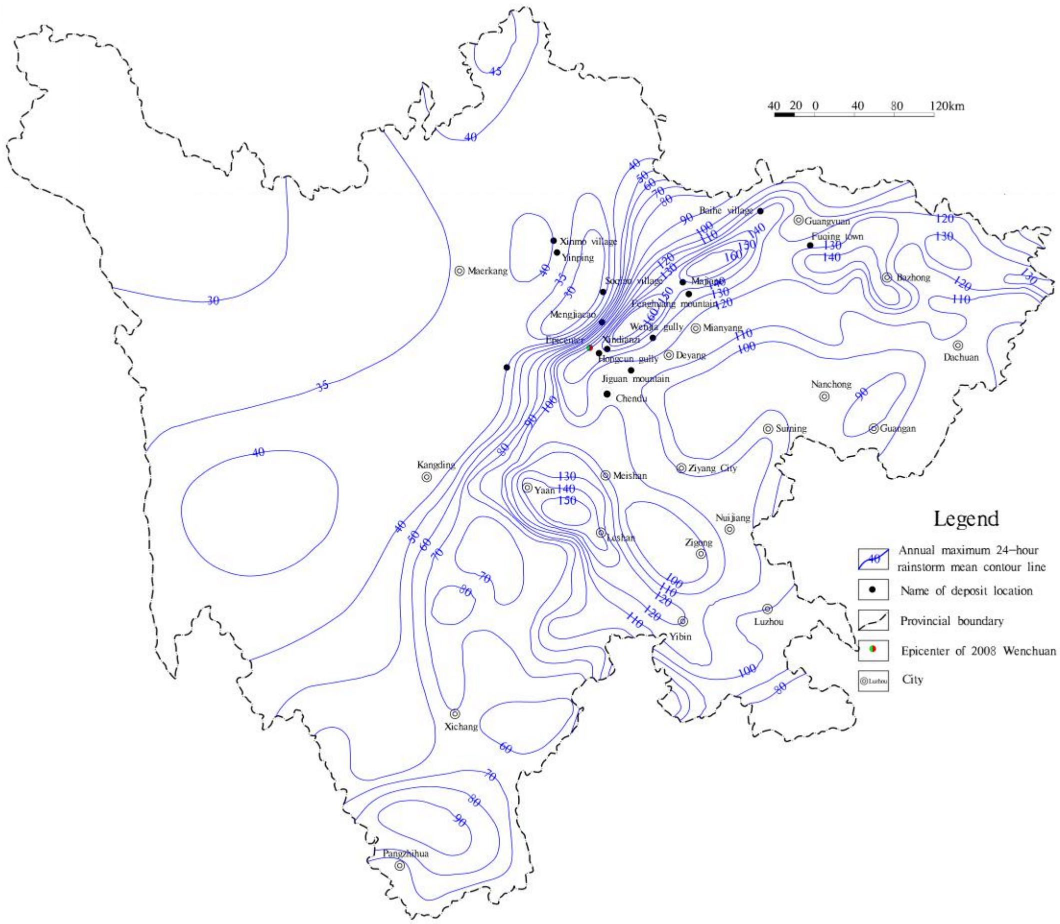


Fig. 4 24-hour rainfall in Sichuan Province

3. Investigation Methods

Field investigations were performed to understand the geological features in the area and the mechanism of the landslide deposits. The methods include outcrop observations and topographical measurements, as well as the use of drilling, trenching and pit exploration to investigate the internal conditions of loose deposits. Geological drilling and standard penetration testing (SPT) were also used to study the particle composition of some large loose deposits. Due to the complex and diverse lithology of the landslide loose deposits, the engineering geological profile of typical loose deposits is drawn based on the investigation and analysis of the lithology of the strata. Finally, based on a field survey of the representative large loose deposits slopes along the 50 km-wide Longmen mount fault zone, the deformation and failure mechanisms are analyzed. (Fig. 4).

The field investigation results reveal that the typical lithology of the deposit is bedrock, which consists of weakly weathered, moderately weathered and strongly weathered coarse and fine granite, limestone and sandstone. Under weathering or postearthquake weathering, the bedrock is covered with a large amount of loose clay, broken rock mass or a mixture of the two, which is the main component of the landslide sediments.

According to field investigation statistics for the Wenchuan earthquake area in 2010 (CGS), these deposits can be classified into four types based on the topography and type of movement (Cruden and Varnes, 1996), i.e., slide, rockfall, erosion, and debris flow representing 62.74%, 24.57%, 11.38%, and 1.31% of the deposits, respectively. The ratios of slide, rockfall, erosion and flow types are 41:29.1:28.6:0.4, respectively, in the plateau mountain areas. In the high to medium mountains in a transitional zone from the plateau to the basin, the slide of landslide deposits induced by the Wenchuan earthquake is the main failure mode (up to 65.3%), followed by the erosion mode with 26.6%, rockfall type with 6.5%, and debris flow with 1.6%. However, in the basin and mountain areas in Sichuan Province, the ratios of slide, rockfall, erosion and debris flow types are 66.9:31.1:0.5:1.5 (Table 1).

Table 1 Category of the landslide deposits in the study area

Topographic and geomorphic zoning	Type of movement			
	Slide	rockfall	Erosion	Debris flow
Plateau and alpine region	3105	2268	2166	34
High to medium mountain area	2311	231	940	57
Basin and mountain area	8361	3886	65	184
Total number	13777	6385	3171	275

4. Typical failure modes of loose deposits

4.1 Slide

The slide type of deposits is usually caused by the reconstruction of rock or soil slopes. Under the action of external geological forces, e.g., rainfall, aftershocks and human engineering activities, the loose deposits move along the weak surface or subsurface. According to topography, materials, motion characteristics, and on-site investigation, we classify the slide into four categories, including the rotation of the loose deposit, sliding along the weak interlayer, the shallow sliding of deep deposits and translation on bedding rock.

4.1.1 Rotation of loose deposits

A stable or almost stable ancient landslide deposit body is induced by the earthquake, and subsequently global or partial rotation may occur that leads to deformation and failure of the accumulation body under the effects of rainfall conditions, aftershocks and human construction activities. For instance, the Xindianzi landslide, located in Yinxiu town, Wenchuan County, obviously the epicenter of the 2008 Wenchuan earthquake, is a typical **rotation of loose deposits**

(Fig. 5). The source area of the Xindianzi old landslide is nearly 0.8 km long and 0.5 km wide, while the old slope angle is 25°～30°. The angle of the old main scarp behind the deposits is steep (45°～75°). The estimated volume of the deposits is 6×10^6 $m^{3,}$ and the landslide material is a single and homogeneous, mostly loose medium granular soil.

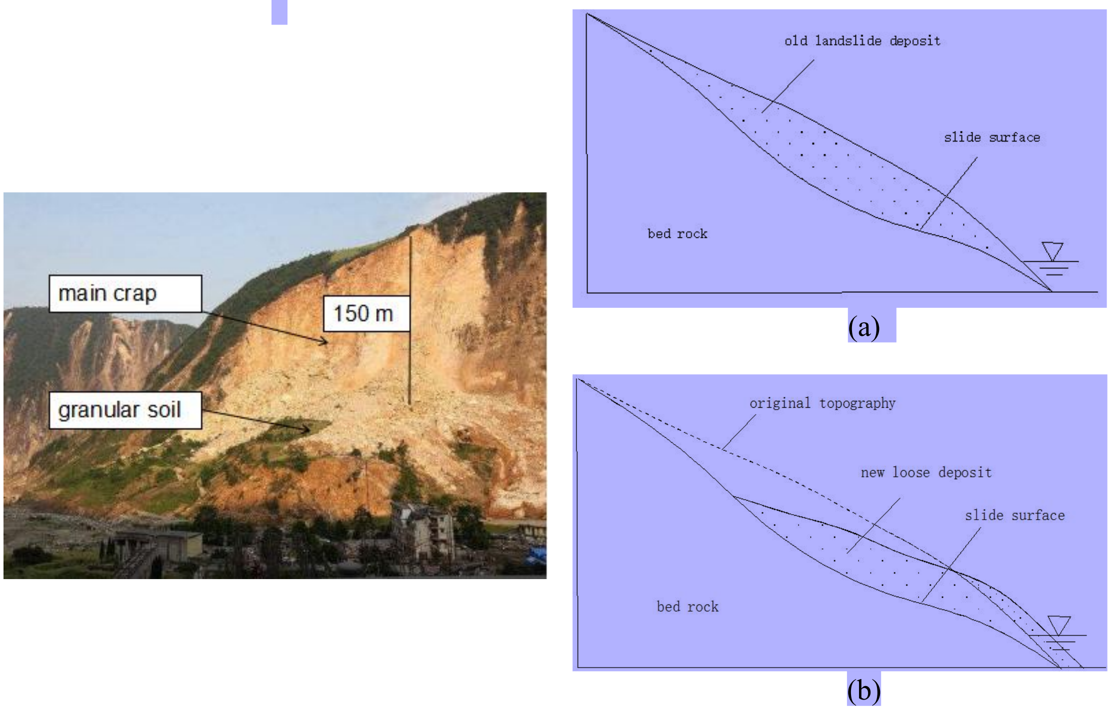


Fig. 5 A slow soil slide on the Xindianzi old landslide: (a) schematic of loose deposits before deformation and (b) schematic of deposits after failure showing that large homogeneous materials stop at the slope foot.

The creep and sliding deformation of the Xindianzi old landslide were slow at the beginning, but after the strong rainfall infiltration on August 11, 2010, and the slope excavation on the crown, the landslide displacement and deformation increased rapidly. The water content of this loose soil accumulation increased rapidly after the rainfall, and the gravity of the sliding body also increased. As a result, the shear strength of the main body composed of loose deposits decreased, and even the strength of the soil decreased, resulting in liquefaction. The loose granular structure and high sensitivity to rainwater softening are the basic conditions for the resurrection of ancient landslides, while the most significant localities with extra sensitive loose deposits are largely distributed around the Yingxiu-Beichuan main fault zone. A large number of rotations of loose deposits have also been found near Mount Tangjia (Hu, 2009)

4.1.2 Slide along with the weak interlayer

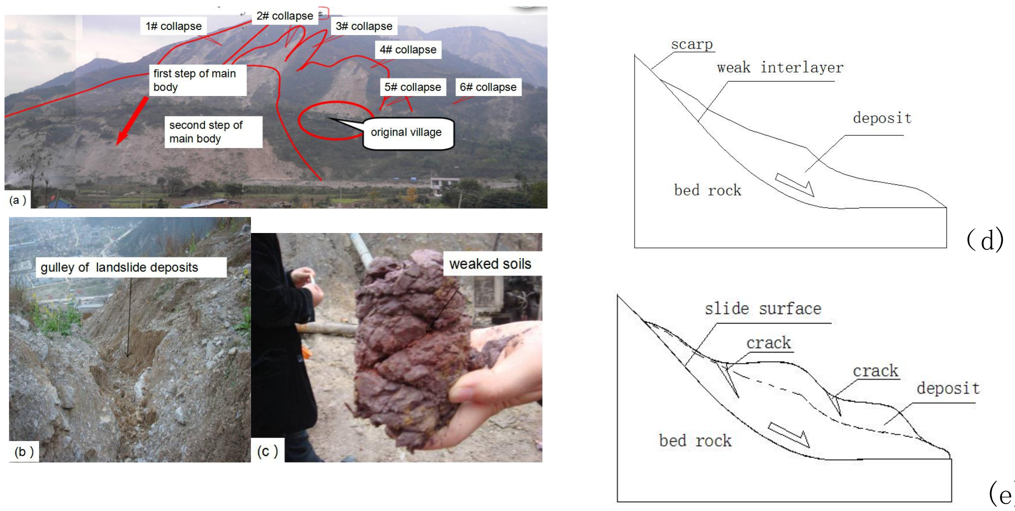


Fig. 6 The landslide that occurred at Fenghuang Mountain, Sichuan, China, in 2011: (a) image of Fenghuang Mountain landslide; (b) Gully at the trailing edge of a landslide; (c) soft crushed soil from drilling; (d) Schematic of loose deposits before failure; and (e)Schematic of loose deposits after failure.

Slides along with the weak interlayer usually occur in deposits with weak substrate. The main body consists of loose deposits, broken rocks, and their mixtures. The weak interlayer consists of plastic-soft clay or clastic sediments, and the bedrock usually consists of fully weathered-weathered shale, mudstone or sandstone. Before the deformation of the rock and soil in the weak interlayer occurs, the landslide generally moves slowly, and the moving speed is usually less than 0.1 m/a. However, under the influence of earthquakes, rainfall and human engineering activities, the loose deposit will suddenly accelerate in the case of the transfixion of a weak interlayer or a weak zone (Huang, 2011).

The Fenghuang Mountain landslide is located in Ershe village, Leigu town, Beichuan County, with a total volume of approximately 1.08×10^6 m^3; it is a slide on a weak interlayer, and the landslide deposit is nearly 420 m long and 1560 m wide, with an average slope angle of 25°, which is affected by deformation. The main scarp is 25 m high on average, presenting two moving steps, with a horizontal distance of 167 m and a height of 80 m. The middle of the deposit is 111.6 m thick, 94 m thick at the slope toe and 58 m thick at the slope head. Most of the material in this landslide deposit is composed of limestone, carbonaceous shale, silty clay, crushed stone or pebbly clay. The soil sample exposed by drilling is characterized by kneading and water absorption, suggesting that the soil sample is subjected to high compression and grinding. According to geological hazard monitoring, the slip velocity of this accumulation body is 0.08 m/year. Excavation of the road at the toe of the slope resulted in the rapid downward movement of the deposit along the weak interlayer (Fig. 6).

4.1.3 Shallow slide of deep deposits

A shallow slide on deep earthquake deposits generally occurs in highly consolidated deep rock and soil. The velocity is extremely high (often greater than 0.1 m/a), and sometimes the surface fragmentation of the soil accelerates as the slope increases throughout the movement. This type of failure is caused by earthquakes, rainfall or human activities and leads to the deterioration of the structure and strength of the shallow surface of the stratum, followed by the creep and sliding deformation of the shallow part of the deposit body (Fig. 7).

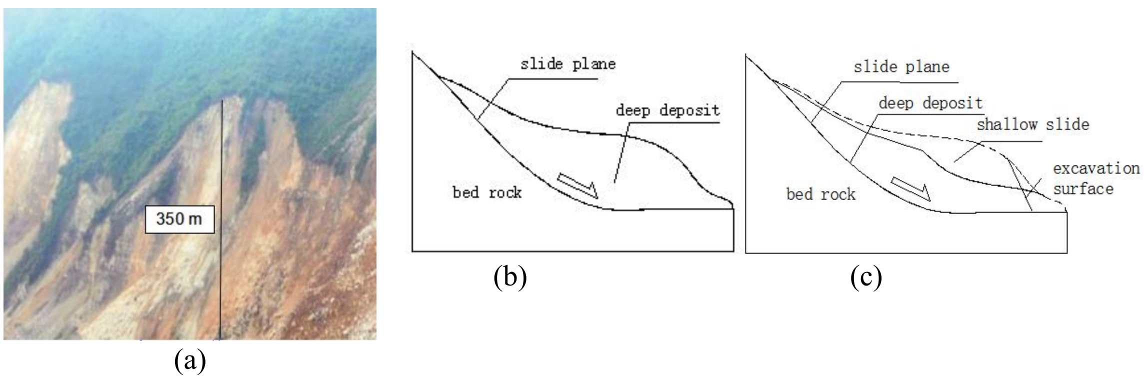
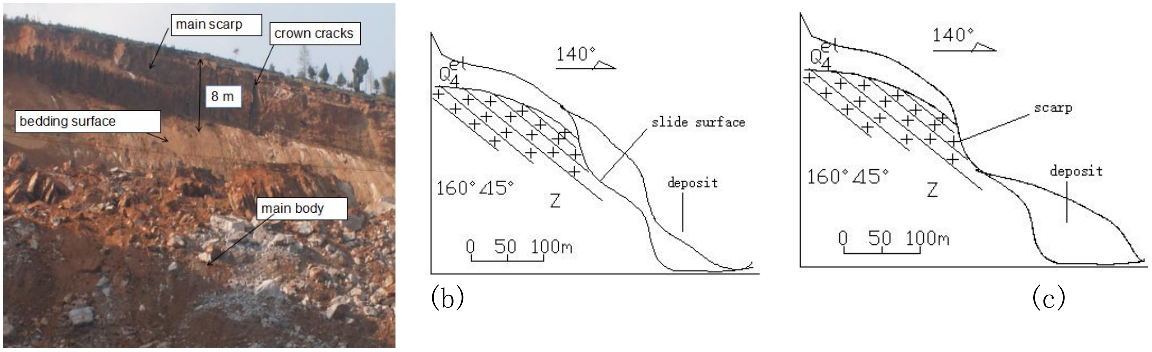


Fig. 7 Majiapo landslide in Beichuan County: (a) photograph of a shallow slide in the Majiapo shallow landslide, Sichuan Province, China; (b) schematic before failure; and (c) schematic after failure.

The Majiapo landslide, which is nearly 330 m wide and 230 m long, is located in Yuli town, Beichuan County. The landslide volume is nearly 4×10^5 m^3, and the main body is less than 10 m thick. The landslide deformation was very slow before the Mount Tangjia earthquake lake was formed. However, after the toe of these deposits was submerged by the water, the shallow landslide moved quickly. The landslide deposits have a steep ($25°\sim45°$) slope angle approximately 28 m high. The composition of the deposits is largely gravelly soils with highly weathered phyllite and slate (50-60%). Likewise, these shallow landslides are known to occur both on the surface land and under the earthquake lake water.

4.1.4 Translation on bedding rock

Translation on bedding rock generally occurs in loose rock deposits with a forward gentle laminar rock layer. The topography of this failure mode is characteristic of V-shaped or U-shaped valleys. These slopes are composed of medium-to-sloping layered rocks. They may slide along the bedding plane under the action of their weight or load, or they may incur deformation and failure caused by external loads, such as rainfall or earthquakes.



(a)

Fig. 8 Photograph and schematic of a slide in Fuqing town, Wangchang County, Sichuan Province, China, in 2011.

A translational landslide is located in Fuqing town, Wangchang county, Sichuan Province. The landslide was formed during the 2008 Wenchuan earthquake, and the tectonic crown cracks were 0.5-1.0 cm wide and 1-2 m long or 0.5-0.8 cm wide and 2-3 m long. The landslide, with a deposit area of 1.36×10^4 m^2 and a total volume of 1.31×10^5 m^3, occurred after constant rain in July 2011. The formation lithology in the landslide deposit primarily consists of sandstone of the Triassic system (*T*) and Quaternary residual slope alluvial soil (*Q*). The angle of the bedding rock is steep (more than 35°), and the main body is 9.6 m high on average, of which the main scarp is 8 m in height. The remaining unstable landslide height of 8 m may slide suddenly in the future. According to field reconnaissance, the velocity of this landslide is 0.5 m/year, and rainfall infiltration and a weak surface along the bedding limestone are the main failure factors (Fig. 7).

4.2 Rockfall

Rockfall is produced in steep slope deposits under external forces, including gravity, earthquakes, weathering denudation or human activities. It is a single or compound movement with sharp fall, caving, sliding, rolling, jumping, and other special forms; sometimes rocks hit each other in the process of movement and then pile at the slope toe (Rens, 2008). Most of the rockfall sources are rock deposits with low shear strength and 2-3 groups of penetrating fractures. Whether rockfall occurs depends on the deposit steepness and deposit stability. Based on the rockfall travel velocity and movement method, the rockfall type can be split into the following three subtypes.

4.2.1 Rockfall slide

The Xinmo catastrophic rockfall sliding avalanche is a recently famous massive rockfall in the Wenchuan earthquake area, with 10 deaths and 73 people missing. These massive deposits are located in Xinmo village, Diexi town, Mao County, Sichuan Province. This event may have originated from the 1993 Diexi Ms 7.3 earthquake, which caused several cracks in the crown of the slope. Besides, after a long period of weathering, rain erosion, and the 2008 Wenchuan Ms 8.0 earthquake, the trailing edge fissure on the slope stretched downward and finally passed, and then the massive rock mass traveled more than 2 km. The total volume of the rock mass deposit is approximately 4.5×10^6 m^3, it is approximately 210 m long and 300 m wide, and the fastest traveling velocity of the massive loose landslide deposit is approximately 74.6 m/s (Fig. 9) (Xu, 2017; Fang, 2017; Meng, 2018).

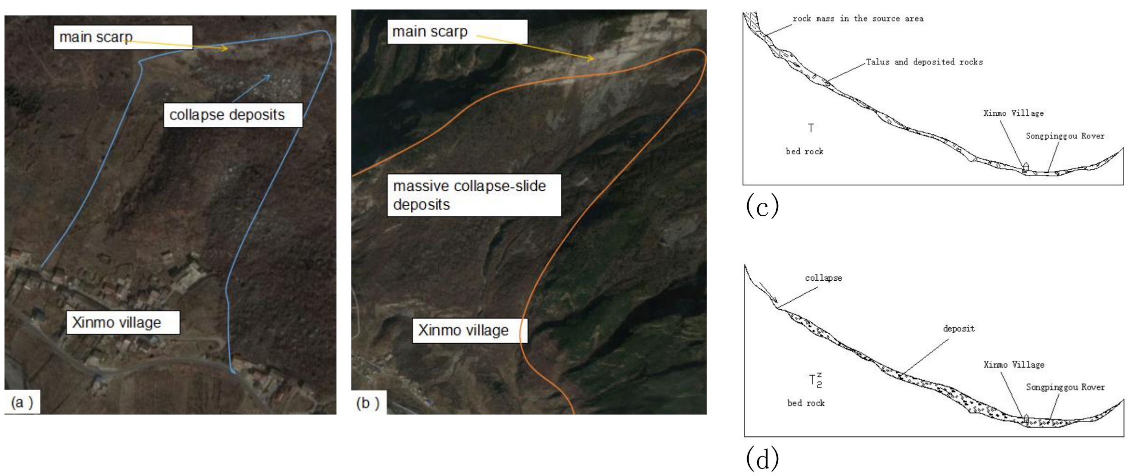


Fig. 9 Photograph and schematic of the massive rockfall in Xinmo village, Diexi town, Sichuan, China, in 2017: (a) photograph of the rockfall deposits on May 10, 2017; (b) photograph of the massive rockfall-slide deposits on May 20, 2018; (c) schematic of the massive deposit before failure; and (d) schematic of the massive deposit after failure.

Massive rockfall-sliding is one of the catastrophic disasters that pose threats to people's lives in earthquake areas. If the loose deposits consisted of densely structured rocks and joint fissures that had an unstable effect on the rocks that were extensively distributed, fractures would be formed through a plane. Subsequently, under the action of multiple earthquakes and long-term gravity, aging deformation is generated. Under the continuous rainfall infiltration, the water level in the loose accumulation body continues to rise, and the anti-slip force decreases., the stability of the loose deposits slope decreases, and a catastrophic landslide may occur suddenly.

4.2.2 Crack-slide rockfall

A crack-slide rockfall is a form of a steep slope characterized by steep and vertical fractures on the crown of the slope, occurring when loosely cemented material or rock layers move a short distance and dump at the toe of the slope (Tarbuck, 1998). Although the surface of the slope displacement is small, deep crown cracks are formed by rain infiltration, earthquakes, or weathering (Fig. 10). Moreover, the gravity of overburden deposits based on the weak layer increases in the process of rainfall, thereby causing deposits to fall gradually along a parallel surface. This deformation mostly occurs in the consequent bedding landslide deposits.

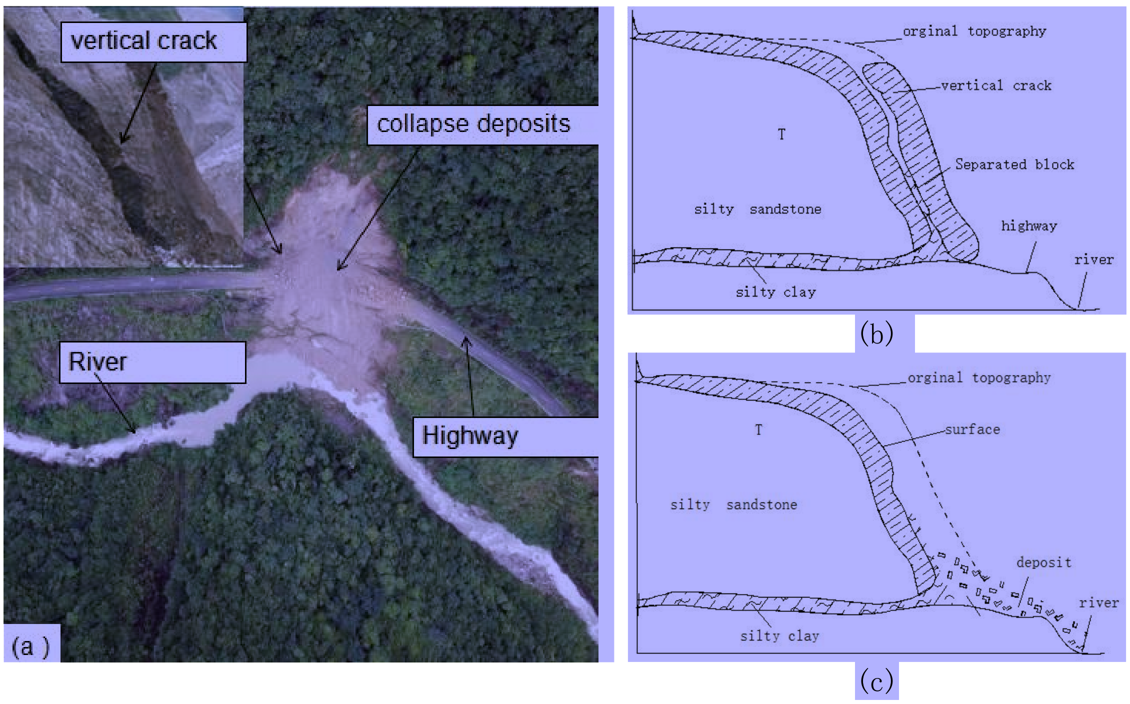


Fig. 10 Aerial photograph and schematic of crack-slide rockfall in Jiguan Mountain, Chongzhou city, Sichuan, China, in 2018: (a) aerial photograph of Jiguan Mountain; (b) schematic of loose deposits before failure; and (c) schematic of the crack-slide rockfall.

The Jiguan Mountain crack-slide rockfall, which is approximately 40 km south of the epicenter of the 2008 Wenchuan earthquake, occurred on July 9, 2018. Fig. 10 shows an aerial photograph of the rockfall. At the crown of the rockfall, there were several vertical cracks approximately 2.5 m deep. The rockfall deposits were approximately 250 m wide and 560 m long with a total volume of approximately 3.8×10^{6} m^3. Most of the materials in the deposit were primarily composed of silty sandstone and limestone that formed in the Triassic period of the Mesozoic era. In the area where the rockfall occurred, the artificial slope was 7.5 m high with an angle of over 70° and covering considerable underlying rocks on the consequent bedding sandstone layer.

4.2.3 Toppling rockfall

Toppling failure is one of the most common failure forms of rock deposit slopes in strong earthquake areas. The main failure mode of the toppling failure is bending and overturning, which is caused by bending stress. Toppling generally occurs in steep rocks with vertical joints. Moreover, soft rock and hard rock interbedded sedimentary strata often undergo toppling failure. When the lower soft interlayer is weathered or eroded by rainfall, the upper loose accumulation body is suspended, falls and rebounds or rolls downhill under the action of gravity. Toppling rockfall is characterized by breaking rocks and discontinuous structural cracks, usually triggered by earthquakes or human activities (e.g., hydropower station building, highway building, and other works) (Guo, 2017). In addition, effective intergranular stress would decrease in the deposited material due to the increase in internal seepage pressure and the decrease in pore water pressure, thereby causing a rockfall. This deformation failure model can be defined as toppling rockfall.

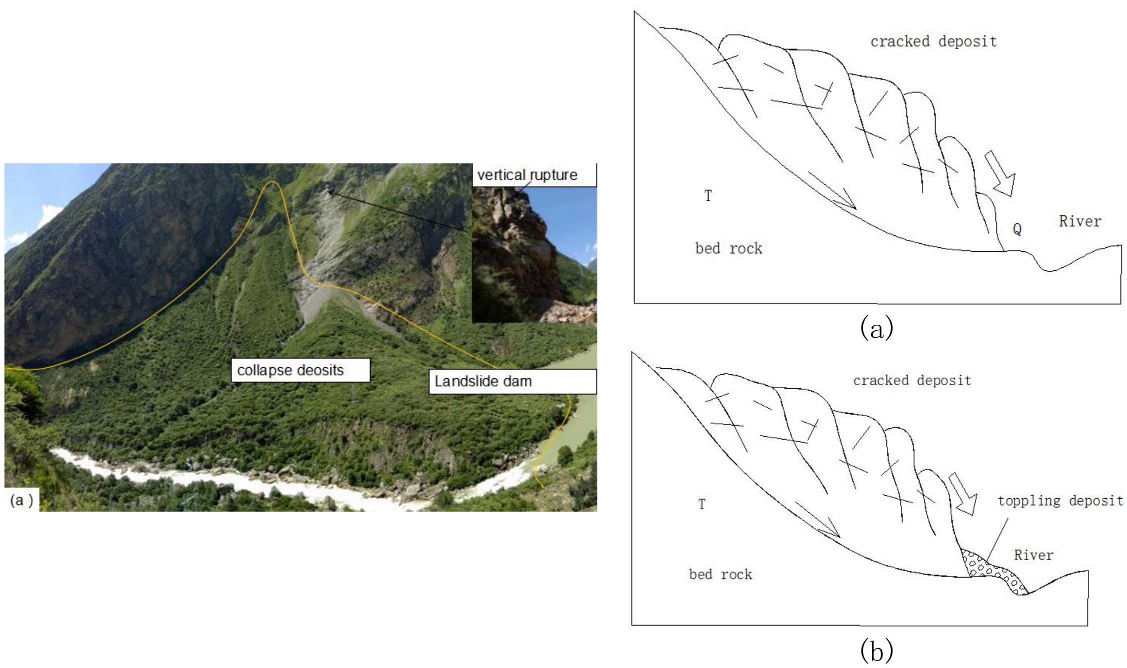


Fig. 11 Aerial photograph and schematic of toppling rockfall at Yinping, Mao County, Sichuan, China: (a) aerial photograph at Yinping; (b) schematic of toppling rockfall before failure; and (c) schematic of toppling rockfall after failure.

For instance, the Yinping toppling rockfall was triggered by the 1933 Diexi Ms 7.3 earthquake and the 2008 Wenchuan earthquake. These rockfall deposits formed from 1993 and blocked the Min River. The geostructure of this landslide dam is featured by the consequent bedding structure and cliff. Because the rock has been falling for 85 years, the rockfall deposits are approximately

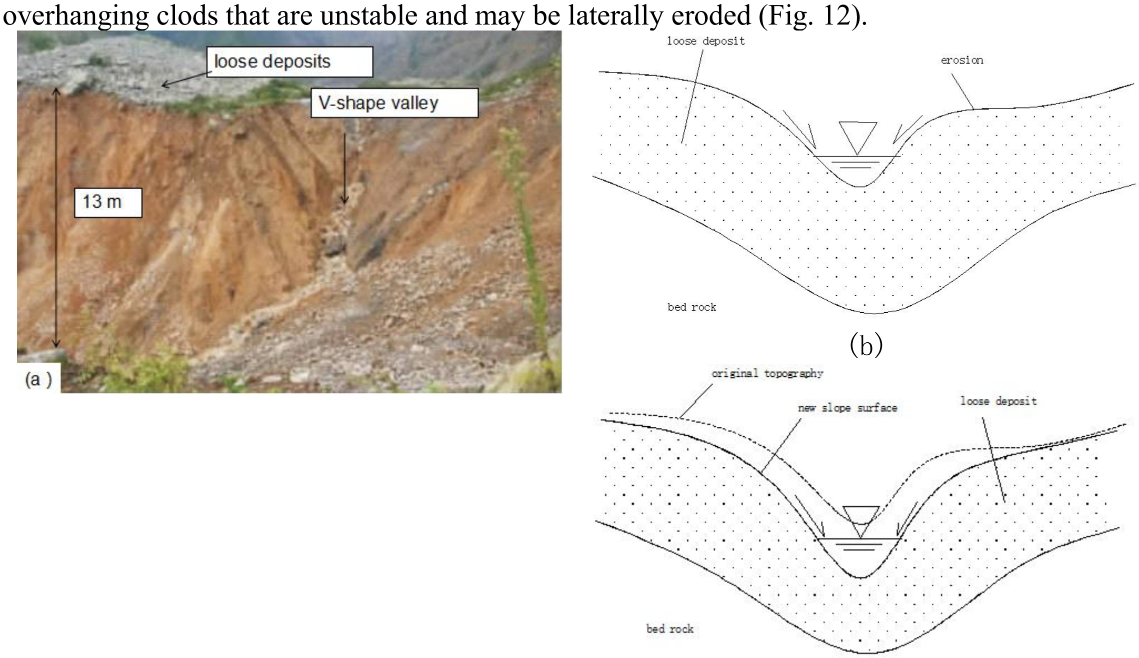
1000 m wide and 1500 m long, and the rockfall rock travels a distance of more than 1400 m (Huang, 2009). After the 2008 Wenchuan earthquake, the average thickness of the rockfall deposits was over 180 m, and the total volume was over 2.1×10^{8} m^3. The stratigraphic lithology of such landslides is generally composed of quaternary (Q) residual slope sediments, Triassic metamorphic rocks and crystalline limestone (T).(Fig. 11).

4.3 Erosion

Erosion often occurs in loose deposit bodies induced by rainfall or flow in areas with undulating landscapes. This mode of motion is usually a spatially continuous motion, and the deposit is carried away by the current from high to low elevations. These processes contribute to the formation of unstable rock and soil masses on the surface of gullies during different courses of geological erosion (J. Dvorak, 1994), deformation and destruction, and the deposits finally move with the grading movement of mud (sand) flow, which depends on the water content, mobility and movement evolution.

4.3.1 Sheet erosion

Sheet erosion has two main mechanisms: scouring and lateral erosion. River erosion is the direct removal of soil particles by the current. The rate of scouring is determined by the impact of the flow and the erosion resistance of the bank's loose deposit material. When the weight of the upper deposit is greater than the strength of the slip zone, the failure will occur subsequently, resulting in lateral erosion. The process depends on many factors, including the particle composition of the slope material, the water content and the coverage by vegetation. These two erosion processes are interrelated because the scouring at the bottom of the riverbank produces steeper slopes or overhanging clods that are unstable and may be laterally eroded (Fig. 12).



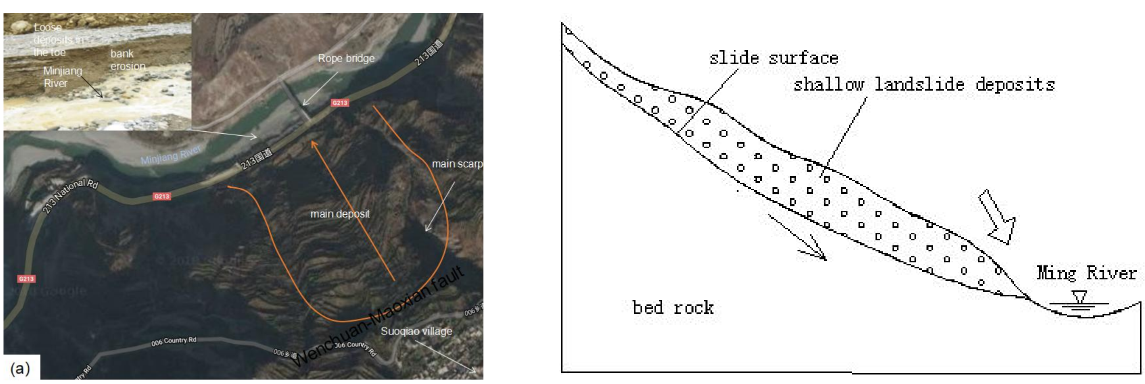
(c)

Fig. 12 Schematic and photograph of sheet erosion of loose deposits at Baihe Village, Qingchuan County, Sichuan Province, China, in 2014: (a) photograph of sheet erosion of the Baihe deposit; (b) schematic of deposits before the failure; and (c) schematic of deposits after the failure.

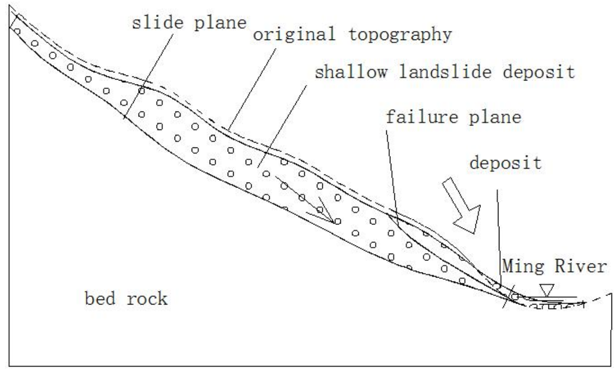
This type is primarily formed on the surface of loose deposits, and both sides of the slope usually have U-shaped or V-shaped canyons. Sheet erosion will be strengthened if the process occurs on a hillside with less vegetation or on both sides of gullies that have lost vegetation by earthquake or mining deforestation. Under heavy rain and extreme rainfall conditions, the upstream water continuously washes away the loose deposits, thereby causing the slopes on both sides of the valley to be washed repeatedly, and the valley section gradually expands and deepens, finally causing slope failure (Fig. 12). For instance, the sheet erosion of deposits near Baihe village, Qiangchuan County, Sichuan Province, China, in 2014, which destroyed 15 houses and caused 3 deaths, are underlain by sericite phyllite of the Silurian system (S). After thousands of years of erosion, the erosion efficiency determines the speed of the material in the rockfall process, so the erosion accelerated after the Wenchuan earthquake.

4.3.2 Gully erosion

Gully erosion often occurs at the toe of loose deposits that are damaged and washed away by a stream, river or floods. Due to the scour, dredging and erosion by water currents, the upper part of the deposit is not balanced, resulting in local downward cutting or rockfall as the deformation mode. This study has a typical example of stream bank erosion of the slope deposit in Soqiao village, Wenchuan County, Sichuan province, China (Fig. 12)(Yang, 2012).



(b)



(c)

Fig. 13 Schematic and photograph of bank erosion in Rope bridge/Soqiao village, Wenchuan County, Sichuan Province, China, in 2014: (a) photograph of gully erosion of the bank deposit; (b) schematic of deposits before the failure; and (c)schematic of deposits after the failure.

Streambank erosion in Suoqiao village is located on the left bank of the Minjiang River, which has a middle mountain canyon landform. The deposit is approximately 200 m wide and 220-250 m long, while the main body area is approximately 3.88×10^4 m^2 with a total volume of 6.52×10^5 m^3. Most of the material in the toe is gravelly soil, including 10%～30% phyllite and limestone debris. The movement of the eroding bank is slow in winter, but the loose deposits move faster in the rainy season. The Suoqiao deposits are unstable because of the bank erosion at the toe, and it has a weak sliding surface. Accordingly, landslides are expected to occur in future heavy rain or earthquake conditions.

4.3.3 Debris flow cutting

Debris flow cutting typically occurs on a slope of loose deposits with a slope up to 45° and is usually initiated during heavy rainfall, with upstream materials driven by a rainstorm or debris flow. When the water accumulates rapidly upstream, a debris flow will form in the middle and lower reaches, subsequently rushing out of the channel, and cutting the slope foot, which results in a steep exposed surface. The existence of these loose materials on the slope and the development of heavy rainfall events are the main reasons for the deformation and failure of these deposits (Xu, 2012).

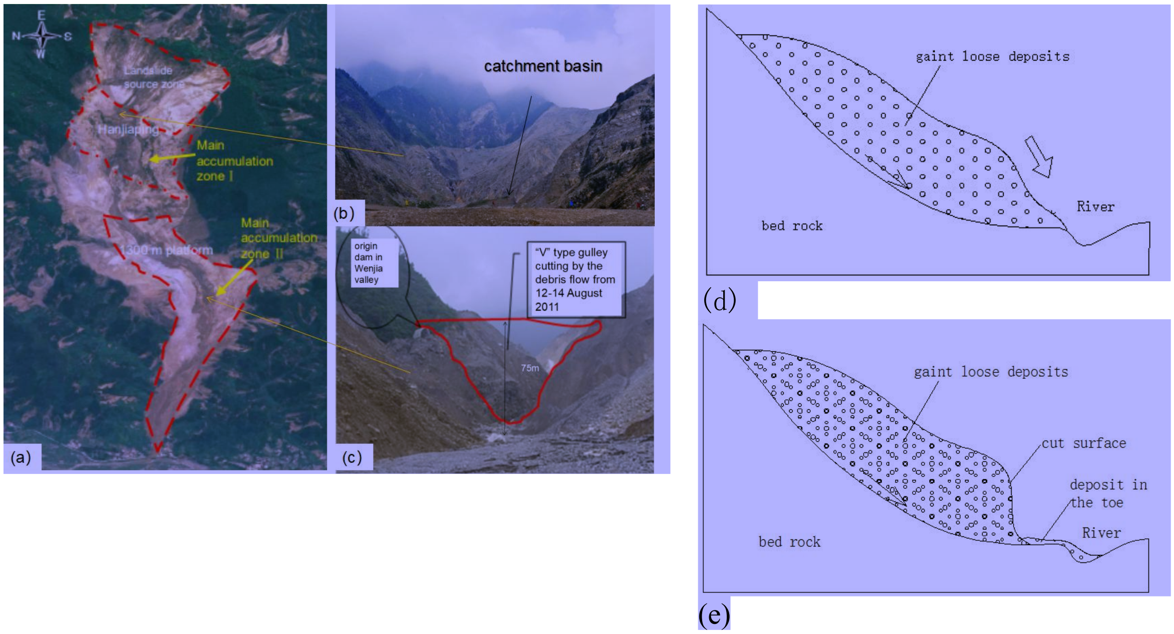


Fig. 14 Schematic and photograph of debris flow cutting in Wenjia gully, Qinping town, Sichuan Province, China, in 2010: (a) aerial photograph of Wenjiagou deposits; (b) photograph of upstream debris flow deposits; (c) photograph downstream of the Wenjiagou debris flow deposits; (d) schematic of the deposits before the failure; and (e) schematic of the deposits after the failure.

The famous debris flow cutting type is in Wenjia gully, which is located north of Qinping town, Mianzhu city, Sichuan Province, China. The catastrophic deposits were formed by the 2008 Wenchuan earthquake and have experienced several events of heavy rain and continuous rain. From September 2008 to September 2011, six large-scale debris flows were formed, which seriously endangers the safety of life and property downstream. The accumulation body has a relative height difference of 1.49 km and a ditch length of 4.9 km, and the overall slope dropped by 306%. The profile of the accumulation body shows three-level platform accumulation with the upper slope, middle and lower level. The trailing edge and the leading edge of the accumulation body of Hanjiaping, the first-level platform, are both steep (the gradients are 673.8‰ and 644.4‰, respectively), which significantly contributes to the formation of the catchment power accelerating the discharge. The slope falls of the secondary platform (1300 m) and the tertiary platform is relatively small (140.3‰ and 322.5‰, respectively), whereas the ditch is deep and narrow and the accumulation body exhibits a large loose thickness, which makes it extremely easy for erosion and erosion cutting deformation and failure.

4.4 Flow

4.4.1 Rock avalanche

The rock avalanche originated from collapsing material caused by the earthquake. Because of the steep slope, scarce vegetation and extremely loose structure of the deposit, combined with exterior geological forces (e.g., aftershocks and human activities), debris flow material in a superficial layer of loose deposits slipped downward with high speed, accompanied by the flow of dust and the sounds of tumbling rocks.

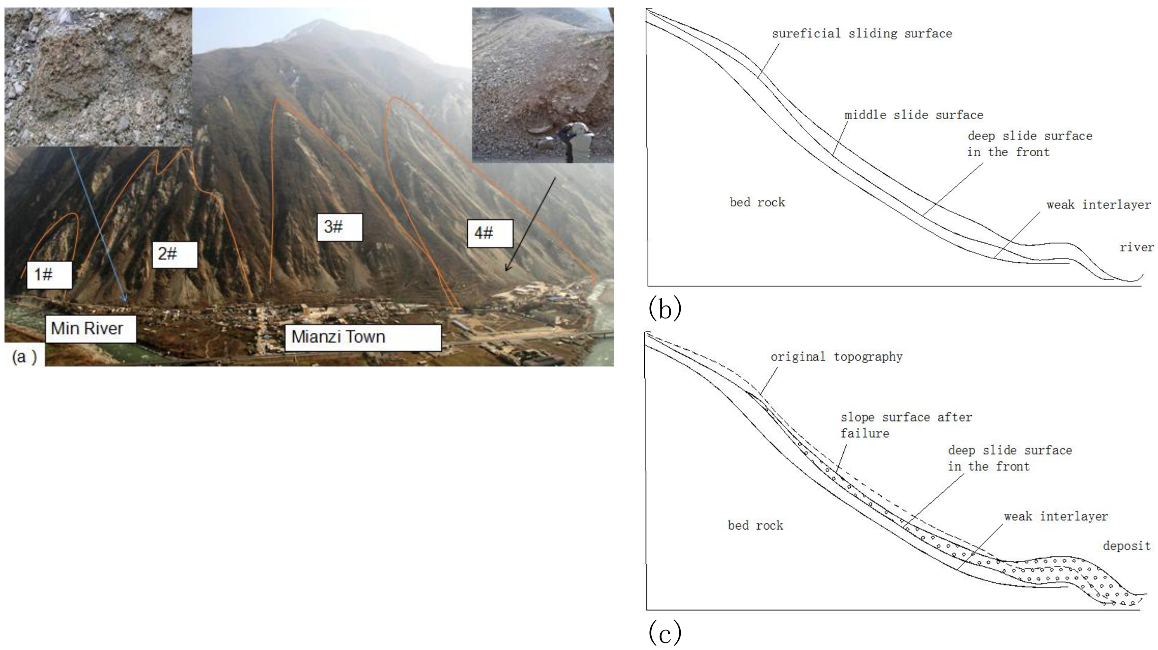


Fig. 15 Photograph and schematic of the rock avalanche at Mengjiacao, Mianzi town, Wenchuan, Sichuan, China: (a) photograph at Mengjiacao; (b) schematic of toppling rockfall before failure; and (c) schematic of toppling rockfall after failure.

Since 2008, there have been hundreds of rock avalanches induced by rainfall or aftershocks in the Wenchuan earthquake area. The speed of the avalanche chute to the steep channel is usually more than 10 m/s, whereas some of the landslide flows are much faster. For instance, the Mengjiacao rock avalanches, located in Mianzi town, approximately 10 km south of Wenchuan County, Sichuan Province, are typical avalanche flows in this area. Because of the rockfall flow since 2008, the rock or soil has accumulated at the toe of the slope, and the total volume of these deposits is over 2.5×10^6 m^3. The materials of these landslide-debris flows contain characteristics of the loose coarse and fine particles that are distributed in the different rockfall areas. The landslide debris in the steep channels usually attains speeds of over 12 m/s (Fig. 15).

4.4.2 Debris flow

Although the number of mudslides in the Wenchuan earthquake area is only a small proportion, accounting for about 1.31% of the total number of mudslides in the country. But because of the loose deposits, mudslides occur more frequently in the region than in other parts of China, attracting a lot of attention from engineers and the government.. For instance, the Hongchun gully debris flow occurred near Yinxiu town, Wenchuan County, Sichuan, on August 14, 2010, resulting in 17 missing persons. The debris flow has battered the new 213 National Highway, blocked the Min River, and then destroyed Yinxiu town (Fig. 16).

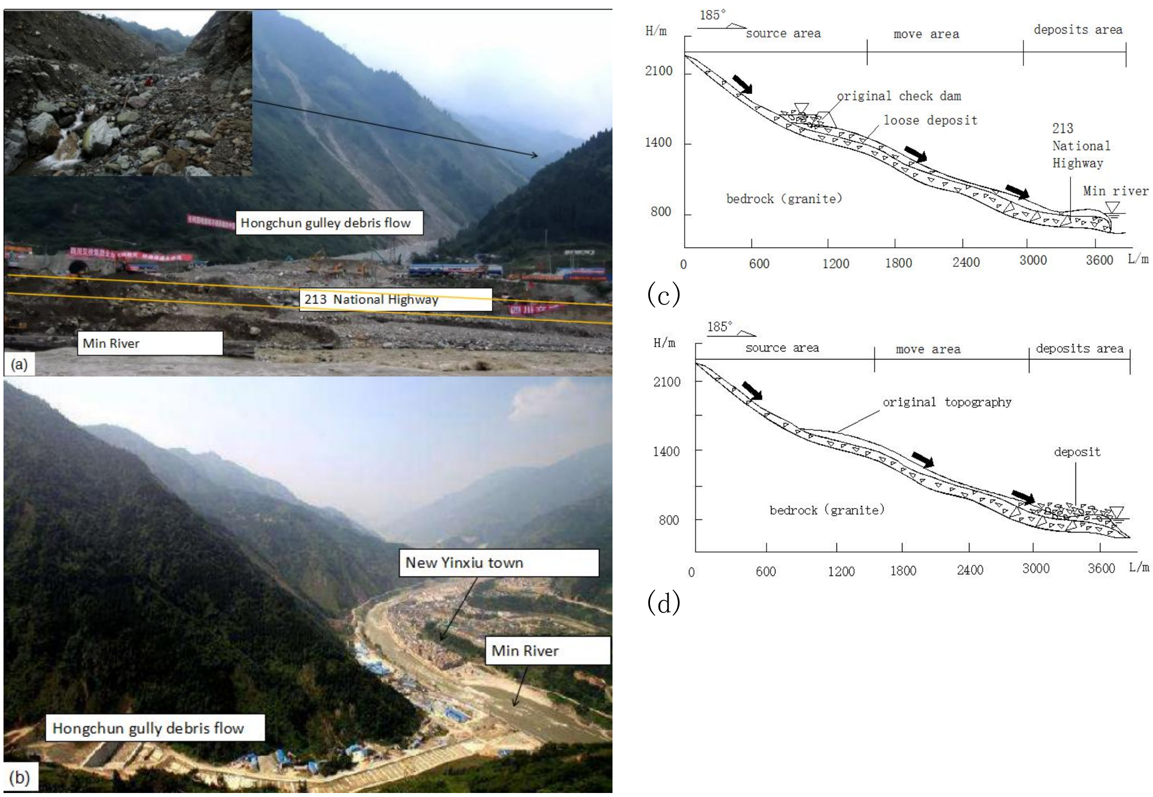


Fig. 16 Photograph and schematic of debris flow at Hongchun gully, Yinxiu town, Wenchuan, Sichuan, China: (a) photograph at Hongchun gully in 2009; (b) image of Hongchun gully in 2018; (c) schematic of debris flow before failure; and (d) schematic of debris flow after failure.

The Hongchun gully debris flow is one of the 72 debris flows near the Beichuan-Yinxiu fault in August 2010, which is characterized by the number of loose deposits, the steep drop in the shape of the gullies and critical rainfall (Tang, 2009). The total volume of this debris flow is nearly 80.5 $\times 10^4$ m^3, and all of the loose materials of the debris flow are composed of granular soil (60%), boulders (25%), rubble (10%) and sand (5%). The channel catchment area covers 3.35 km^2, the main channel length is 3.6 km, and the average longitudinal slope of the channel reaches 35.8%. The top of the slope is 2168.4 m asl, and the gully mouth of debris flow is at 700 m asl. The debris flow materials mainly come from three branches in the upper reach of the Hongchun gully, among which 52% are landslide or rockfall deposits, and the total amount of loose solid material is 3.57×10^6 m^3. Moreover, because the rainfall prior to the “8.14” debris flow outbreak in Hongcun gully was 16.4 mm per hour and the total rainfall reached 162.1 mm in 34 hours, heavy rainfall was the inducing factor of the debris flow outbreak (Gan, 2012).

5 Discussion

Previous studies have suggested that different types of accumulation slopes have significantly different deformation and destruction mechanisms and failure modes (Zhang, 2012; Cui, 2014; Huang, 2015). Controlled by various factors (e.g., rock and soil mass structure, geological structure, rainfall, and geography and geomorphology) of the study area, the accumulation body presents different deformation and failure modes, and its movement type, speed, scale, geomorphology, landform and failure modes are also different (Table 2).

Table 2 Table of characteristics of deformation and failure of loose deposits in the Wenchuan earthquake area

Failure type of landslide deposits		Topography	Material	Travel velocity	Volume	Triggering mechanism
slide	Rotation of the loose deposit	Mountain, Hill, Talus	Gravel, Sand, Clay, limestone	Various	Small to Large	Rainfall, Earthquake, Human activities
	Slide on weak interlayer	Mountain, Hill	Weak rock, Gravel, Sand, Silt	Slow	Large	Rainfall, Earthquake, Human activities
	Shallow slide of deep deposits	Mountain, Hill or Valley	Gravelly soils, Weathered rock,	Slow to Ex. Rapid	Small	Earthquake, Weather, Human activities
	Translation on bedding rock	Talus, Mountain	Consolidated Soils, Rocks	Slow	Large	Earthquake, Rainfall, Human activities
rockfall	Rockfall-slide	Mountain	Rock, Soil	Rapid	Small to Large	Weathering, Rainfall, Earthquake
	Cracking sliding of rock rockfall	Mountain, Hill	Rock	Slow to Ex. Rapid	Small, Middle	Weathering, Rainfall, Earthquake
	Toppling rockfall	Steep Cliff	Rock	Rapid	Small to Large	Weathering, Rainfall, Earthquake

erosion	Sheet erosion	Valley, Gully	Loose Soil or Clay, rock deposits	Slow	Small to Large	Rainfall, Weather,
	Gully erosion	Valley, Gully, River	Soils, Sand, Silt	Slow to Ex. Rapid	Small to Large	Rainfall, Weather
	Debris flow cutting	Valley, Gully	Rock，Sand	Ex. Rapid	Middle，Large	Rainfall, Weather
flow	Rock avalanche	Mountain	Rock, Clay	Slow to Rapid	Small, Middle	Earthquake, Weather, Rainfall,
	Debris flow	Mountain, Hill, Valley	Stone, Soil, Sandy gravel	Ex. Rapid	Middle, Large	Rainfall

It is worth noting that topography is a factor that significantly affects the failure of landslide deposits. It also determines the scale, shape and deformation and destruction mode of these accumulation slopes. Macroscopic topography controls the development and distribution of deposit bodies. Slopes with different gradients, heights, shapes and vegetation significantly affect the disaster mode of landslide deposits.

There was no clear relationship between the failure mode of the deposits and the observed particle sizes. Deposits are composed of fine-particle soil (e.g., sandy soil, gravel soil, and clay) that can cause sliding, erosion and debris flows. Deposits composed of medium and coarse particles can also fail as long as there is sufficient rainfall. The precipitation process of the rainfall intensity significantly affects the formation of debris flows. This study suggests that continuous rainfall and rainstorms can lead to different failure modes through the same deposits with the same particle sizes. Vegetation and its root system can lessen erosion and protect the deposits from being eroded by rainwater. Investigations reveal that deposits with well-developed vegetation primarily form slip-type deformation and destruction, and it is unlikely to develop into erosion or rockfall. In contrast, rockfall or erosion deformation and destruction often occur in places with poor development or underdeveloped vegetation in landslide deposits.

Moreover, the formation of accumulations was controlled by geological structure. The closer the distance to the Longmen Mountain seismic fracture zone, the greater the seismic forces, and the structure of the accumulation becomes loose to form debris flows, which may likely be transformed into the rockfall type and erosion if the landslide deposit produced is much closer to the fracture zone. Investigations reveal that the failure of landslide deposits in the Wenchuan earthquake area was primarily developed in rock and rock-soil (e.g., granite, quartzite, dolomite, and limestone). Translation on bedding rock mostly occurred in rock deposits composed of hard rock at the top and weak rock at the bottom. Deposits are largely composed of rocks at the top with a highly compacted density and weak structural bedding surface, thereby easily inducing a slide on a weak interlayer. Most giant landslide deposits are located on the steep slopes near the Longmen Mountain fault belt, and it is extremely easy to produce catastrophic landslides or debris flows.

6 Conclusions

Previous classification studies on loose deposits were based primarily on the material, velocity, water content, geotechnical parameters, and other geological hazards, and the effects of topography, landform, volume, and triggering mechanisms were generally not considered. This paper presented a world-recognized classification improvement from the perspectives of the topography, velocity, material, volume and triggering mechanism of loose deposits in a strong earthquake area. Thus, the basis of these factors in this classification is comprehensive and especially suitable for the actual classification of geological disasters in the meizoseismal area, which helps provide a scientific basis for the prevention and control of geological disasters.

According to the results of field investigations and statistical analysis, there were four main types and 12 subcategories of failure modes in the loose deposits after the 2008 Ms 8.0 Wenchuan earthquake area as follows: (1) slide, including rotation of the old deposits, slide along the interlayer, shallow sliding of deep deposits and translation on bedding rock; (2) rockfall, including rockfall-slide, cracking-sliding rock rockfall, topping soil rockfall and debris flow cutting; (3) erosion, e.g., sheet erosion, gully erosion and debris flow cutting; and (4) flow, e.g., rock avalanche and debris flow. The investigation on hotspots in the Wenchuan earthquake area, Sichuan Province, suggests that the failure mode of the loose deposits was mostly of the slide type, some of which may have occurred as rockfalls and erosion, and the fewest failures were debris flows.

The categories of failure modes in landslide deposits proposed here can serve as a preliminary hazard and risk assessment. More reliable assessments should consider the geotechnical investigation method and means under various conditions and rely on accurate geological analyses of landslide deposits. These massive deposits are still highly likely to induce geological disasters under the effects of rainfall, earthquakes or human activities. Accordingly, the prediction and stability evaluation of the deformation and damage of loose deposits formed by strong earthquakes remain a matter of great concern.

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