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The 2008 Wenchuan Earthquake Induced Landslides and Associated Rainfall Induced Debris Flows

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Abstract

The 12 May 2008 Wenchuan earthquake (Mw = 8.0) induced widespread and large scale landslides over an area of about 50,000 km^2, some of which also produced many fatalities and extensive damage to housing settlements and irrigation channels. In addition, highways and bridges were destroyed, and the city of Wenchuan and many other towns became isolated. The Wenchuan earthquake produced large amounts of loose material (landslide debris) that are still present on the steep slopes and in the gullies. This loose material creates an important hazard as subsequent rainstorm can promote the development of devastating debris flows. This paper reviews and presents a preliminary study of the distribution of landslides induced by the Wenchuan earthquake in China. Two typical areas, the Beichuan and Qingchuan area, were selected as pilot studies. The paper further identify and examine the debris flows that occurred in the Beichuan, Longchi, Yingxiu, and Qingping area and analyzes the triggering rainfall characteristics.

Key words: *Wenchuan earthquake, co-seismic landslide distribution, triggering rainfall patterns, debris flows*

Introduction

Landslides are one of the most destructive geological processes, being the primary cause of damage and fatalities associated with severe storms and earthquakes in mountainous regions. Although progressive erosional processes can provide sufficient conditions for slope failure, the majority of landslides are induced by earthquakes and rainfall (e.g., Keefer, 1984, 2002; Harp and Jibson, 1996). Landslides induced by earthquakes have often been considered as secondary effects of these events. However, they have been the sources of much or most of the loss to people and property. Much has been learned about the characteristics of seismically induced landslides from previous major earthquakes that occurred in mountainous areas, (Jibson and Keefer, 1989; Jibson et al., 2004; Keefer, 1984; Khazai and Sitar, 2003; Sato et al., 2007; Owen et al., 2008). Keefer (1984) and Rodriguez et al. (1999) made a global study of the

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landslides that occurred after 40 and 36 earthquakes respectively, and presented the relations between the distribution, type and area coverage of the landslides with parameters such as the distance to the epicenter, the magnitude of the earthquake and the distance to fault rupture.

On 12 May 2008, an earthquake with a moment magnitude of 8.0, and epicenter location at 31°N., 103.4°E. occurred near Yingxiu town in Wenchuan county, China. The earthquake source was located at a depth of 12 km. The earthquake was the most destructive in China's recent history and led to 69,197 fatalities, 18,341 persons missing, 374,176 persons injured, 6.5 million houses destroyed, and 5 million persons left homeless. The earthquake triggered more than 60,000 landslides of various types in steep mountainous terrain over an area of about 50,000 km^2. The landslides caused more than 20,000 fatalities (i.e., 1/4 of the total of fatalities and persons missing due to the earthquake were related to landslides; Yin et al., 2009).

The direct economic damage was estimated to be US$ 170 billion while the long-term impact is likely considerably higher. Thousands of strong aftershocks occurred for several months after the earthquake. The aftershocks extended from the major earthquake source in a north-eastern direction along the Longmen Shan fault zone into the Gansu and Shanxi Provinces for a length of more than 300 km. The largest aftershock had a magnitude, Ms, of 6.4 and occurred in the Qingchuan area (Dong et al., 2008).

The earthquake triggered landslides also produced extensive damage to housing settlements and irrigation channels. In addition, highways and bridges were blocked and /or destroyed and the city of Wenchuan and many other towns became isolated. These occurrences greatly frustrated the rescue and relief efforts. Landslide dams generated 34 large barrier lakes threatening the residents who lived downstream of these dams.

After the Wenchuan earthquake, research on landslide distribution and characteristics was carried out by several authors. Yin et al. (2009) analyzed the distribution of earthquake induced-landslides and the mechanisms of some typical landslides, and evaluated the potential hazards caused by some of the landslide dams. Ouimet (2010) used satellite images and aerial photography taken in the months following the earthquake to map the extent and density of landslides associated with the main earthquake and aftershocks and noted that there is a good correlation between the magnitude and distribution of ground shaking experienced during the earthquake and the mapped landslide density. Wang et al. (2009) presented preliminary investigation results of some large landslides triggered by the earthquake and discussed the influences of seismic, topographic, geologic, and hydro-geologic conditions for seismic landslide occurrence. Chigira et al. (2010) also used ALOS imageries to interpret the distribution of seismic landslides in the affected areas and showed that landslides were concentrated on the hanging wall of the Longmen Shan fault zone and in the valley of the Minjiang River. Tang et al. (2009) developed a numerical rating system, using five factors that contribute to slope instability to assess the landslide susceptibility in Qingchuan County, Sichuan.

Cui et al. (2009) identified 257 landslide dams in the earthquake-hit region and carried out a preliminary risk evaluation of some key landslide-dammed lakes. Gorum et al. (2011) and Dai et al. (2010) generate a comprehensive data base of landslides triggered by the Wenchuan earthquake, based on multi-temporal image interpretation, and correlate these with seismic and environmental factors.

In the Wenchuan area, an abundance of loose co-seismic landslide debris was present on the slopes after the earthquake, which in later years served as source material for rainfall-induced debris flows or shallow landslides. In the three years since the earthquake, intense rainfall events have triggered massive debris flows, leaving more than 2000 people dead or missing, and creating many problems during the restoration and reconstruction of the earthquake-affected areas.

This paper presents a preliminary result of the landslide distribution triggered by the Wenchuan earthquake and the landslide inventory in two typical areas. This study also identifies and describes the locations of debris flows that occurred in the study area and analyzes the triggering rainfall processes. The study aims to contribute to the understanding of the general characteristics of landslides triggered by the Wenchuan earthquake and associated rainfall-induced debris flows.

Tectonic setting

The Wenchuan earthquake occurred on the easternmost margin of the Tibetan plateau, along a series of predominantly north-northeast striking thrust faults that lie at the base of the Longmen Shan Mountains on the northwestern edge of the Sichuan Basin (Fig. 1; Burchfiel et al., 1995). This area is deforming as a result of the collision between the Indian plate and the Eurasian plate. The Indian plate has been moving northward at a rate of about 40 – 50 mm/yr, resulting in the uplift of the Tibetan Plateau. The deformation also results in the extrusion of crustal material from the high Tibetan Plateau in the west against the strong crustal material of the Sichuan Basin, which is a part of the Yangtze block (Xu et al., 2008a).

There is historic information on 66 earthquakes since 638 AD with Ms larger than 4.7 that occurred in the eastern margin of the Tibetan Plateau, mainly concentrated on the Minjiang fault and the southern part of the Longmenshan fault zone (Li et al., 2008). For instance, in 1933, a strong earthquake (Ms 7.5) was induced by the tectonic activity along the Minjiang fault zone. Two earthquakes with Magnitude Ms 7.2 occurred between Songpan and Pingwu on August 16 and 23, 1976. The Longmen Shan thrust belt comprises three main faults, the Yingxiu-Beichuan Fault, the Guanxian-Anxian Fault and the Mao-Wen Fault, of which the Yingxiu-Beichuan fault is seen as the main structure that generated the earthquake in 2008 (Li et al., 2008).

The Wenchuan earthquake generated a surface rupture extending for ~250 km

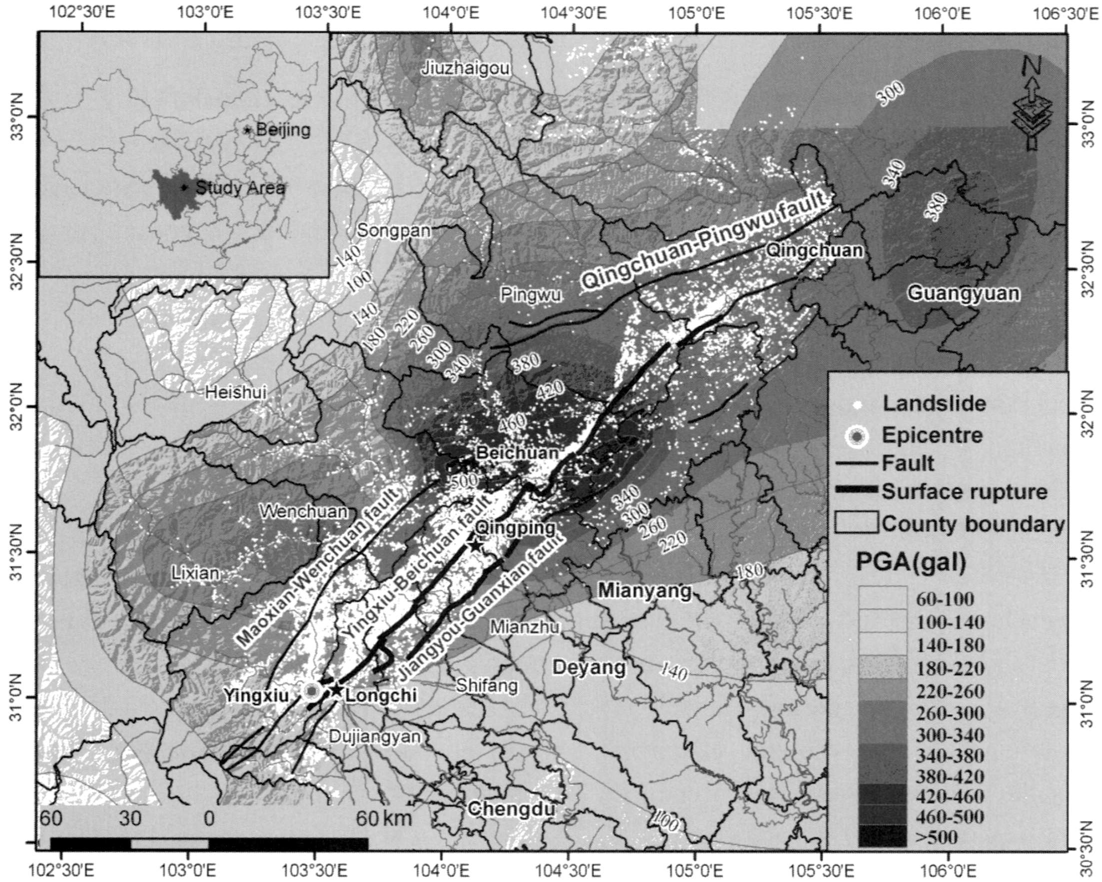

Fig. 1. Maps showing seismically triggered landslides and the Peak Ground Acceleration (PGA) distribution in the Wenchuan earthquake affected area. The epicenter of the Wenchuan main shock is located in the Yingxiu area.

along the Yingxui-Beichuan fault system and for ~72 km along the Pengguan fault. The field investigations immediately after the Wenchuan earthquake showed that the earthquake ruptured two NW dipping imbricate thrust faults along the Longmen Shan fault zone. The maximum vertical and horizontal displacements are respectively 6.2 m and 4.9 m in the Beichuan area (Ouimet, 2010). Its surface rupture length is the longest ever reported for inland reverse faulting events among the co-seismic surface rupture zones (Xu et al. 2009). Therefore this earthquake has led to many landslides in this region. In the ground motion recordings, there are over 560 components with peak ground acceleration (PGA) values over 10 Gal, the largest being 957.7 Gal, which is a very high level of ground shaking (Li et al. 2008). The maximum acceleration occurs at the upper part of the slope on the mountain ridges, leading to the initiation of landslides that move debris into the valleys. Figure 1 shows the distribution pattern of co-seismic landslides for the whole Wenchuan earthquake area, as described by Huang and Li (2009).

Previous work about inventories of the earthquake induced landslides

Landslide inventory mapping is an essential first step in the analysis of landslide development in the study area. The landslide inventory maps provide information for the assessment of the influence of different terrain factors. Many earthquake-induced landslide inventory maps have been generated (Huang and Li, 2009; Dai et al., 2010, Gorum et al., 2011). Huang and Li (2009) mapped 11,308 landslides in 16 seriously damaged counties using 10 m resolution ALOS imagery and aerial photography associated with a field investigation and noted that most significant landslides were located on the hanging-wall side of the main fault, although some occurred in deeply incised river gorges further away from the main rupture zone (Fig. 1). Sato and Harp (2009) carried out a preliminary study in the Beichuan area on landslides interpretation by using pre- and post-earthquake FORMOSAT-2 imagery and Google Earth. 257 large landslides were identified and plotted. Dai et al. (2010) used aerial photographs and remote sensing images taken after the earthquake to interpret over 56,000 earthquake-triggered landslides over an area of about 41,750 km^2. Gorum et al. (2011) mapped more than 60,000 individual landslide scars in an area of around 35,000 km^2.

The general characteristics of the landslides in the study area were similar to the landslides observed after large earthquakes in mountainous regions in other parts of the world (Lin et al., 2003; Sato et al., 2007; Owen et al., 2008). Observations in the field and the interpretations from satellite imagery and aerial photography indicate that the most common types of landslides were the falls (including rock falls, debris falls); slides (rock avalanches, debris slides, and earth slides); and flows (debris flows) according to the classification of Cruden and Varnes (1996).

The distribution of landslides is within two main concentration zones; one is the area along the fault rupture, and the other is along the deeply incised valley-side slopes of the river system. The maximum distance of the landslides from the co-seismic fault is around 70km, while most of the events occurred within a 10 km range from the fault Landslide concentration exhibits an inverse relationship to the distance from the fault (Huang and Li, 2009).

The landslide distribution shows a very distinct "hanging wall" effect, It is observed that the 57% of all landslides occurred on the hanging wall of the Yingxiu-Beichuan fault and 13% on that of the Pengguan fault (Gorum et al., 2011). Some research also indicate that the landslide distribution of the Wenchuan earthquake is more a function of the distance from the major surface rupture, rather than a function of the distance from the epicenter (Dai et al., 2010; Huang and Li, 2009). Figure 1 also shows this distribution pattern of the Wenchuan earthquake induced landslides.

The inventory map of co-seismic landslides shows that within the general outline, rivers exhibit a secondary influence upon the specific location of landslides. Chigira et al. (2010) pointed out that the landslides along rivers could be related to the process that formed inner gorge. This phenomenon is possibly more related to some geomorphological aspects, such as slope angle, altitude, and slope aspect. Altitude however does not seem to be an important factor for landslide occurrence. In the study area, altitudes vary between 500 m and 5940 m, whereas landslides are observed between 600 m and 4900 m. While the mean altitude of the area is 2361 m, the landslide average altitude is 1936 m. Therefore landslides in the study area tend to occur on moderately high mountainous terrains of the Longmenshan range (Gorum et al., 2011). In addition, it can be observed as expected that the initiation of co-seismic landslides frequently occurred along ridge crests, due to the topographic amplification of seismic waves. This adds to the apparent elevation control on landslides, initiating at similar heights along ridges and peaks.

The second topographic factor examined in this study is slope gradient which influences the landslide distribution. The majority of landslides occurred on slopes with gradients between 20° and 50°, while the highest landslide concentration is found on the steepest slopes in the range between 40° and 50°. Thus, it can be concluded that the recent landslides in the region commonly occurred on the slopes having very high values of slope gradients.

The highest landslide concentration appeared in carbonatic rocks (limestone and dolomite), which is followed by igneous rocks and phyllites (Gorum et al., 2011). These rocks are generally hard, but the surface and near-surface rock mass is fragmented. Slopes that are composed of carbonatic rocks are typically steep and prone to rock fall (Chigira et al., 2010). Data from Huang and Li (2009) suggest that the highest landslide frequency occur in harder rock types, including magmatic (igneous) rocks, carbonatic and sandy conglomerates. Second to this are sand-slate, phyllites and argillites with medium level landslide densities, while soil layers exhibit relatively little landslide activity. However, Dai et al. (2010) found that slopes composed of Pre-Sinian schists, and Cambrian sandstones and siltstones have the most concentrated landslide activity, followed by Permian limestones and Devonian limestones.

Methods

A co-seismic landslide inventory map was developed at a 1 : 50,000 scale on the basis of intensive field work after the main earthquake shock. Field observations were made in areas with the highest density of landslides. Some potential landslides were examined that are still precariously positioned on the slopes, which could not be identified by aerial photographs.

Field measurements with hand-held GPS and laser Rangefinders were conducted on debris-flow fans to estimate run-out length and lateral width. To estimate deposit volumes on the fans, more accurately, 1 : 2000 scale topographic maps were used based on a new topographic survey undertaken after the debris flow events. Estimations of planimetric deposit areas and depths are based on field measurements and these topographic maps.

The 1 : 200,000-scale geological map of the study area, compiled by the China

Geology Survey Bureau, provided information on the regional lithologic, stratigraphic, and tectonic setting. This data was used to evaluate the effects of lithology and faults. In this study, the locations of the event-based individual landslides were detected from the post-earthquake satellite images and aerial photographs. The images consisted of ALOS AVNIR-2 (10 m resolution), and aerial photographs (0.5 m resolution) data. The aerial photographs taken on May 18, 2008 were enlarged to a 1 : 5,000 scale and provided supplementary interpretation of landslide location points. The debris flows and new landslides that were triggered by subsequent heavy rains were identified using SPOT 5 multi-spectral imagery. They were used, combined with low-altitude aerial photos taken after the debris flow events on the 28th of August 2010, to delineate the depositional areas of debris flows. The resulting digital landslide inventory map documented the landslide location points. ArcGIS was used to overlay all the data with the DTM and the geological map. Using this method, the spatial distribution of different types of landslides could be analyzed.

Rainfall records from the rain-gauge stations in the Beichuan, Longchi, Yingxiu, and Qingping area were used to determine the daily rainfall totals associated with the debris-flow events. Hourly precipitation data collected at the rain gauge stations was used to analyze the rainfall intensity for each debris flow producing storm.

An investigation on co-seismic landslides in the Beichuan area

The study area is selected in the central part which was affected by the Wenchuan earthquake in the Beichuan County in the province of Sichuan. The area is 160 km north of Chengdu, between the eastern longitudes of 103°44′ and 104°44′ and the northern latitudes of 31°41′ and 32°14′. The area covers 2,865 km^2 and has approximately 161,000 inhabitants. The Yingxiu-Beichuan fault cuts through this area. Cambrian sandstones and argillaceous limestones, Silurian slates and phyllites, and Devonian and Carboniferous limestones are exposed in the study area. Loose Quaternary deposits are widely distributed in the form of terraces and alluvial fans.

During the post-earthquake field investigations and the interpretation of images of the study area (i.e., 2,865 km^2), a total of 1,754 earthquake-triggered landslides were identified (Fig. 2). Shallow landslides were dominant, but large deep-seated landslides also developed in the study area. Some of the larger landslides remained on steep slopes after partial displacement, while other large landslides ran out completely from their source areas and formed blockages in the main rivers and their tributaries. Most landslides in this inventory have volumes between 1,000 and 10,000 m^3. There are several thousand smaller landslides that were not recorded. Eighteen large landslides exceeded a volume of one million cubic meters. Although the large deep-seated landslides triggered by the earthquake were less numerous than the shallow landslides, the large landslides contributed significantly to the total volume of landslide material in the study area. The large landslides were much more destructive than the smaller

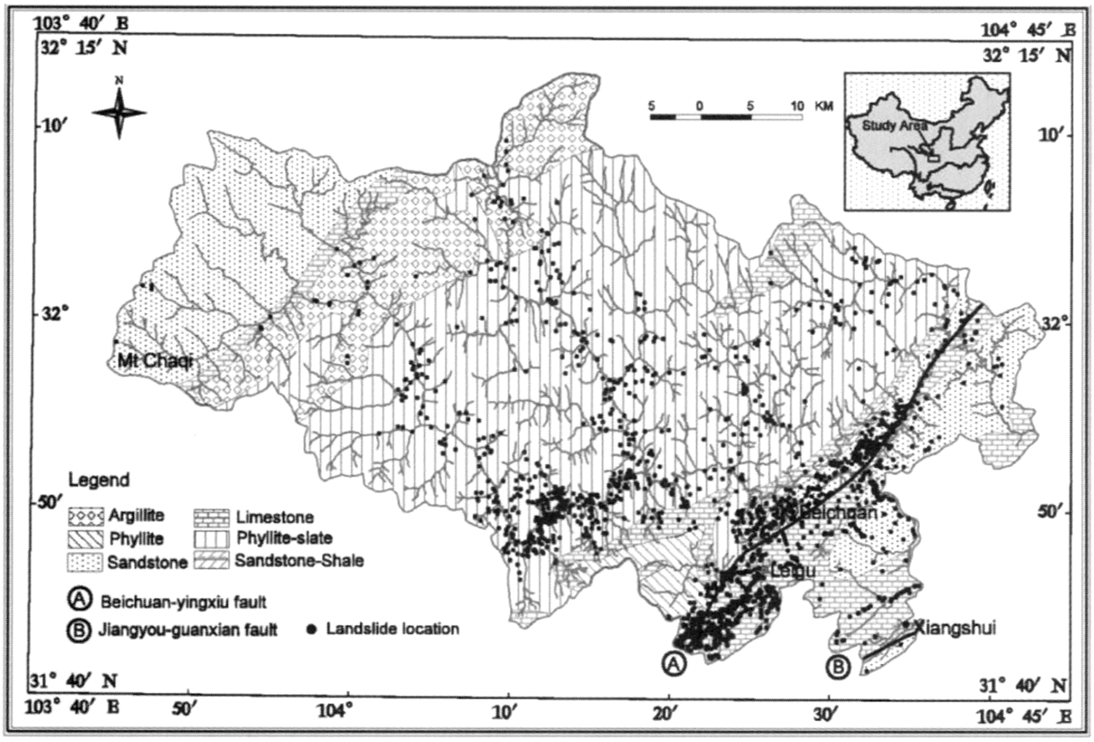

Fig. 2. A simplified geological map of Beichuan county with an overlay of the co-seismic landslide inventory map.

landslides. Some slump failures developed on reactivated deep-seated landslides.

The highest density of landslides occurred within a zone that stretches along the Yingxiu-Beichuan fault and on both sides of the rivers. In some places several landslides joined together to form complex landslides. As much as 20 – 40% of the hill slopes in these areas have been stripped by land sliding.

A majority of co-seismic landslides were adjacent to the Beichuan-Yingxiu surface rupture and the landslide number decreased exponentially as distance from the rupture increased. We also found that the landslides were concentrated on the hanging wall (i.e., the northwest side) of the surface rupture in the Beichuan area. Most slope failures were concentrated on the top of steep slopes associated with ridges and along rivers. The reactivated landslides are characterized by numerous newly opened cracks and fissures that were formed along the main scarps. The majority of the landslides in the study area occurred in Silurian slates and phyllites, Cambrian sandstones and Devonian limestones. The largest number of landslides occurred in areas dominated by slates and sandstones near the fault traces. Three of the largest landslides, (the Tangjiashan, Wangjiayang and New Benchuan Middle School landslides), were truly catastrophic. These landslides were responsible for most of the lives lost by landslides in Beichuan county (Fig. 3).

The Tangjiashan landslide: The Tangjiashan landslide occurred 5.5 km upstream from Beichuan city along the Jian river. The landslide occurred on a dip slope of shales and slates and travelled about 600 m downslope to the valley floor forming a dam with a

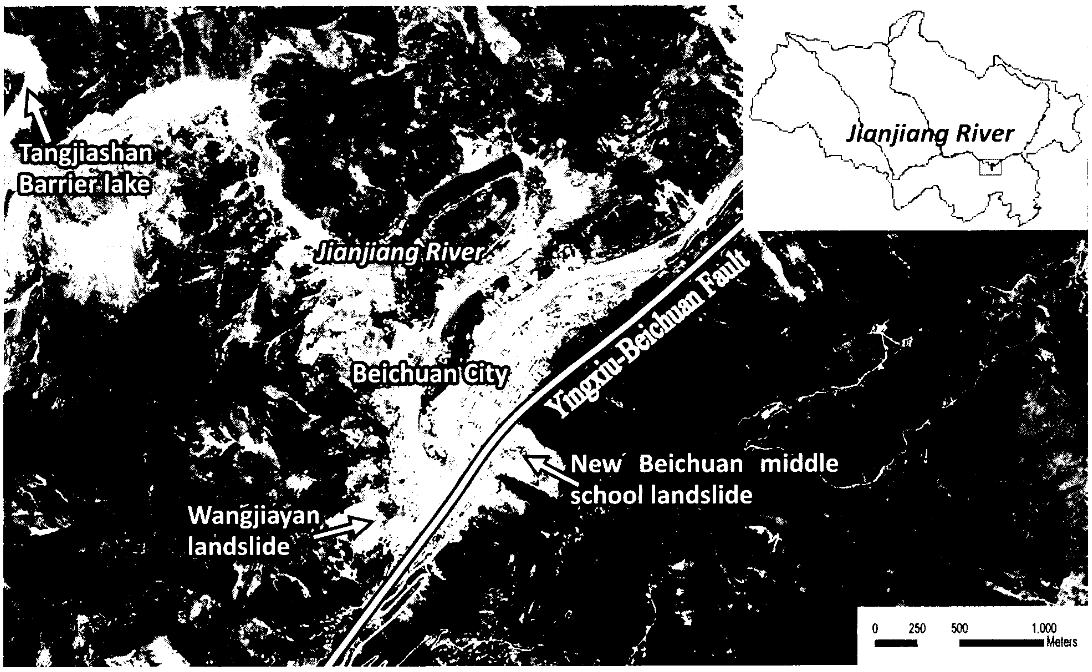

Fig. 3. Aerial photograph taken on May 18, 2008 with an indication of the locations of three major catastrophic landslides and barrier lakes in the surrounding of Beichuan City.

height of 82 – 141 m across the valley of the Jian river It is the largest landslide dam in the affected area. The impounded lake reached a length of more than 20 km. The volume of the sliding materials was about 20.5 million m^3 and the landslide dam was 610 m in length across the river, and 800 m in length along the river. The dam consists mainly of quaternary deposits, colluvial soil and broken rocks from the landslide. Figs 3 and 4 show the landslide dam, dammed lake and the failure surface associated with the Tangjiashan landslide.

The Wangjiayan landslide: The Wangjiayan landslide was a pre-existing landslide complex that was reactivated by the earthquake on the steep western valley slope in Beichuan city (Fig. 3 and Fig. 5). This catastrophic landslide destroyed more than 100 residential buildings and claimed the lives of about 1,600 people. The sliding mass consisted of about 7 million m^3 of metamorphic rocks. The main scarp was about 180 m high. Witnesses of the landslide reported that they heard a loud noise about 10 minutes after the main shock, and saw a heavy dust cloud produced by the landslide. This indicated that the movement of the slide, which probably transformed into a rock avalanche, was very rapid and that nearly all the landslide material came down shortly after the main shock. Air-blasts resulting from the rapid failure and movement of the landslide were observed in the ruined zone.

The New Beichuan Middle School landslide: The New Beichuan Middle School landslide was mobilized on the steep eastern valley side in Beichuan city (Fig. 3 and Fig. 6). The landslide buried 906 people at the toe of the landslide. The landslide deposit is 610 m long, 380 m wide, and about 20 – 25 m thick. The volume of the

Fig. 4. The Tangjiashan landslide with the dam induced by the Wenchuan Earthquake.

Fig. 5. The Wangjiayan landslide induced by the Wenchuan Earthquake.

Fig. 6. The New Beichuan Middle School landslide induced by the Wenchuan Earthquake.

landslide material is about 5 million m^3. The landslide probably began as a block slide and disintegrated into a debris avalanche that ran down the mountain to form a cone-shaped deposit consisting of a chaotic mixture of massive blocks of various sizes. Parts of a planar basal sliding surface are still visible, dipping about 50° down-slope towards the city.

An investigation of co-seismic landslides in the Qingchuan area

This area is situated in the northeast of the earthquake's epicenter and belongs administratively to the Qingchuan County of Sichuan province. The area was selected because of its moderate-high seismic activity. Three of the aftershocks exceeded magnitude 6 including the maximum aftershock with a magnitude of 6.4. It is 250 km away from the northern part of Chengdu, with eastern longitude of 104°36′ to 105°38′ ,and northern latitude of 32°12′ to 32°56′. It is 105 km long from east to west and 96 km long from south to north, covering 3,271 km^2 and accommodating approximately 250,000 people. The Yingxiu-Beichuan Fault is located just in the southern central part of the study area, and is developed as a thrust fault with a NW dipping angle of 60° to 70°. The Guanxian-Jiangyou fault runs far south of the study area. In the northern central part of the study area lies the active Pingwu-Qingchuan fault with a NEE orientation.

Post-earthquake field investigations and interpretation of aerial photographs throughout an area of 3,271 km^2 were conducted immediately following the earthquake and a total of about 971 earthquake-triggered landslides (see Fig. 7) were identified. Each of the majority of the identified landslides has a volume of more than 1,000 m^3, and each of the forty largest landslides has a volume of more than one million cubic meters. More than several thousand small landslides were not recorded. The Wenchuan earthquake event-based landslide inventory is shown in Figure 7. The Donghekou, the Shibangou and the Magong landslides, were the most catastrophic and responsible for most of the landslide fatalaties in Qingchuan County. The Donghekou landslide, a catastrophic avalanche, buried four villages and 184 houses, resulting in more than 480 deaths, and in addition, caused the formation of two landslide dams, which formed barrier lakes (Fig. 8). The Donghekou landslide dam failed by naturally overtopping only 4 days after it was created.

The spatial distribution of earthquake-induced landslides in the Qingchuan area is primarily controlled by topography, lithology, fault rupture, and stream. The correlation of the number of landslides with elevation shows that the 97.8% landslides occurred at elevations below 1,400 m asl, and 61.5% of all landslides are at an elevations below 1,000 m asl. Few landslides are found at elevations above 1,800 m asl. Most land sliding occurred on slopes between 25 and 35° and less on very gentle (0 – 15°) and very steep (>45°) slopes (Tang et al., 2009).

To analyze the influence of each factor class with regard to landslide occurrence, a

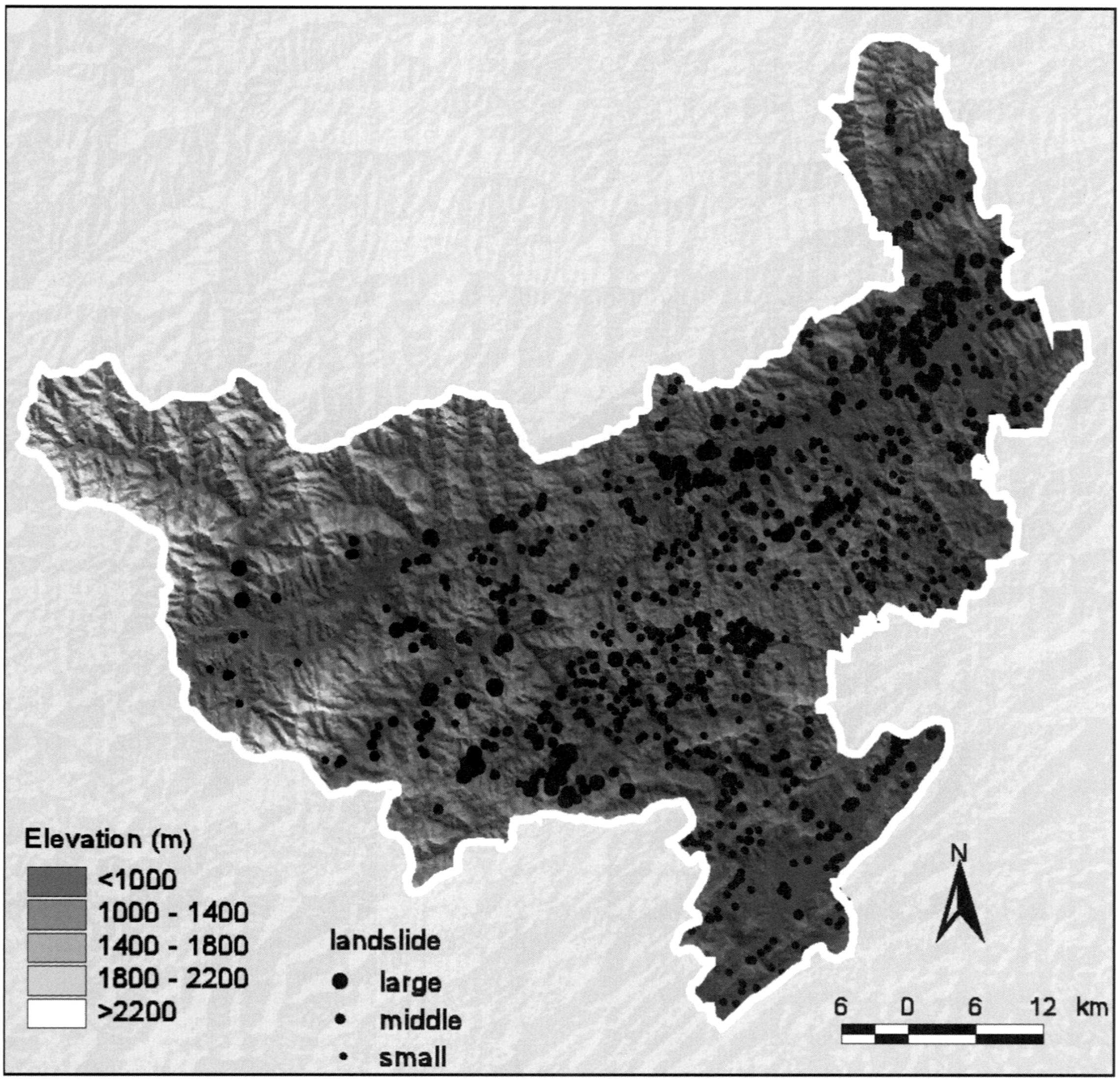

Fig. 7. The Wenchuan Earthquake-induced landslide distribution in the Qingchuan area.

'Susceptibility Index' was calculated by comparing the numbers of landslides occurring in the area occupied by each factor class. The index represents the relative hazard of a landslide occurrence as attributed by each factor class. The study showed that the susceptibility index of landslides increases with the proximity to the fault lines (0.603 within the 500 m zone; 0.535 within the 500–1,000 m zone; 0.425 within the 1,000–2,000 m zone and 0.239 beyond the 2,000 m zone). Landslide susceptibility is also closely related with its distance from streams. The study also showed that the susceptibility index of landslides increases with proximity to the stream (0.55 within the 200 m zone; 0.49 within the 200–400 m zone; 0.31 within the 400–600 m zone, 0.28 within the 600–800 m zone and 0.11 beyond the 800 m zone (Tang et al., 2009).

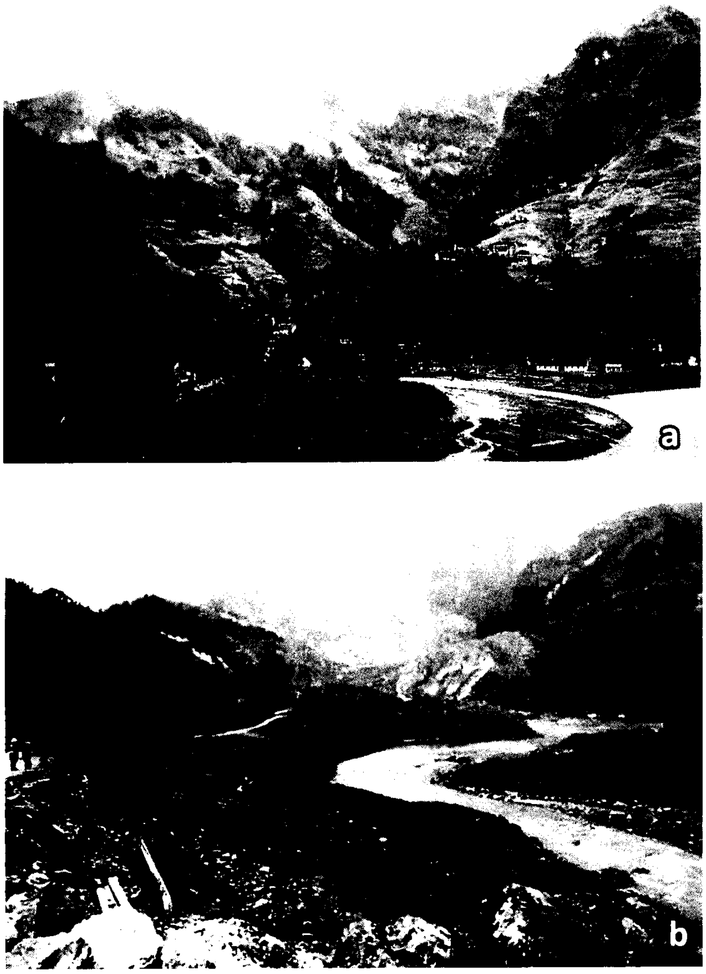

Fig. 8. The Donghekou rock avalanche in Qingchuan County. a) The Donghekou area prior to the Wenchuan Earthquake. b) The Donghekou rock avalanche induced by Wenchuan Earthquake.

Subsequent rainfall-induced debris flow events

The Wenchuan earthquake has resulted in a large number of earthquake triggered landslide bodies that are now still present on the slopes in the area. Also slopes have been observed that are weakened and brought into a meta-stable state by the earthquake (Tang et al., 2011). For that reason, some extreme rainfall events after the earthquake have initiated excessive debris flows. This has created a secondary hazard category with rainfall as trigger. The characteristics of rainstorm triggering patterns was investigated, as part of the study on the debris flows, in four selected areas.

Debris flows in the Xishanpo gully around the city of Beichuan

On September 24, 2008, seventy-two gully debris flows were triggered by a severe rainfall event in Beichuan County, close to the earthquake epicenter, and caused the deaths of 42 people as well as serious damage to roads and the relocation areas for the earthquake-struck people. A debris flow from the Xishanpo torrent moved earth, debris and boulders down into the older part of Beichuan city and buried most of it. Fortunately, nobody died as all the residents had already been evacuated to other secure places after the Wenchuan Earthquake.

The Xishanpo gully has a catchment area of 1.54 km^2 and a channel length of 2.3 km. The upslope elevation is 1,040 m asl and the gully mouth is at 700 m asl. The highest part of the debris flow source area is at 1,740 m asl on the hanging wall side of the Beichuan-Yinxiu Fault at a distance of some 1.4 km. The lithology exposed in the source area is mainly Cambrian sandstones and sandy shales.

In the upper reaches of the Xishanpo gully, three landslides with surface areas of more than 10,000 m^2 were induced by the Wenchuan Earthquake, as well as ten smaller landslides and rockfalls. In Fig 9 the catchment area of the Xishanpo gully is delimited on the aerial photograph taken on 18 May 2008. The largest landslide is situated between 880 m and 1,200 m asl and has a length of 410 m and a width of 250 m. The average thickness is 10 - 15 m hence the volume of this landslide is estimated to be 1.1 million m^3. It blocked the drainage channel, forming a 120 m long deposit in the gully with a height of 5 - 10 m. Two other landslides can be identified in the upper reaches of

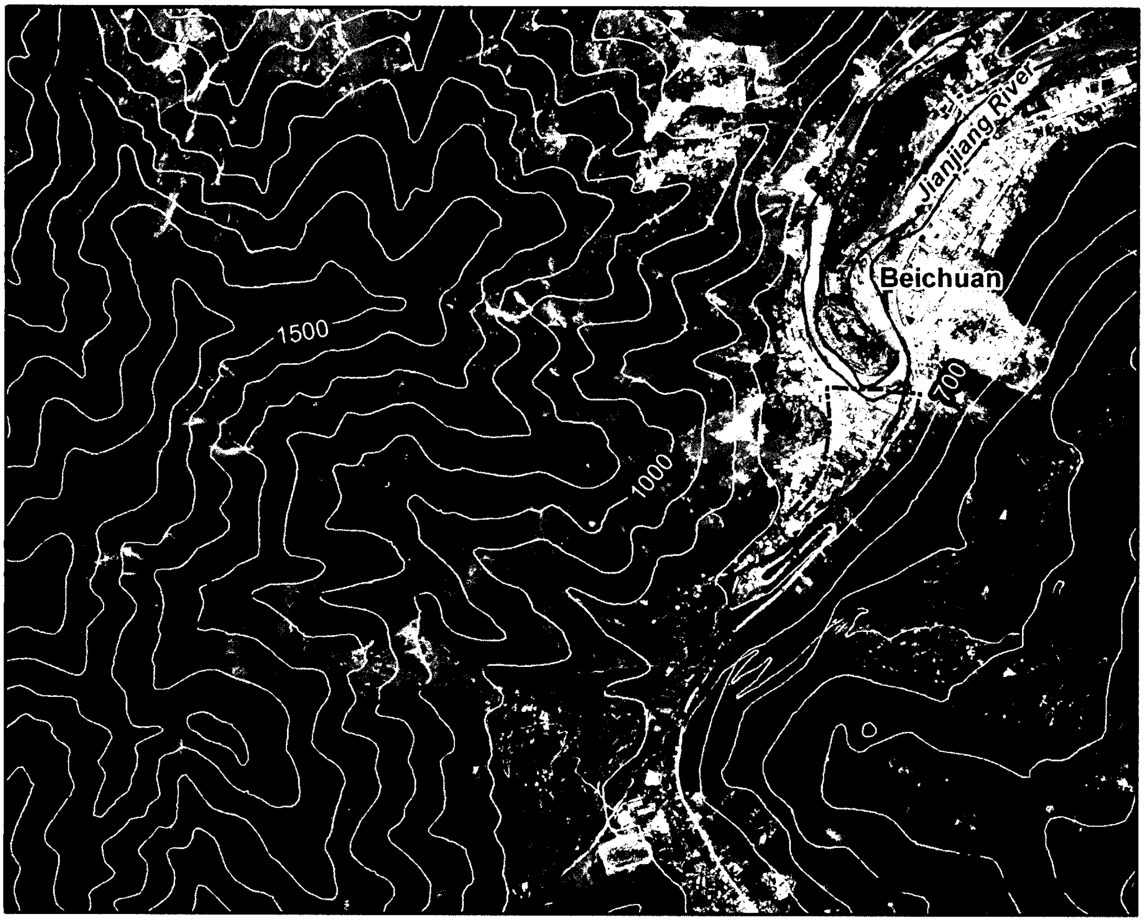

Fig. 9. Aerial photograph of the Xishanpo debris flow gully taken on May 18, 2008, prior to the September 24, 2008 heavy rainfall.

the gully with an estimated total volume of 1.2 million m^3. In addition, the weathered near surface material and the Quaternary deposits would also have provided a large amount of loose material following the earthquake shaking.

An automatic rain gauge in the study area was set up on the Tangjiashan landslide to assist in monitoring the hydrological modifications of a lake created by a landslide dam and to analyze the possibility of a dam breach that would lead to flooding. A rainfall recording station was also set up at Beichuan. Rainfall data was recorded hourly at these two stations. On September 23, the day before the debris flows occurred, the Beichuan Station failed to record the precipitation, but 173 mm of rainfall was recorded at the Tangjiashan Station. Rainfall data from September, 24 2008 showed 57.9 mm of rainfall at the Tangjiashan Station between 0 : 00 and 5 : 00 am. The rainfall that induced new landslides and debris flows likely occurred between 5 : 00 and 6 : 00 am since 41 mm of rainfall was recorded at the Tangjiashan station during that time period (Fig. 10). The amount and the intensity/duration of the rainfall recorded in this area had a return period of about 20 years. Our analysis revealed that these two days of heavy rainfall provided sufficient antecedent precipitation and hourly rainfall intensity to trigger a large number of shallow landslides and debris flows on September 24.

The debris flow initiation area was situated at an elevation between 1,150 m and 1,250 m asl. The fluid concentrated in the upper part of the channel flowed down to an elevation of 1,050 m and was blocked there by a barrier of loose landslide material that had been deposited in the gully bottom. The failure of this landslide dam produced a fast increase in the flow discharge. For the analysis of the debris flow discharge in this gully, two mud trace cross sections in the transport channel were surveyed: one in the upper part of the flow channel and the second in the lower part. The first cross-section

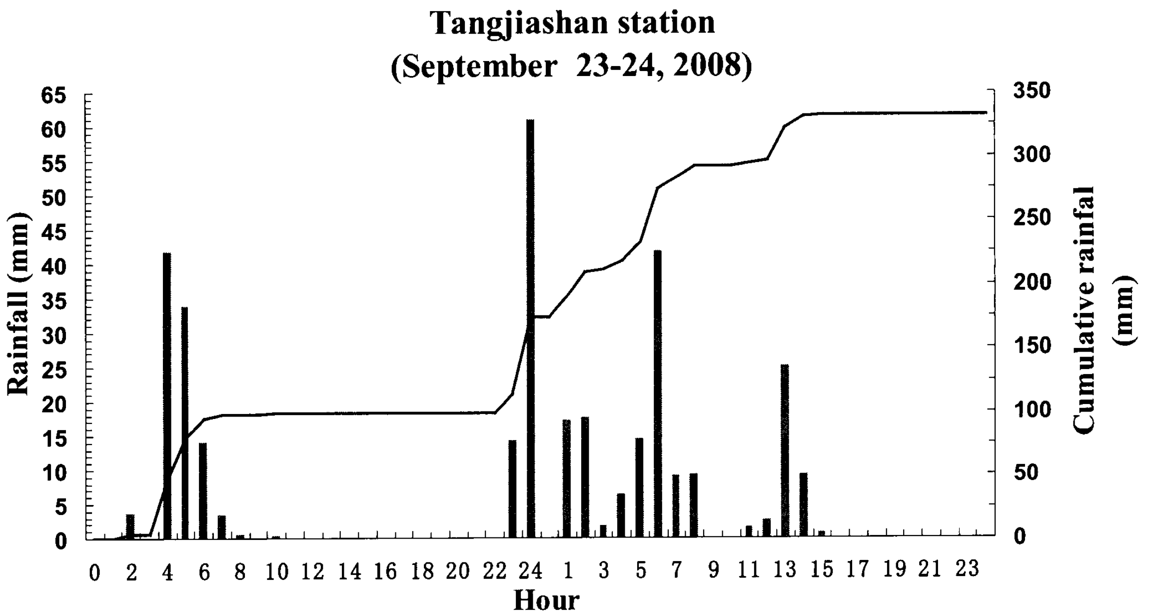

Fig. 10. Hourly and cumulative rainfall during 23 – 24 September 2008 measured at Tangjiashan station.

at an elevation of 900 m asl is trapezoid in shape, 14 m wide and 5 m deep. The second one, at an elevation of 780 m asl, is rectangular, 32 m wide and 2.2 m deep. From these data it was calculated that the peak discharge of the debris flow reached 260 m^3/s, which appears to be a high value for a gully catchment area of 1.54 km^2. However, with the failure of the landslide dam in the gully, there would have been an instant dramatic increase in the flow discharge. Ground investigations of the deposition area indicate the run-out of the debris flow was some 340,000 m^3 – a relatively high volume from such a small catchment.

Fig. 10 is an example of a triggering rain fall pattern with a slow response time. It means that the rainfall duration before triggering is relatively long with multiple peaks and the mean intensity is relatively low. Generally speaking this slow response might be ascribed to the fact that debris-flows triggering is infiltration driven, taking relatively more time bringing the groundwater to a critical level or increasing soil moisture to a critical level to induce shallow landslides and to break the landslide dam which transformed into a debris flow.

After the debris flow moved out of the steep gully, it rushed into the old city of Beichuan (Fig. 11), forming an accumulation area some 900 m in length with a maximum width of 150 – 200 m. The surface area was 0.17 km^2 and the thickness of the deposits reached 9 – 12 m in the upper segments. Near the center, the debris is 7 – 8 m thick, with a concentration of stones around 50%, having diameters between 50 – 300 mm. Relatively large boulders and wood blocks are concentrated in the front part of the deposit.

Debris flows in the Longchi area of Dujiangyang city

The study site, which covers an area of approximately 120 km^2, is situated in the Longchi area, belongs to Dujianyan in the Sichuan Province. It is located only 5 km to

Fig. 11. Debris flows which inundated the old Beichuan city (Photograph taken September 24, 2008).

the east of the epicenter of the Wenchuan earthquake. At least 36 gullies along the Longxi River with debris flows were triggered by two rainstorms on 13 August and 19 August, 2011 (Fig. 12). The recorded data show that precipitation in the Longchi area started at 14 : 00 p.m. on 13 August. The cumulative rainfall of 229 mm was recorded from 14 : 00 p.m. on 13 August to 07 : 00 a.m. on 14 August. The rainfall intensity that triggered the debris flows occurred between 16 : 00 and 17 : 00 p.m.: 75 mm/h was recorded during that hour. This is an amount with a return period of more than 20 year. In this case one can speak of a rapid response triggering pattern. The rainfall duration until triggering is relatively short and the intensity relatively high. (Zhou et al., submitted). In combination with a high initial moisture content which developed during the antecedent rain period, a high amount of surface run-off was generated. Therefore debris flow initiation might be run-off driven in this case, which means that intensive run-off caused severe erosion of loose material in steep gullies generating debris flows.

The surface area of the individual catchments ranges from 0.04 to 8.1 km^2, with approximately 72% being < 1 km^2. The debris-flow channels include steep, short parts (length < 2 km; average channel gradient $> 33°$) and gentler, longer parts (length > 2 km; average channel gradient $> 22.1°$). In catchments with debris flows the internal relief ranges from 260 m to 1.65 km.

The deposits of the Longchi debris flows were mainly distributed along both sides of the Longxi River. The riverbed increased in height between 6 – 8 m (Fig. 13). The investigated debris flow deposits contain predominantly coarse-grained particles, probably because the sediment supply for debris flows mainly originated from co-seismic landslides. The maximum travel distance on fans varied between 110 m and 1.06 km and the maximum lateral spreading is between 30 m and 880 m. The volume of deposits on individual fans varies by many orders of magnitude, from 210 m^3 to of 1.16 million m^3. The total volume of deposits on the fans for the surveyed 36 gullies amounted to about 9.1 million m^3.

Debris flows in Hongchun torrent around the town of Yingxiu

A heavy rainstorm on August 13 – 14, 2010 around the town of Yingxiu, located near the epicentre of the Wenchuan earthquake, triggered many hill-slope and channelized debris flows. Among them, the debris-flow from the Hongchun torrent was truly catastrophic. It traveled across the Minjiang River and caused a natural debris dam of 10m height, 100 m in length across the river, and 150 m in length along the river. The dam caused a change of the river course and the flooding of the newly reconstructed Yingxiu town. Figure 14 is an aerial photo taken on August 15, 2010 showing the debris-dam and the inundated Yingxiu town. The flood water-depth was 2.0 – 3.5 m and the flood lasted 7 days until the debris dam was excavated on August 20, 2010 (Fig. 15). This catastrophic debris-flow event claimed the lives of 32 people. More than 8000 residents were forced to evacuate after the debris flow and the flooding struck the town.

The Hongchun gully, located on the left bank of the Minjiang River, has a

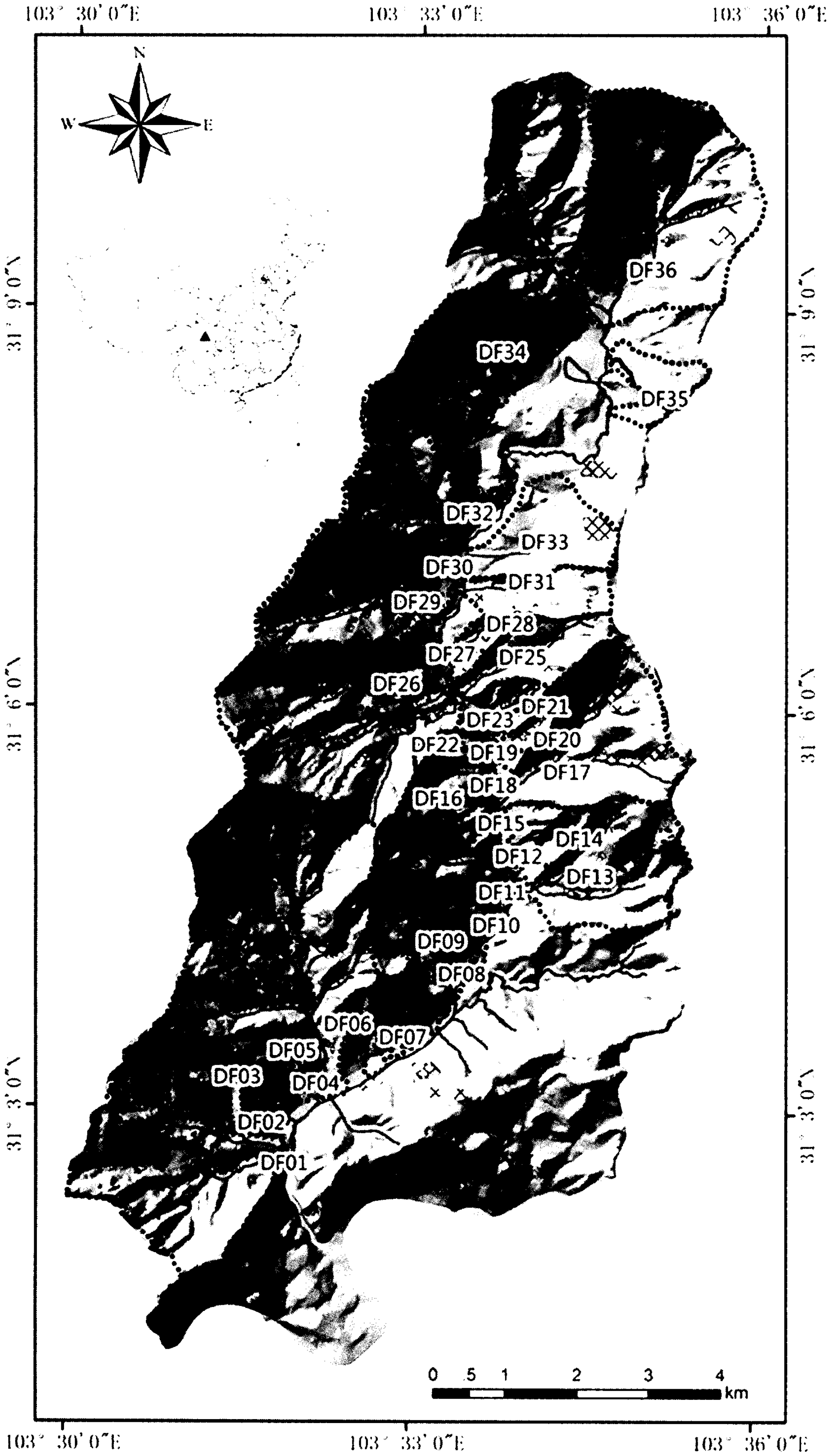

Fig. 12. Thirty-six catchments with debris flows in the Longchi quadrangle. Debris flow gullies are marked. The landslides triggered by the Wenchuan Earthquake are plotted.

Fig. 13. The deposits of Longchi debris flows along both sides of the Longxi River. The Longchi town was damaged by debris flows and flooding.

Fig. 14. Aerial photo taken on August 15th, 2010 showing the Hongchun debris flow fan, the debris flow dam, and the inundated area in the reconstructed town of Yingxiu (Photograph provided by the Sichuan Institute of Geological Environmental Monitoring).

catchment area of 5.35 km^2 and a channel length of 3.55 km (Fig. 16). The upslope elevation of the gully is more than 1,700 m asl and the gully mouth is at 880 m asl. The highest part of the debris-flow source area is at 2,168 m asl. The Yingxiu-Beichuan fault just runs through the Hongchun gully. In the source area mainly granitic rocks are exposed, which are deeply fractured and highly weathered, and massive co-seismic landslides were developed on the slope.

Field evidence shows that the debris-flow was initiated in the erosive channel rills on the landslide deposits in the upper reaches of the Hongchun gully. The overland flow of water resulting from the intense rainfall eroded the loose sediment material to move into the gully. When the incipient debris-flow reached a landslide dam at 1,080 m asl, it

Fig. 15. Flooding of the reconstructed Yingxiu town due to a debris flow dam. The flood water runs through the town and flows back into the original river channel.

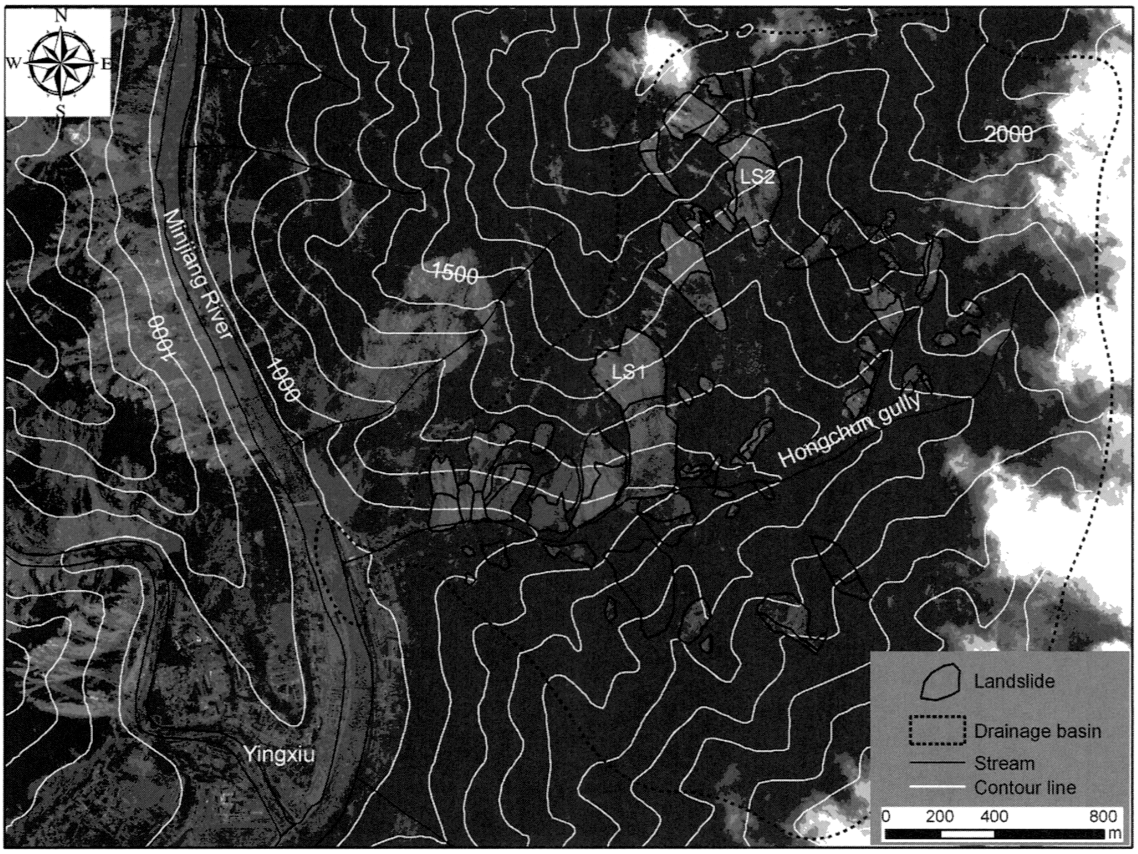

Fig. 16. Aerial photograph taken on May 18, 2008 (immediately after the Wenchuan earthquake) showing the catchment area of the DF01 Hongchuen debris flow with the earthquake induced landslides.

caused the failure of the landslide dams and produced a fast increase in the flow discharge and the transported debris volume.

A rain-gauge station at Yingxiu town records hourly rainfall data and is located about 600 m from the debris flow alluvial fan with an elevation of 880 m asl. Precipitation generally increases with elevation. In our study area most debris-flow catchments have the elevation lower than 2,000 m asl. Figure 17 shows the hourly and cumulative rainfall for August 12 – 14, 2010 recorded at this station. On 12 August 2010, two days before the debris flows occurred, 19.9 mm of rainfall was recorded between 17 : 00 and 24 : 00 hours. A total of 126.8 mm was recorded on the entire day of 13 August. For 14 August 23.4 mm of precipitation was recorded between 0 : 00 and 02 : 00 hours. The rainfall pattern between august 13 18.00 hours and august 14 2 : 00 hours can be interpreted as a slow response triggering pattern. The hourly rainfall intensities are relatively low and the duration to triggering relatively long. Despite the fact that intensive run-off erosion was observed in the upper part of the gully we considered the triggering mechanisms as infiltration driven. Obviously the main debris flow could be initiated after saturation of the landslide dam by infiltrating rain and run-on water.

The triggering rainfall intensity that saturated the landslide dam to a critical level, inducing the main debris flow, occurred between 02 : 00 and 03 : 00 am: 16.4 mm/hour was recorded during that time period. Many eyewitnesses said that the most important debris flows started around 03 : 00 am and ended at 04 : 30 am. After that, flooding was reported in a few long channels until 9 : 00 am on August 14, 2010.

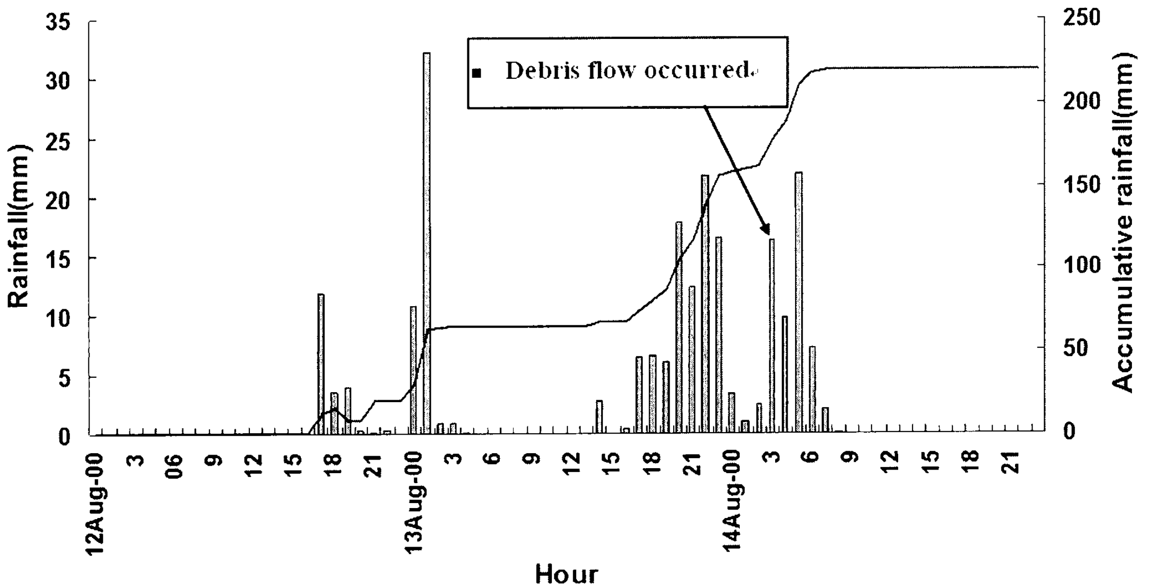

Fig. 17. Distribution of hourly and accumulated precipitation between Aug. 12 and Aug. 14, 2010 in Yingxiu area. The debris flow occurred on August 14 between 02 : 00 and 03 : 00 am at a rainfall intensity of 16.4 mm/hr and after antecedent rainfall of 162 mm.

Debris flows in the Wenjia torrent in the Qingping area

The Wenjia torrent is situated in the Qingping area, which is a part of the Mianzhu County in Sichuan Province. It is located about 80 km to the northeast of the epicenter of the Wenchuan earthquake. The main branch of the torrent has a length of 3.25 km and a drainage area of 7.81 km^2. The head of the torrent is called Dingziya and forms the source area of a huge co-seismic rock slide- avalanche (Fig. 18). The main part of

Fig. 18. Aerial photograph, taken on May 18, 2008 showing the entire Wenjia rock avalanche after the Wenchuan earthquake, which destroyed the village of Yuanbao, causing 48 deaths.

the deposits of this large co-seismic landslide, which covers an area of about 1.08 km^2, was deposited in the Wenjia catchment. Figure 19 shows two main locations of landslide deposits: the so-called Hanjia platform located at the toe of the back scarp, with an elevation between 1,600 and 1,890 m asl, and the so-called 1,300 platform with elevations between 990 m and 1,400 m asl. The upper avalanche deposit, which originated from the detachment of the rock slide in the initiation zone, consists of a chaotic jumble of angular limestone and dolomite blocks with an overall length of 560 to 630 m and an average width of 850 to 930 m. The depth of the deposits varies from 30

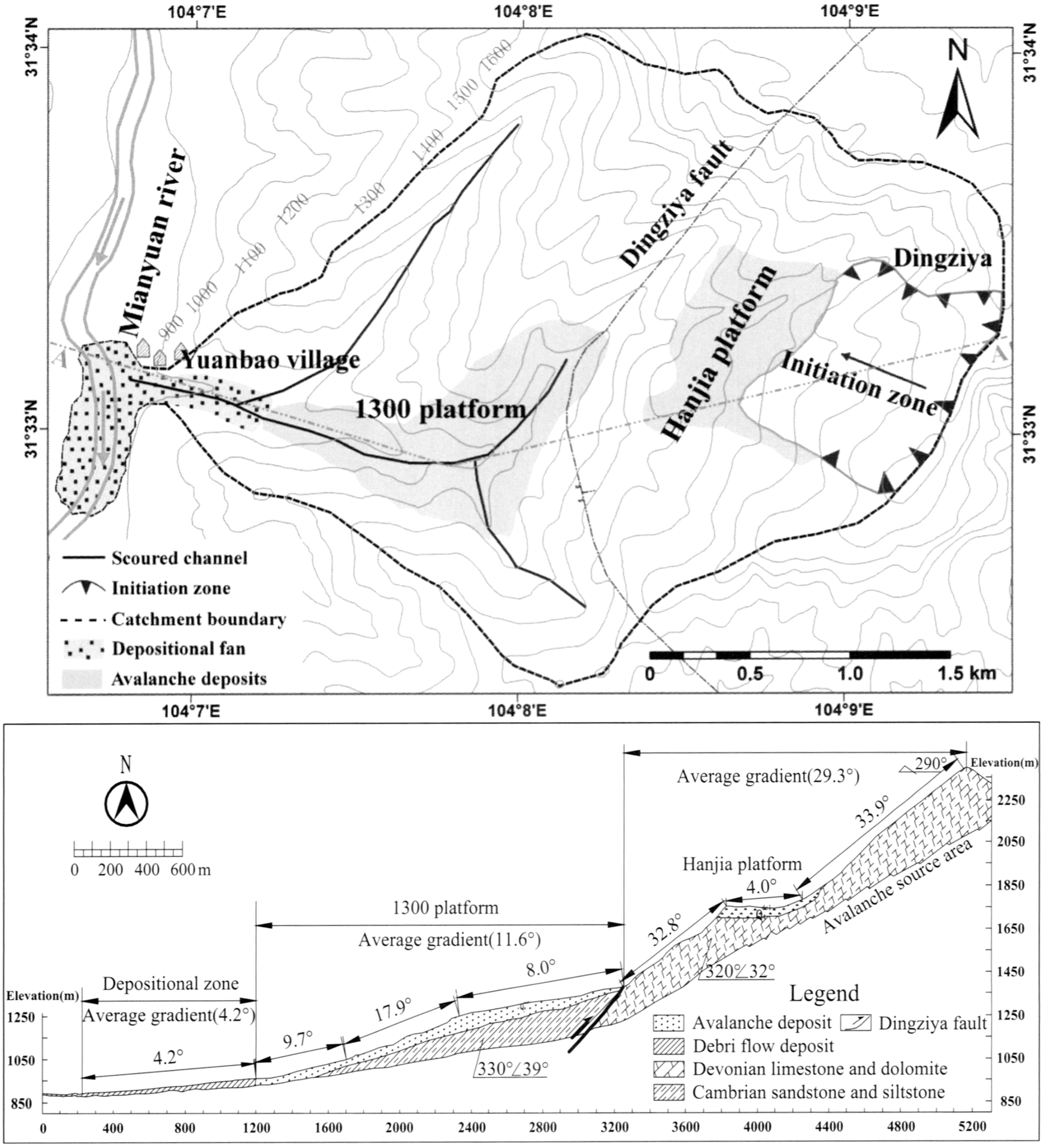

Fig. 19. Geomorphological sketch map of the Wenjia rock avalanche and the debris flow fan. (a: Plan map; b: cross section A-A' in the plan map). A-A' in the fig is not clear.

to 50 m, with an estimated volume of about 23 million m^3. The lower deposit zone on the 1,300 platform has a length of 1,900 m and a width of 350 to 630 m (Fig. 19). The thickness is 30 – 110 m, suggesting that the volume of this avalanche deposit was about 55 million m^3. It comprises thick accumulations of loose, fine material prone to erosion and remobilization as debris flows during future periods of intense and prolonged rainfall.

The Namugou meteorological station, which is located on the alluvial fan of the Nanmugou torrent about 6 km from the Wenjia torrent, recorded rainstorm data. Before the debris flow event on 13th August 2010, the antecedent rainfall recorded at Namugou station from 22nd July to 12th August amounted to 514.2 mm (an average of 23.4 mm/day), while the antecedent rainfall from 1st to 12th August recorded a cumulative precipitation of 342 mm (an average of 28.5 mm/ day). A total 137.6 mm of antecedent accumulated precipitation for seven hours was recorded before the debris flows occurred. This quantity of short term antecedent precipitation is likely to have significantly contributed to the debris flow occurrence because it wetted the soil, generating a high initial moisture content. Locally it may have been sufficient to generate overland flow. The rainfall with a peak intensity of 38.7 mm/h appears to have triggered the debris flows in the period on 13th August between 1 : 00 am and 2 : 00 am. Field evidence showed that the Wenjia debris-flow was most likely initiated in the erosive channel developed in the deposits entrained by the rock avalanche at an elevation between 1,200 m and 1,300 m asl. The concentrated overland flow resulting from the intense rainfall scoured the loose debris material and eroded deep gullies into these deposits

More than 3.1 million m^3 materials from the 1300 Platform deposits of the rock avalanche was transported to the Mianyuan River. A total of 19 check dams had been constructed to control the sediment transport in the main drainage channel of the basin, but all of them failed during the debris flow event. There was no materials stored behind these recently constructed check dams. The failure of the check dams in the lower reaches of the gully may have contributed to an instantaneous increase in the flow discharge and also a longer run-out distance (Fig. 20). Yu et al. (2010) estimated that the peak discharge reached 1,530 m^3/s, which appears to be much higher than any other event in the Wenchuan earthquake affected region.

The flows created deposits with a thickness between 5 and 15 m on the river flood plain and formed a large debris dam 400 m in length across the river and 820 m in width along the river (Fig. 20). The material of the debris dam consisted mainly of fine-grained and easily liquefying sediments which are very vulnerable for surface erosion by overtopping. Therefore, the life of the dam lasted only one day before it broke.

There was no obvious remobilization of avalanche deposits on the Hanjia platform. The coarse dolomite blocks need higher run-off intensities to be remobilized. However, the entrained deposits in the zone at 985-1,400 m asl at the 1300 platform contain mainly fine debris material, which is more susceptible to be eroded and remobilized as debris flows by a concentrated water flow.

Fig. 20. Overview of the debris flow fan of the Wenjia catchment and the inundated area of the newly reconstructed houses of Qingping. The upper part of the photograph shows the 1,300 platform rock avalanche deposits, located in the lower reach of the torrent which formed the source material of the debris flow.

Controlling factors which determine the triggering rain fall pattern

There are two main mechanisms of initiation of debris flows; run-off driven intensive channel erosion and infiltration driven material failure and subsequent liquefaction in this loose co-seismic landslides This may explain the differences in rain fall-response patterns as described above, A number of factors will determine which triggering mechanism is the most dominant and hence determine the character of the triggering rainfall pattern. Important factors are the hydraulic conductivity of the soil, the initial moisture content of the soil, soil thickness, the slope gradient and the soil strength.

One can make a tentative approach to reconstruct the circumstances, which determined the triggering rainfall patterns for debris flows in the investigated areas.

In case of a rapid response triggering rainfall pattern, which might be the case during the triggering of the debris flows in the Longchi area, the debris flows could be triggered by concentrated run-off erosion of loose soil material. The rainfall intensity is relatively high. The hydraulic conductivity must be relatively low and (or) the soil had a high initial moisture content due to a long period of antecedent rain. Steep slopes in loose material are in case of run-off erosion triggering favorable for debris flow initiation due to rapid loading of the flow by solid material. The fact that the debris flows started already shortly after the rain event indicates that run-off erosion and rapid loading of solid material might have been in this case the dominant process for debris flow initiation.

The determining factors for a rainfall pattern with a slow triggering response are in most cases contrary to the factors that determine a fast response pattern. Probably failure of loose material induced by infiltration of rain water in combination with infiltrating run-off water is the most dominant process initiating debris flows. This might be the case for the initiation of the debris flow in the the Xishanpo gully. The long duration of the rainfall with a relative lower intensity indicates (see Fig. 10) in the first place that the loose soil deposits of the landslide dam are relatively thick, requiring longer rain and infiltration of run-off water to become unstable. Additional factors determining the length of the triggering rainfall period are the hydraulic conductivity, the steepness of the slope and the strength of the blocking landslide material.

Conclusions

In the field investigation and interpretation of aerial photographs and satellite images after the Wenchuan earthquake, seismically induced landslides and associated subsequent debris flows were studied. The dominant types of co-seismic landslides are rock falls and rock slides, whereas earth slides were much less frequent. Some of these larger landslides are hanging on the steep slopes after their partial displacement, while some other large landslides are separated completely from their source areas, to form blockages in the rivers and their tributaries. Most of the landslides occurred along the major surface rupture, and were concentrated on the hanging wall of the rupture. Landslide concentration has an exponential increase with slope gradient.

After the Wenchuan earthquake, an abundance of loose landslide debris was present on the slopes. The debris later served as source material for rainfall-induced debris flows. Four catastrophic debris flow events in the Beichuan, Yingxiu, Longchi, and Qingping area were selected as an extreme case to show in detail the mechanism of debris flow formation as a result of run-off driven intensive channel erosion and infiltration driven material failure in this loose co-seismic landslides and landslide dams. These two significant differing mechanisms of debris flow initiation are determinant for the triggering rain fall pattern.

This study reveals that there is a continuing threat in the region because of the huge amount of loose material still available in the catchments, which will be mobilized into debris flows under future heavy rainfall conditions.

Acknowledgements

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