CATASTROPHIC LANDSLIDES TRIGGERED BY THE 2008 WENCHUAN EARTHQUAKE

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ABSTRACT

The 12 May Wenchuan earthquake killed at least 70,000 people and left nearly 5 million homeless. In the disastrous event, numerous landslides were triggered, especially as rapid and long runout landslides. For example, the earthquake sent about 2 million cubic meters of limestone rubble hurtling down a mountainside here, obliterating houses in Xiaojiaqiao village and creating a 70-meter-high dam on the Chaping River. These landslides traveled over extraordinarily large distances, and the dynamic regimes of emplacement are poorly constrained, because giant landslides are rarely seen in operation and because, apart from surface layers, only limited data are available about the nature of their deposits. Therefore, four kinds of rapid and long runout landslides were studied in detailed investigations, especially the largest landslides in volume, the longest in runout and landslides moving at the fastest speed, as well as the most disastrous landslides-dammed lake. The detailed information was described about these slides and debris flows, and their mechanisms were preliminarily analyzed. The paper thus aimed to describe key relations between landslide runout, drop height and volume, and so offer the prospect of improving hazard assessment and mitigation strategies in mountain districts.

Key Words: Catastrophic, Rapid and long runout landslides, Dammed-lake, Wenchuan earthquake

INTRODUCTION

On May, 12, 2008, the great Wenchuan earthquake triggered numerous landslides and debris flows.After the image interpretation and detailed field investigations, most of catastrophic landslide were shown in an inventory map (Fig.1). The landslides were distributed along the Central Longmenshan fault, e.g. the Yinxiu-Beichuan fault, especially in zones of intensity more than 10 (Wang *et al.*, 2008; Yuan, 2008) . Meanwhile, it can be seen that more than 80% landslides occurred on a hanging wall of the Yingxiu-Beichuan fault, while few landslides were found on a hanging wall of the coseicmic Mingzhu-An County falut (Huang and Li, 2009). From literature reviewed, this extreme landsliding event was related to strong quaking, cosemic thrust faulting and subsurface ruptures (Huang *et al.*, 2008; Yin, 2008 and 2009).

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From Table 1, it was found that tens of landslides occurred with a volume of 10^7 cubic meters, in which the largest landslide is the Daguangbao landslide in An County, involving 7-10^8 cubic meters of rock masses. A rapid landslide was triggered with runout exceeding 4km, and a extreme disasterous landslide caused more than 1600 fatalities. It was also known that more than 33 dammed-lakes might pose damage to life and property in the disaster-affected areas, in which the most dangerous dammed-lake named as Tangjiasan can threat the safety to Mianyang City (Cui *et al.*, 2009; Yin *et al.*, 2008).

These landslides traveled over extraordinarily large distances, and their dynamic regimes of emplacement are poorly constrained (Stephen and Herome, 2002), because giant landslides are rarely seen in operation and because, apart from surface layers, only limited data are available about the nature of their deposits. Therefore, four kinds of rapid and long runout landslides were studied in detailed investigation, especially the largest landslides in volume, the longest in runout and landslides moving at the fastest speed, as well as the most disastrous landslides-dammed lake.This paper aimed to statistically analyze a variety of extreme landslides in volume, runout and causing fatalities. The mechanicsm of selected extreme landslides was particually explored based on detailed investigations.

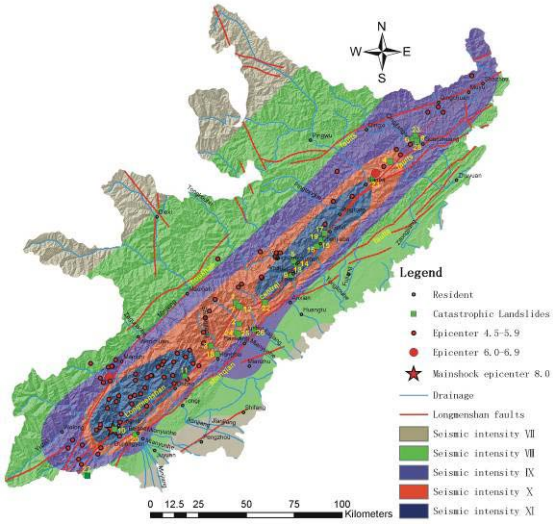

Fig. 1 Map showing catastrophic landslides in the Wenchuan earthquake event

Table 1 Ranking of extreme landslides triggered by Wenchuan earthquake

No.	Name	Location	Volume rank (m^3)		Rank of runout (m)		Rank of fatalities		capacity rank of dammed lakes (m^3)	
1	Daguangbao debris avalanche	Quanshui village, Gaochuan Town, Anxian County	1st	7.4× 108	2nd	3500m				
2	Wenjiagou debris avalanche	Qingping Town, Mianzhu County	2nd	1.5× 108	1st	4200m				
3	Shuimogou debris avalanche	Hongbai Town, Shifang County	3rd	3600× 104	7th	2100m				
4	Woqian debris avalanche	Woqian village, Magong Town, Qingchuan County	4th	3000× 104	6th	2150m				
5	Tangjiashan landslide	The right bank of Jianjiang River, Beichuan County	5th	2800× 104					1st	0.25 billion
6	Shibangou debris avalanche	Guanzhuang Town, Qingchuan County	6th	2700× 104	8th	1800m				
7	Hongshigou debris avalanche	Quanshui village, Gaochuan Ttown, Anxian county	7th	2600× 104	5th	2200m				
8	Donghekou debris avalanche	Guanzhuang Town, Qingchuan County	8th	2300× 104	4th	2400m	4th	400	6th	10 million
9	Fenghuangshan	Leigu Town, Beichuan County	9th	2000×						

No.	Name	Location	Volume rank (m^3)	Rank of runout (m)	Rank of fatalities	capacity rank of dammed lakes (m^3)
	landslide		104			
10	Niujuangou debris avalanche	Yingxiu Town, Wenchuan County	10th	2000×104 3rd 2600m		
11	Xiejiadianzi debris avalanche	Team 7, Jiufeng Village, Longmenshan Town, Pengzou County		9th 1750m	10th 100	
12	Luojiadaping east debris avalanche	Quanshui village, Gaochuan Town, Anxian County		10th 1550m		
13	Qushan township west landslide	Qushan town, Beichuan County			1st 1600	
14	Xinbeizhongxue collapse	New Junior High School, Beichuan County			2nd 500	
15	Longwancun landslide	Longwancun village, Chenjiaba Town, Beichuan County			3rd 400	
16	Zhangjiagou landslide	Chayuanliang village, Chenjiaba Town, Beichuan County			5th 190	
17	Taihongcun debris avalanche	Taihongcun Village, Chenjiaba Town, Beichuan County			6th 150	
18	Hongsong landslide	Hongsong, Shitingjiang River,Shifang County			7th 150	
19	Majiabadebris avalanche	Hongyan Village, Chenjiaba Town, Beichuan County			8th 141	
20	Limingcun landslide	Liming Village, Zipingpu Town, Dujiangyan City			9th 120	
21	Shuicaoba landslide	Shikanhe river, Nanba Town, Pingwu County				2nd 50 million
22	Xiaojiaqiao landslide	Chapinghe River, Chaping Town, Anxian county				3rd 20 million
23	Majialiang landslide	Qingjianghe River, Guanzhuang Town, Qingchuan county				4th 20 million
24	Xiaogangjian upstream landslide	Mianyuanhe River, Mianzhu County				5th 11 million
25	Xiaogangjian downstream landslide	Mianyuanhe River, Mianzhu County				7th 7 million
26	Guantan landslide	Kaijiang River				8th 5 million
27	Zhugendingqiao landslide	Jiguanshan Town				9th 4.5 million
28	Hongshihe landslide	Hongshihe River				10th 3 million

CHARACTERISTICS OF THREE LARGE SCALE LANDSLIDES

The Daguangbao rock avalanche

The Daguangbao landslide is the largest landslide in volume, with a length of 4200m, a width of 1160-3200m and a maximum thickness of 690m (Fig.2). The affected area is estimated to 6.2 km^2, and the volume to be 7.42×10^8 m^3. The main sliding direction is NE60°, and the maximum runout is estimated to be 3.5 km. The bedrock is mainly composed of schist, mudstone, limestone and dolomite. Geologically, rock masses were dissected mainly by two joints of NE 50°∠80° and SE 120°∠60°. The slid masses were originally from an isolated rocky mountain after strongest quaking, and the elevation of toe is up to 1900m asl. The motion of displaced masses then triggered rapid movement of dip-slope rock on a steep slope. It can be noted that the slid masses moved through the Hongdongzi gully, and then collided with rock masses on a slope of another gully bank. Finally, the maximum of deposition

reached up to 690m in the Hongdongzi gully. It was also noted that the direction of sliding was the same as those of the seismic wave propagation and coseismic rupture, which can make great contribution to the occurrence of rapid landslides. The process of landsliding can be interpreted as rock rupture-throwing motion of rock masses-rapid slide directing to one way along a dip slope-collision and final deposition of debris flows.

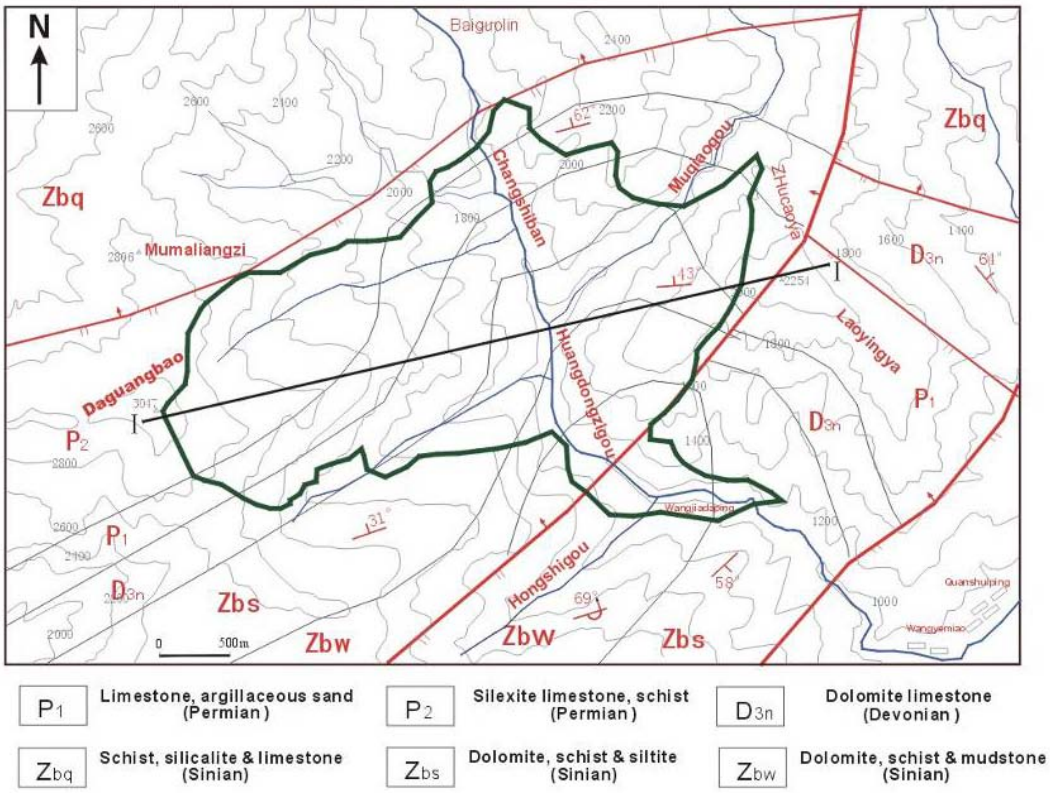

Fig.2 A sketch map of the Daguangou landslide (refer to Yin (2009))

The Wenjiagou landslide

The Wenjiagou landslide is the second largest landslide in the Wenchuan earthquake event. It has a length of 4500m, an average width of 600m and an average thickness of 50m (Fig.3). The landslide was located in an EW deep-cut gully of Mianyuan River in Mianzhu City. Topographically, the lowest elevation of gully is around 890m, while the elevation of the watershed is 2402m, thus the elevation difference is 1500m. The upper gully is fan-shaped, and its average slope is 45°. The bedrock consists of dolomite, sand-shale, limestone and quartz sandstone with an attitude of 280°-310°∠35°. It was noted that the combination of geological and topographic features was susceptive to landsliding in this area. After the triggering of quaking, dip-slope rock masses slid with a high speed and moved forward to be thrown at an elevation of 1600m. Parts of displaced masses flied off the gully and collided with a ridge on the right bank of the gully, and then moved back to the gully. These parts re-collided with other parts from displaced masses, and deposited in the gully. After this process of collision, debris flows occurred with a high speed.

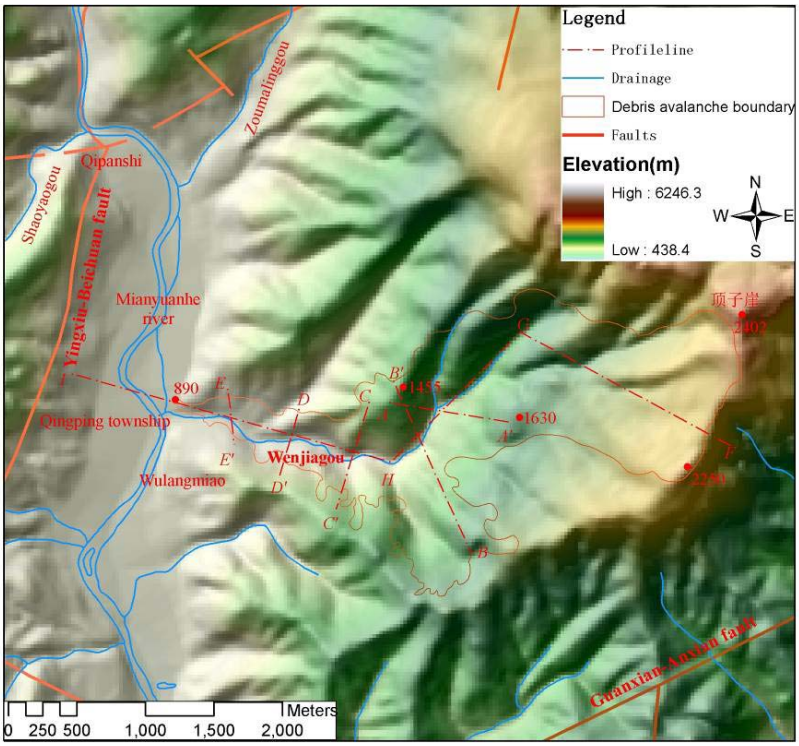

Fig.3 Relief and faults distribution map around the Wenjiagou landslide region

The Shuimogou rock avalanche-debris flow

A rock avalanche-debris flow occurred in a mining zone of Hongbai Town in Shifang City, causing 50 fatalities. This geohazard is closed to the coseismic fault zone. The rock avalanche-debris flow was shaped as a converse mushroom with a area of $9.0\times10^5 m^2$. In the flowing area of debris flow, it is a long shape with a width of 450, while the area of accumulation is wide up to 1000m. Its average thickness is up to 40m and the volume of debris flow is $3.6\times10^7 m^3$.

The debris flow is originally generated on a convex slope with a degree of 47. Its back scarp was located at an elevation of 1930m, and the toe is 1000m asl. The bedrock is composed of granodiorite and limestone, and superficial rock was fractured due to the development of joints and weathering. After the earthquake happened, the rock masses fell down slope and were projected. After the projectile motion, the masses moved speedily and then collide with other slid rock masses. Finally, most of debris deposited along the toe of gully slope (Fig.4).

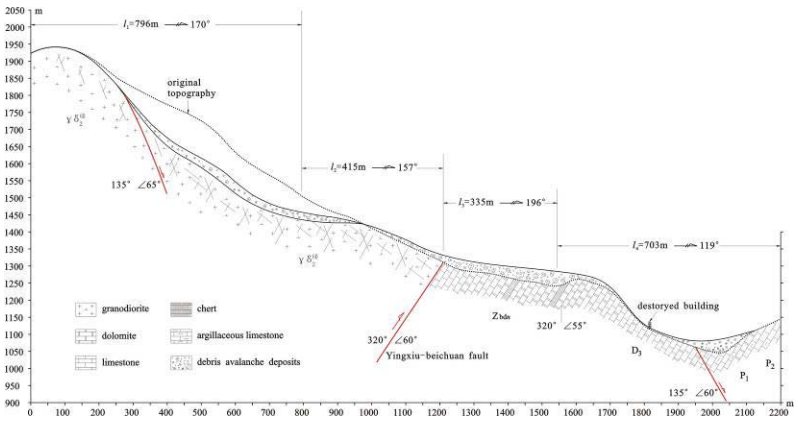

Fig.4 Profile of rock fall-debris flow in the Shuimogou Gully

DESCRIPTION OF TWO RAPID LANDSLIDES WITH LONG RUNOUT

The Niuquangou slide-debris flow

A slide-debris flow occurred in the Niuquangou around the epicentre of Wenchuan earthquake. The runout is estimated to be 2.4 km. The back scarp is 600m in elevation and displaced masses is originally from strongly weathered granodiorite on a steep slope. After quaking, the upper part of rock was ruptured and slid to the gully with a high speed. Then, the slid masses moved forward to collide with rock on another bank of gully. The masses were fractured, and debris was generated to flow from West to East (Fig.5). It was noted that the rapid debris flows moved up to another bank and then collided each other four times, indicated as different impact points in Fig.5. During its rapid movement, the debris flow moved forward 1km, and then accumulated to destroy more than ten buildings, causing 30 dead. The accumulation area was 500m long, 100-150m wide and 30m thick. Its volume is estimated to be 150 m^3. The deposit is composed of fractured granodiorite and sandstone, as well as colluviums, of which average diameter is 10-30cm.

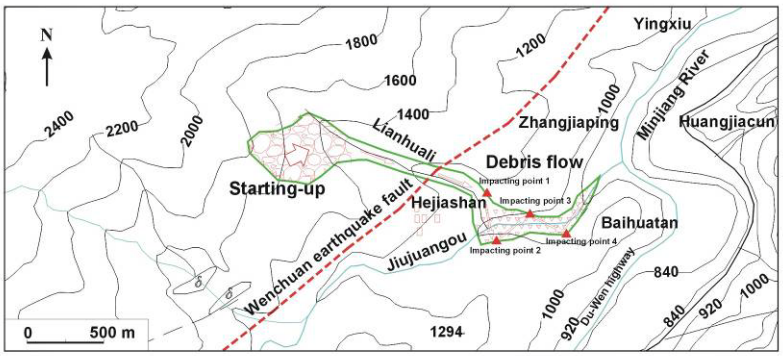

Fig. 5 Sketch map of the Niuquangou slide-debris flow (refer to Yin(2009))

After the detailed investigation, it was found that strong quaking generated wave propagation and coseicmic rupture, which made rock masses from the back scarp throwm to move forward. Meanwhile, narorowness of gully and slope difference can make contribution to the rapid sliding. Throughout analyses of geological and geomorphical features, the process of rapid slide can be interpreted as following: being thrown of rock masses on a slope-sliding down slope-collision-transfer of ruptured rock masses-rush over the deep cut gully-colliding over four impact points-accumulation of debris flow.

The Donghekou rock avalanche-debris flow

The Donghekou slide is a rapid, long runout slide which blocked a river forming a landslide lake at Donghe village of Qingchuan County. This slide moved over 2.4km and its volume is estimated to be $1.0\times10^7 m^3$. The slide occurred at the confluence of the Jinzhujiang River and the Hongshi-he River. After this sliding triggered by the earthquake, more than 400 people were killed and seven villages buried.

The main scarp was located at an elevation of 1350m asl, and the height difference between the main scarp and the toe is 700m. The slide masses are originally from sandstone, shale, and schist on a slope with a degree of 35 (Fig.6A). This area was affected by the coseismic fault, and weathered rock on the upper slope was fractured due to strong quaking. Rock masses were thrown at a direction of NE60°, and then rapidly moved down slope (Fig.6B). At a

elevation of 900m, the rock masses flied off and an air blast generated, making its movement extremely rapid. Parts of slid masses blocked the Honghe River, a dammed lake was then generated (Fig.6C). Other parts of slid masses moved forward to collide with rock on the opposite slope. After collision, the debris was generated and flowed on the main sliding direction (Fig.6D). The debris flow scoured the left bank of the Qingjiang River and generated a landslide dam consisting of loose debris and large rocks, which was 700 m long, 500 m wide, and 15–25 m high. A river in the travel path forms an important hydrogeological condition for the slide, and may have induced undrained behavior in the sliding mass during movement, resulting in rapid and long runout sliding. To conclude, the geohazard was formed by the process of being thrown by strong vertical quaking-rapid movement-air blast-collision-debris flow-liquefaction-debris accumulation.

Fig. 6 Photos showing the Donghekou slide-debris flow before and after the earthquake

FEATURES OF TWO DISASTEROUS LANDSLDIES

The Wangjiayan slide

The Wangjiayan slide was located in Beichuan County. The slide destroyed hundreds of buildings and caused 1600 fatalies, which is one of the most disasterous geohazards over the world. The slide was activated from an old landslide, which is closed to the seismic fault.The bedrock is composed of shles and schist. The height difference is 350 between the main scarp and the toe of slide. After rock avalanche, the slid mass was thrown at an elevation of 200m asl. After an air blast generated, the displaced masses slid over 550m, and then buried more than 50 of six-floor buildings.The deposited masses were 400m long, 400m wide and 300m thick, and its volume is estimated to around $4.8\times10^{6}m^{3}$. The slide has three segements as shown in Fig.7:

1. Rapid throwing segement in the source area

Rock masses were thrown from a slope at an elevation of 500 to 800m. The slope of bedrock is 55°, of which the shape is typically convex. The sliding of upper parts of displaced masses make the lower segement of bedrock slide.

2. Sliding segement

After the slid masses were thrown and collided with other rock, an air blast was generated. The masses then flied over 400m and destroied more than 100 buildings.

3. Areas destroyed by the air blast

Due to the air blast, the destroied buildings directionally accumulated on the toe of rapid slide.

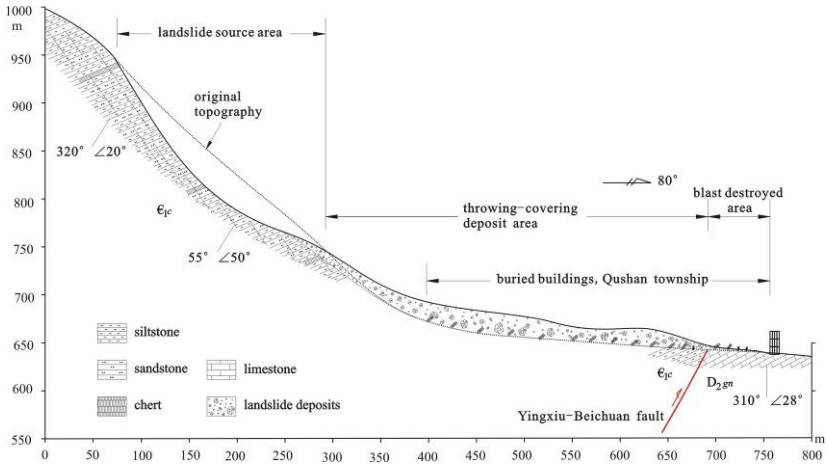

Fig.7 Profile of the Wangjiayan slide closed to Beichuan County

A slide in a new middle school of Beichuan County

Triggered by the Wenchuan earthquake, a sldie was reactivated at the Middle School of beichuan County, buring parts of building in the school and causing 500 fatalities.The slide is 560m long, 200m wide and approximately 20m thick, and its volume is estimated to $2.4\times 10^7 m^3$. The main scarp is located at an elevation of 900m and the height difference is 280m between the main scarp and its toe (Fig. 8). The bedrock mainly consists of thick limestone of Upper Devonian and lower Carboniferous Periods.

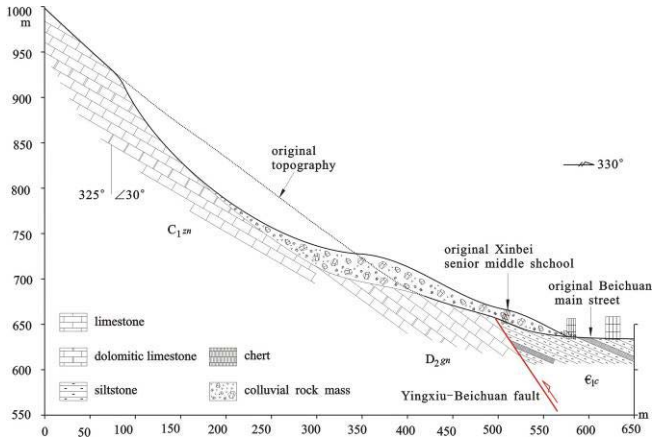

Fig.8 Profile of a slide closed to a new middle school of Beichuan County

DESCRIPTIVE ANALYSIS OF THE LARGEST DAMMED LAKES

The Tangjiashan dammed lake

The largest lake dammed by debris is located at Tangjiashan, 3.2 km upstream from Beichuan

Town. The height of dam is 80-120m, and its length is 610m. It has an estimated water storage capacity of 2.4×10^8 m^3, and a submerged area over 8.9 km^2 up to Zhicheng Town 23 km upstream from the dam. The water level rose at the end of May and increased the risk of dam outburst greatly threatening the lives and property of more than 30 thousand people downstream in Mianyang City. After the engineering measurement of constructing a spillway taken in June of 2008, the water level in the front of dam decreased from 743 to 719m, which was the target elevation deemed to be safe.

The Tangjiashan slid masses were composed of medium highly weathered schist, slate, and sandstone on a dip slope. The original attitude of the bedrock is NW30°∠42°. The height difference between the toe and main scarp was 650 m, and the horizontal distance was about 1,250 m. Because of the collision with rock on the slope of the north river bank, the debris reached a thickness of 30–50m at the north margin of the landslide dam. This is an area where the landslide debris ran up the opposite slope and then receded part of the distance of the initial run-up.

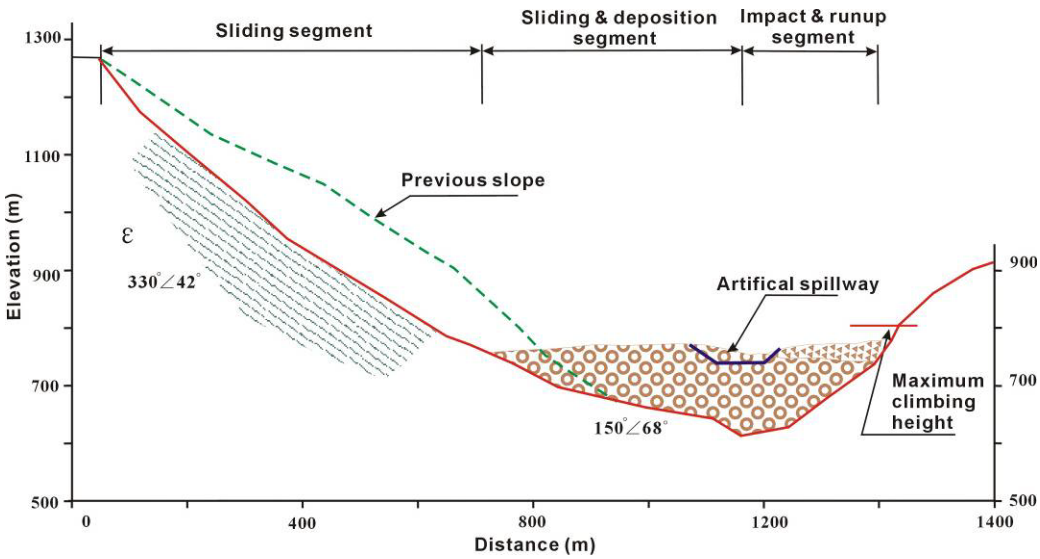

Fig.9 Profile of the Tangjianshan slide (refer to Yin (2009)

CONCLUSIONS

In the disastrous event, numerous landslides were triggered by quaking, especially as rapid and long runout landslides. These landslides traveled over extraordinarily large distances, and the dynamic regimes of emplacement are poorly constrained, because giant landslides are rarely seen in operation and because, apart from surface layers, only limited data are available about the nature of their deposits. Therefore, four kinds of rapid and long runout landslides were studied in detailed investigations, especially the largest landslides in volume, the longest in runout and landslides moving at the fastest speed, as well as the most disastrous landslides-dammed lake. It can be concluded after data collection, image interpretation and field investigation as following.

(1) Extreme disastrous slides and debris flows were found within the area of intensity from X-XI along the central Longmenshan fault, e.g. the Yinxiu-Beichuan fault. More than 80% of extreme rapid landslides were shown on the hanging wall of the fault, while few can be found on the hanging wall of coseismic faults. The strong quaking force, main wave propagation

and seismic fault activity of extending northeastward made great contribution to the extreme disastrous landsliding in the study area.

(2) The Wenchuan earthquake triggered many rapid landslides or with long runout. The largest slide is the Daguangbao slide with an estimated volume of $7.42\times10^8 m^3$, and its maximum runout reached to 3.5km. The longest runout is estimated to be 4.2km for the Wenjiagou slide with a volume of $1.5\times10^8 m^3$. It can be interpreted that particular geomorphic features and steep dip slopes make great contribution to the occurrence of this kind of slides, beside the trigger of strong quaking and ruptures of coseismic faults.

(3) The disastrous landslides were located to the areas with dense population in Beichuan County and other towns. Ten extreme slides and debris flows caused 3751 fatalities, in which single slide killed more than 1000 persons in this populated area.

(4) A variety of dammed lakes was formed in this earthquake event. The largest lake dammed by slide-debris flow is located at Tangjiashan, 3.2 km upstream from Beichuan Town. The height of dam is 80-120m, and the length of dam is 610m. It has an estimated water storage capacity of 2.4×10^8 m^3. After the engineering measurement of constructing a spillway taken in June of 2008, the water level in the front of dam decreased from 743 to 719m, which was the target elevation deemed to be safe.

ACKNOWLEDGEMENTS

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