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The Mechanic Model of Tension-shearing Landslide Triggered by Wenchuan Earthquake

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Under complex geologic conditions, the Wenchuan Earthquake, with its high magnitude and unusually long duration of shock, has triggered massive landslides. Based on the field work of investigation and referring to the literature concerned, the present study concludes that the Zhengjiashan landslide is of type I mechanical failure. The Zhengjiashan landslide is triggered by the forceful dynamic shock of the "5.12" Wenchuan Earthquake. Over 2 million cubes slid at high speed caused by shattered and tension rock mass shearing the leading edge of the locking-up area, and rushed the school and farmhouses in the leading-edge body, causing 33 deaths including 12 students, 2 teachers and 19 farmers. It was, then, blocked by the opposite mountain mass when entering into the Ziku River and formed a barrier lake after the concussion and accumulation. The landslip is a typical earthquake-triggered tension-shearing landslide, characterized by high-speed slide-falling with strong dynamic force that can grow into smooth slide bed near the causative fault and bedding fault.

1. Introduction

Under complex geologic conditions, the Wenchuan Earthquake, with its high magnitude and unusually long duration of shock, has triggered massive landslides at 112 localities in the seismic area, the total area (including the landslide source area, the accumulation area and the clastic flow area) of which reaches over 50000 m^2 (XU Qiang (2008); Xu Chong (2009); Xu Xiwei (2008); CUI Peng (2008)). These landslides, thus induced, have been classified by Prof. Yin Yueping (2009) into five categories, i.e., staircase-shaped, convex-shaped, bowel-shaped, slump-shaped and huge rock-stone. According to the characteristics of the dynamic forces based on the formation mechanism of geological hazard, Prof. Huang Runqiu (2009a) has classified the seismic landslides into the shattering-sliding type, the shattering-falls type, the ejection type, the peeling type, and the concussion fracture type. The landslides at the sites of Daguangbao, Wangjiayan, Laoyingyan are of typical shattering-sliding type, while the one at Niujuangou site the typical shattering-falls type (Huang Runqiu (2008a, 2008b, 2009a); Pei X J (2010); XU Xiangning (2014); Yin Yueping (2009)). Through site investigation and mechanical analysis of the landslides at the sites of Mt. Zhengjiashan and Wenjiagou, we have identified them as the typical tension-shearing landslides that are of the same mechanical model. Therefore, we mainly focus on the mechanical analysis of Zhengjiashan landslide in the present study.
The landslide of Mt. Zhengjiashan is located in the Zhengjia Mountain Groups of Xinping village of Shikan Town in Nanba, Pingwu County. Lying 25 km away from the Pingwu County seat, Mt. Zhengjiashan is an isolated thin ridge with discontinuities and broken rocks. Induced by the Wenchuan Earthquake, the landslide body reached about 210×10^4 m^3 and slid down at such a high speed that it destroyed the farmhouses on the mountain top and buried the houses, schools, and roads at the mountain foot, causing great economic losses and 33 deaths including 12 students, 2 teachers and 19 farmers.

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Figure 1: The landform and physiognomy of the landslide region

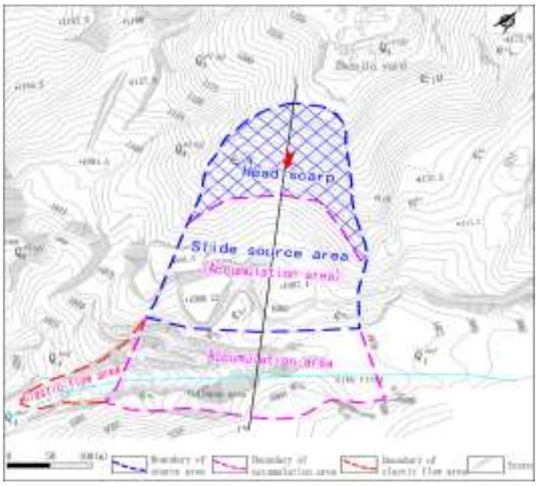

Figure 2: The zoning map of landslide

2. The geological condition of sliding region

2.1 Landform and Physiognomy

Lying on the eastern edge of the Qinghai-Tibet Plateau and in the northern mountainous area of Sichuan Province, the Zhengjiashan landslide is situated in the transitional zone between the Qinghai-Tibet Plateau and the Sichuan Basin, which forms a large terrain with great height disparity from the north to the south. With valleys crisscrossing, this area is also heavily disrupted and is characterized by the typical Mountain-Canyon relief. In the slide area, since the trailing edge reaches 1225 ~ 1475 m and the leading edge 1030 ~ 1090 m, there is an relative elevation of 300 ~ 475 m. The overall slope angle is about 20 ~ 40°, and up to 70° locally. The transverse landform consists of three valleys and one ridge (See Fig. 1).

2.2 Stratigraphic Lithology

The major strata of the investigated area consist of the Quaternary colluvim, the Quaternary eluvium, the Quaternary alluvium, and the siliceous slate of the Qiujiahe formation in the lower series of the underlying Cambrian system.

2.3 Tectonic Setting

Pingwu County is at the juncture of three primary tectonic units, namely, the Yangzi quasi-platform, the western Qinling fold belt, and the Songpan-Ganzi fold belt, spanning over from the decken structure at its rear part of Mt. Longmenshan to the thrust-reversal fault at its front. The area under investigation is between two subsidiary faults of the Shikan fault, 500 m away from the NW subsidiary fault and 100 m away from the SE one. Located in the Shikan Village of Nanba Town, the Shikan fault extends northeastwards from the Jianzhuya nek to the Yanmenba flatland, and reaches southwards to the Guandiping fault to form an apposite fault of 21 km long. This Shikan fault has a NE trend, though deviating northwestwardly at a dip angle of more than 60°. The hanging side at the NW end of the fault includes the Shuijin series and the Qiujiahe series, while the heading side at the SE end consists of the Youfang series and part of the Qiujiahe series. And the Qiujiahe series is set between the two subsidiary faults. Therefore, judging by its strata, the superposition of lens-like tectonic structure, as well as the retrogressive fold conditions, the fault in question is identified as a slip-reverse thrust.

3. Development characteristics of slide

The present study elaborates on the source zone, the accumulation zone and the clastic flow zone of the slide, so as to identify the overall boundary of the slide source zone and the general characteristics of the congeries, although the source zone partially overlaps the accumulation zone under the effect of specific terrain conditions (Fig. 2).

3.1 Landslide Source Area

The source area consists of the slide cliff and its trailing edge. The cliff is 200 m high, with an elevation range of 1115 ~ 1225 m and the largest elevation difference of 110 m. The slide cliff is a smooth and straight bedding plane, whose occurrence is 193°∠40°. On the slippy surface are a group of 30 m-long steep discontinuities in NW direction, with the average spacing of 2m and the 5cm-wide opening filled with siliceous slate debris.
In the meizoseismal area, the initial P waves emitted by the earthquake exert great vertical force and shatter the mountain mass along the bedding plane to form extension fractures. When the subsequent S waves arrive, the fractures are pulled further apart and extend deep inside to form the slippy surface of the trailing edge after slide. Since it has been some time before the study after the occurrence of the overall slope failure induced by the earthquake, several slickenside lines in the NNW direction have developed on the slippy surface of slide trailing edge, due to the weathering and denudation of the slate. The tension plane on the trailing edge in the south runs 100 m long in the NW direction, with an elevation range of 1115 ~ 1175 m and the largest elevation difference of 60 m, at a dip angle of 30 ~ 40°.
On the lower course of the landslide are the loose congeries and siliceous slates that are discrete and broken with discontinuities in the NW direction. The P waves of earthquake produce a vertical force that cause tension cracks in the NW direction deep inside the mountain mass. When the S waves arrive, the loose mountain mass at the slide trailing edge slips down and creates extension fractures at the lower course of landslide, during which process the wedge fractures are produced under the dilatancy effect, and the rim of the lower course of the landslide is made saw-toothed with discontinuities in the NW direction.

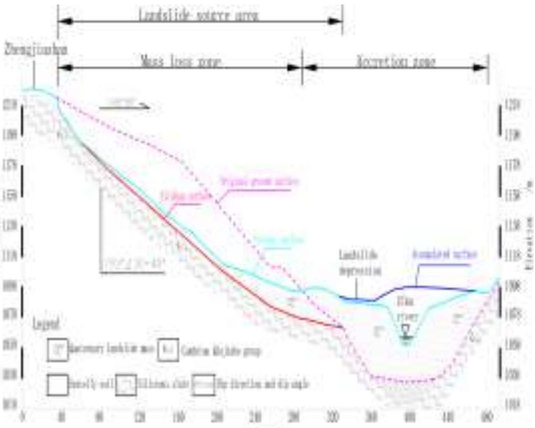

Figure 3: The typical profile of the landslide

3.2 Accumulation area

At great speed, the Zhengjiashan landslide falls along the fault and forms congeries on the SE, which is 280km long, 360 m wide, over 60 m high at the thickest point, and has a volume of 210×10^{4} m^{3}. At first, the sliding m ass rushes across the Ziku River, and then when blocked by the opposite mountain, it reverses to climb as high as 60 m before its loosened rocks, carried by the great inertia, finally turn back and settle down. As a result, the debris flows into the riprap section under the landslide dilatancy effect, moving along the lower reach of the Ziku River to cover a distance of 150 m. Once formed by the landslide, the barrier lake in the Ziku River is dredged later on, and then down-washed and dissected by floods to form the present relief (Fig. 3).
Generally speaking, the relief intensity of the sliding congeries remains low. While furrows alternate with ridges and mounds, the accumulation zone takes on a mild wave-like terrain that seems to be produced by the transmission of seismic waves (Huang Runqiu, Pei Xiangjun, Li Tianbin (2008)). On the basis of the spot

investigation into the fractures and failures, the rock movements in different sections, and the different topographic features of the landslide congeries, the accumulation area can be divided into five section, each with its specific characteristics as follows:

Section 1: the avalanche-debris-cone section. It is formed when the loosened sliding mass falls from the slide crown to fill the heading edge of the landslide bedding. It consists of broken rocks of siliceous slate and a small amount of the Quaternary drift, which are in accordance with the lithology of the landslide cliff at the crown. These broken rocks, ranging from 2 cm to 50 cm, accumulate in a typical way of avalanche deposit with finer rocks on the top and coarser ones at the bottom, covering the heading edge of section 1.

Section 2: the ridge-mound section. After the swift slip of huge landslide mass, the quake-ruptured rocks at the mountain top are softened by the rain, and due to their dead weight and plastic deformation, they creep onto the bottomland and form the wide and mild mound with ridges that runs 40 m long and 200 m wide along the slope. The congeries consists of moderately weathered siliceous slates with particle diameters ranging from 20 cm to 100 cm, covered by loose Quaternary deposit.

Section 3: the landslide bottomland. After high-speed sliding, a typical bottomland forms at the trailing edge of congeries. It is 50 m long and 200 m wide along the slope. The majority of its congeries consists of taupe or yellow-grey collapsed rocks of siliceous slate, though there is a little cinereous carbonaceous slate. The rocks with the diameter larger than 0.5 m take up 40% of the congeries. Mixed with some plants from the mountain top, the congeries are covered by a layer of slide-raised dust as thick as 5 ~ 10 cm.

Section 4: the main accumulation area. It is 150 m long and 200 m wide. The majority of its congeries consists of taupe or yellow-grey collapsed rocks of siliceous slate, mixed with a little cinereous carbonaceous slate. According to the investigation of the riverbed of the Ziku River, there are partially broken rocks of siliceous and carbonaceous slate among the congeries, due to great changes in their occurrences. Less raised dust is found on the surface, but there are many massive corestones, with the diameter of nearly 3 m.

Section 5: the clastic flow section. The collapsed rocks of taupe or yellow-grey siliceous slate mixed with a little cinereous carbonaceous slate are accumulated by the high-speed flow of broken rocks moving toward the low-lying area during the quake oscillation and retracing process. The diameter of most stones is smaller than 0.5 m, and stones with a diameter smaller than 30 cm take up 50% of all.

Generally speaking, the congeries accumulates during the landslide falling on the main course. Separated by the level ground of Wujiaping on the opposite bank, the congeries are divided into 5 sections, with sections 1 being the landslide source, section 2 the accumulation, and section 3 the common area. The size of the sliding rocks increases from section 1 to section 4. Some unbroken masses of rock are found in section 4. Based on the congeries composition on the investigation spot, the landslide accumulation process can be illustrated as follows: the dynamic forces of earthquake shatter the mountain masses and cause the failure. The main landslide body flows down at high velocity like poured water. With space limit in very short time, the main sliding body, then, reverses against the level ground of Wujiaping and climbs up to form the anti-slope tableland of thrust block before it finally settles. The top section of sliding body above the intensive weathered layer is casted forward, with only a fraction retracing when blocked and accumulating with oscillation before the stop of the landslide. The clastic flow is carried by the inertia force down into the riprap section under the dilatancy effect. Since the Ziku River bed is narrow and zigzagging, the riprap moves along the lower reach of the river, covering a distance of 150m. The landslide body blocks the river and forms the barrier lake in the Ziku River, which is dredged later on, and then eroded by floods. Thus, the present accumulation relief comes into being.

4. Mechanical analysis of slide

Based on what has been discussed above, the failure mechanism and the formation of the high-speed and “tension-shearing” landslide of Zhengjiashan can be illustrated by the concept model in Fig. 4. The main features of the model are as blow:

(1) Stages of slope shattering cracking, bedding plane tensile cracking and relaxation

Affected by a long-term earthquake of great intensity, the landslide body goes through great shock and falling, featuring the relaxed rock planes (the principle bedding plane) and the decline of friction-resistance force. During transmission, the seismic waves of strong earthquake, either P waves or S waves, if blocked by fragile plane, will produce tensional stress; on the other hand, repeated shock will cause progressive displacement of the discontinuities. So, the strength of the rock plane gradually decays, its intensity shortly falling from peak to residue.

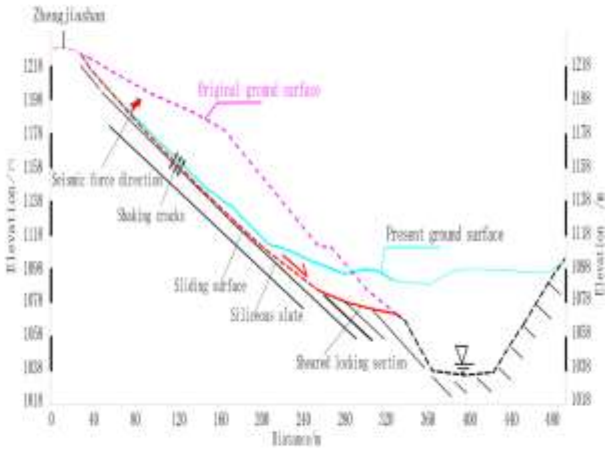

Figure 4: The conceptual model of failure mechanism for zhengjiashan landslide

(2) The Shattering-Sliding Stage of the Sheared Locking Section
When the mountain masses cracked by the earthquake, the heading edge of the slide partially fractures. With the decline of the friction-resistance of the bedding plane, under the stress of earthquake and the dead weight of the sliding body, there is a brittle shear failure of the locking section of rock. Without resistance, the huge sliding body, like poured water, swiftly falls down along the bedding surface.
(3) The Accumulation Stage under Oscillation Effect
The sliding body rushes across the Ziku River, and then when blocked by the opposite mountain, it reverses to climb as high as 60m before its loosened surface rocks, carried by the great inertia, finally turn back and settle down to form congeries in mild way.

5. Conclusions

(1) Mt. Zhengjiashan is an isolated thin ridge with discontinuities and broken rocks, no more than 500m away from the causative fault. The bald mountain magnifies the seismic waves during the earthquake. The shattered rock masses loosen to produce large-scaled failure when friction-resistance declines.
(2) On the basis of the spot investigation into the fractures and failures, the rock movements in different sections, and the different topographic features of the landslide congeries, the landslide can be divided into three areas, i.e., the source area, the accumulation area and the clastic flow zone. The accumulation area can be further divided into the avalanche-debris-cone section, the ridge-mound section, the slide bottomland, the main accumulation area, and the clastic flow section.
(3) The principle structure face of Zhenjiash slide is a bedding plane. The failure is the typical tension-shearing type. According to the present study, the slope failure and landslide accumulation occurred simultaneously in very short time during the quake. The dynamic landslide formation process includes: affected by a long-term earthquake, the sliding body goes through great shock and falling, featuring the relaxed rock planes (the principle bedding plane) and the decline of friction-resistance force. Under the earthquake horizontal stress and the dead weight of landslide body, there is a brittle shear failure of the locking section of rock. Without resistance, the huge landslide body, like poured water, swiftly falls down along the bedding plane.

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