Classification of Landslides Induced by China Wenchuan 2008 Earthquake and Mechanisms of their Sudden Departure

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Abstract

Over 300 large landslides were triggered by 2008 Wenchuan earthquake and many of them caused the felt ground tremor. The surface tremor, different from aftershocks, was induced by the sudden release of elastic strain energy stored in the locked landslide segments in the form of sudden shearing rupture of the locked segments. So that, this ground tremor is named by landslide-quake in this paper. Our study clearly indicates the following two main characteristics of a landslide-quake: (1) landslide earthquake occurs prior to the sudden departure of the landslide and (2) its epicenter is located between the potential sliding mass and the bed of the locked segment, and directly contributes to the departure mode and the acceleration of the sliding mass. Based on the above characteristics, we believe that landslide-earthquake is the essential reason for the sudden departure of most large high speed landslides. Consequently, according to the occurring time of a landslide-quake related to the Wenchuan 2008 earthquake, the large landslides triggered by the earthquake are classified by three categories: (1) *main shock landslide*, for which there is no landslide-quake and the main contributing forces are main shock force of Whenchuan 2008 earthquake and the gravity of sliding mass; (2) *co-seismic landslide*, for which a landslide-quake develops before the end of main shock of the earthquake and the main contributing force are landslide-quake force, earthquake force and the gravity of sliding mass; and (3) *after-main-shock landslide*, for which a landslide-quake happens after the main shock of the earthquake and the main contributing forces are landslide-quake force and the gravity of sliding mass. The processes of sudden departures of these three kinds of landslides were analyzed, by which landslide-quake may be a new explanation for the sudden departure of a large scale high speed landslide.

Keywords: landslide-quake, classification of earthquake-induced landslide, mechanism for sudden departure

1. Introduction

"2008.5.12" Chinese Wenchuan earthquake was characterized by high magnitude of Ms 8.0, shallow focus of 14km, long duration of about 120s and strong destruction. More than 15000 landslides was induced by this catastrophic earthquake resulted in serious lives and properties lost. According to statistics, over 300 landslides were characterized by large volumes, of which 112 landslides have a sliding area of more than 50,000 m2. (*Teng, Bai, Yang, et al, 2008; Burchiel, Royden, Vander, 2008; Meju, Unsworth, 2008; Xu, Huang, 2008; Huang, Pei, Li, 2008; Xu, Pei, Huang, et al, 2009; Yin, 2009; Xu, Dai, 2010*). About 87,000 people died due to the earthquake among which over 20,000 people lost their lives because of landslides.

Aftershocks continued after the main shock. In fact, 12139 aftershocks were detected by the seismic stations in 33 days after the earthquake, of which 208 aftershocks had a magnitude of about Ms 4.0, 28 aftershocks had a magnitude of about Ms 5.0, 6 aftershocks had a magnitude of about Ms 6.0. However, some local ground tremors were not detected by seismic stations. These tremors were triggered by large landslides but not the earthquake or its aftershocks. They generated due to the sudden release of elastic strain energy stored in the locked segments of the landslides because of the sudden shearing rupture of the locked segments. To emphasize the forming, we call this kind of ground tremor landslide-quake here in this paper, which have not been noticed by landslide researchers. Basing on characteristics of landslide-quake, the classification of the landslides induced by Wenchuan earthquake are carried out and the mechanism for rapid departure of different type of landslides is studied.

Many large landslides triggered landslide-quake, which can be proved by the phenomenon when landslides occurred. For example, many survived people heard a big bang bang prior to the occurrence of Daguangbao landslide and Laoyingyan landslide in Anxian county, Wangjiayan landslide in Beichuan county, Donghekou landslide, Woqian landslide, Dayanqiao landslide, Dongjia landslide in Qingchuan county, Wenjiagou landslide in Mianzhu city, Pingxichun landslide in Pingwu county and a landslide at K24 of the expressway from Yingxiu to Wolong. They described the sound as “an explosion”, “a thunderous noise”, “a huge roar”, “a deafening noise”. And they were sure that the sound was heard before the rock masses rushed out. So, the sound can be considered as a prove of landslide-quake.

2. Description of Wangjiayan landslide and the formation of a landslide-quake

Wangjiayan landslide occurred 10 min after the main shock of Wenchuan earthquake (refer to Huang, etc, 2008 for details). Fig. 1 shows the ground stress in the rock mass after the earthquake.

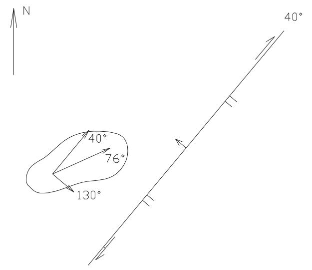

Fig.1 Sketch for Stress of Wangjiayan landslide

From Fig.1, the dip direction of its gravity stress was the same as the slope dip direction, about 76°. The tectonic stress in the landslide had a strike of about 130° due to the oblique impaction of its embedded fault wall because the landslide located in the upper wall of the reverse fault, Yingxiu-Beichuan fault. At the same time, the fault was a strike-slip fault despite a reverse one and the dextral strike slip co-seismic displacement resulted in a co-seismic geotectonic stress with a direction of about 40°. The 40° and 130° stress compounded a 70°-85° stress which was most the same as the gravity stress and the slope dip direction.

Fig. 2 is the sketch of the longitudinal section of Wangjiayan landslide, in which AB and is a tectonic joint with an attitude of 70°-85°∠60° in the landslide. Due to the intense and repeated vibration, the joint had a splitting loose but not linked up to the point D in Fig. 2. The CD section was the locked segment, and strain energy was concentrated in the segment. The increasing strain energy finally resulted in a sudden broken of the rock mass along CD, and the energy released suddenly resulted in a landslide-quake. This imply that not only the gravity but also the tectonic stress were responsible for the forming of the landslide. It was the coupling of the gravity and the tectonic stress that resulted in the landslide. So this kind of landslide is not only a gravity phenomena but also a tectonic geologic phenomena. Thus, we can take the earthquake-induced landslides and landslide-quakes as faults of the rock on the ground surface.

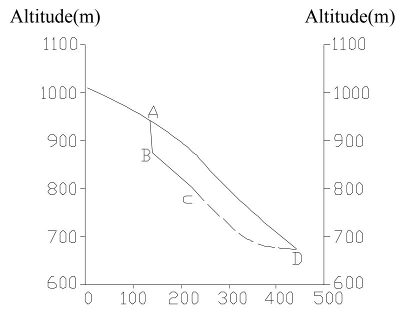

Fig.2 Sketch for the longitudinal section of Wangjiayan landslide after Wenchuan earthquake (revised from Huang, 2008)

From the investigation of the large landslides triggered by Wenchuan earthquake, landslide-quakes have two obvious characteristics as below.

(1) A landslide-quake occurs prior to the sudden departure of the landslide. It is because the sudden releasing of the concentrated strain energy in the locked segment that a landslide-quake formed. And the landslide takes place under the coupling of its gravity and stress due to the landslide-quake. So the landslide-quake is the reason the landslide but not the result of the landslide. There is a short time difference between their two. Again taking the former described

Wangjiayan landslide, it was 10 min after the main shock of Wenchuan earthquake that a big bang bang was heard followed by the dust billowing and debris launching due to the occurrence of the landslide. The similar process occurred in another landslide, Laoyingyan landslide. According to the survivor testimony, after a short time of the main shock of Wenchuan earthquake, a big noise like a huge roar was heard before the landslide occurring with a big sound like water rushing out of Jiangbagou ditch. These two landslides told that the high-speed landslides occurred after the big noises due to landslide-quake were heard.

(2) The focus of a landslide-quake is just on the sliding surface, so its effect on the behavior of the sliding body is very directly without distance. The retain part of a landslide could be considered infinitely-great, while the sliding part is comparatively very small, always a tens depth. So, the strain energy releases just like an explosion.

Despite of a comparative smaller magnitude to an earthquake, a landslide-quake can induce a very high speed of a landslide by its coupling with gravity because of its above characteristics.

Calculation of the magnitude and its releasing energy of a landslide-quake

As explained earlier, the sudden shearing rupture of the locked segment of a earthquake-induced landslide is similar to the process of the shearing broken of a seismogenic active fault. The locked segment can be taken as the focus. Thus, the magnitude of a landslide-quake can be calculated using the method for an earthquake introduced by Wyss in 1979, in which the shearing broken area, A in km2, was used to calculate a magnitude, M, as shown in (1) and the releasing energy of a landslide-quake, E in Erg., can be calculated by the use of M, as shown in (2).

$$M=\log A+4.15 \quad (1)$$

$$\log E=11.8+1.5M \quad (2)$$

In Wangjiayan landslide , according to the investigation, A=350m×350m=0.1225km2, so ML=3.2 can be obtained by using (1), and then E=3.98×1016 Erg.=3.98×109 J.

3 Classification of earthquake-induced landslides

From the investigation of the landslides triggered by Wenchuan earthquake, some landslides were formed under the main shock force and the gravity, and some were formed under the main shock force, landslide-quake force and the gravity, while others were formed by the landslide-quake force and the gravity because there occurred after the main shock. By this, the landslides can be classified into three categories as shown in Tab. 1.

Tab. 1 Classification of large landslides in Wenchuan earthquake

Classification (example)	Forces for un-stabilizing	Noises of main shock and landslide-quake
Main-shock landslide (Beichuan middle school landslide)	Main-shock force, gravity	The noise is smaller than the main shock rumbling when landslide takes place.
Co-seismic landslide (Niumiangou landslide)	Main-shock force, landslide-quake force, gravity	There is a very big bangbang when landslide occurs before main shock ends.
After-main-shoc k landslide (Wangjiayan landslide)	landslide-quake force, gravity	After the main shock, there is a very big bang bang prior the occurrence of the landslide.

In this classification, the landslides refer to those that form directly under the contribution of intense earthquakes excluding the landslides triggered by rain or other factors after earthquakes.

4 Mechanism for sudden departure of large earthquake-induced landslides

Main-shock landslides

According to “acceleration records without correction of Wenchuan Ms 8.0 earthquake”, the PGA by nearby stations are smaller than 1 g with the smallest one of 0.2g, and the PGA times are shorter than 60 s with the shortest of 31.49 s. That is to say, it takes more than 30 s to reach the PGA of no more than 1 g. However, most of the landslides triggered in Wenchuan earthquake were near the seismogenic fault, only several km or even 100s m, so the traveling time of the seismic waves from the focus to the landslide location is shorter than 30 s, and then the PGA was not reached. Additionally, the distance from any landslide location to the focus was more than 14 km, given the focal depth of 14 km. And the energy spreads with the form of elastic waves to all the directions from the focus. The energy decreases with the increasing of its travelling distance. So, it is less possible for the energy from the main shock to eject the rock mass with the volume up to hundreds of thousands, millions, even hundreds of millions m3 out of the slope like an explosive. One may concern what contribute to the high-speed debris of main-shock landslides. As described in table 1, the landslides are made up of rock mass involving rich joints and even loose soil, which have not any locked segment. The materials are on high and steep slopes with the dip angle of 40-50°, resulting in a trend of fluidization under the intense and repeated shock. In the coupling of the main shock force and the gravity, the main shock force may completely offset the gravity resulting in a great reduction of the effective stress between the particles, even to zero. The rock mass or the soil can not remain the original form and transform to fluid. Under the repeated shock, every particle has a trend of traveling down slope. This trend may be illustrated by Fig. 3, in which the vertical and horizontal components of the main shock force are all described with acceleration, and they are all given a value of 0.8 g. The join force of the main shock force and the gravity is OP=0.82 g with a down-slope direction. If the join force is equal to the friction, the landslide will departure, and its speed will increase with the increasing of the difference.

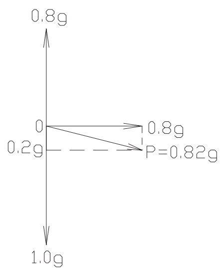

Fig.3 Force analysis for normal-earthquake landslides

Beichuan middle school landslide is here taken as an example to give a further explanation of the mechanism for main-shock landslide. Fig. 4 is the longitudinal section of this landslide which located in the footwall of Yingxiu-Beichuan fault.

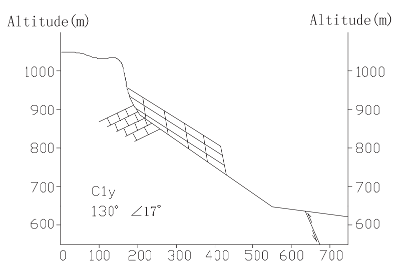

Fig.4 Sketch for the longitudinal section of Beichuan middle-school landslide before sliding in m. (from Xu, 2009)

The rock stratum was C1 gray limestone formation with interlayer of purple and brown sandstone formation. The stratum counter dipped with an attitude of 130°∠17°. There were there sets of joints with attitudes 305~310°∠70~80°, 50~60°∠70~80°, and 300~330°∠40~65°, of which the last one dipped out of the slope. These discontinuities including the joints and the bedding surface cut the rock mass into parts with various sizes. The dip angle of the middle and rear sections of the sliding surface was 40-65°, with and average of 45°. Given the friction angle of the sliding surface was 45° under main shock, the friction applying on the sliding body was f=mgcos45°·tan28°=0.376 mg. The join force of main shock force and the gravity on the sliding body was shown in Fig.3, that is F=0.82 mg>f =0.376 mg. Thus, the loose rock mass would slide down with an acceleration of 0.44 g (4.31m/s2).

After-main-shock landslides

The main character of this kind of landslides is that the landslide-quake occurs after the main shock stops. So the main shock force has no direct contribution on the landslide occurring. It is the coupling of landslide-quake and gravity that ignites a landslide. The initial velocity can be calculated by the use of releasing energy by the landslide-quake. Still taking Wangjiayan landslide as an example, the releasing strain energy was 3.98×109 J as calculated earlier in this paper. The strain energy, E, changed to the kinetic energy of the rock mass in the locked segment, the CD part as shown in Fig. 2 and resulted in the initial velocity, V. According investigation, the volume of this landslide was 14 million m3 with unit weight of 25 kN/m3. By the use of the expression, E=0.5mV2, the initial velocity V=1.49 m/s with a perpendicular direction to the sliding surface. From the velocity, the PGA at Wangjiayan landslide must be larger than 1 g, about 1.20 g. With this acceleration, the rock mass flied at high speed for 400 m and finally buried the old Beichuan county.

By the earlier analyses and the calculations, the mechanism of after-main-shock landslides can be concluded as below:

(1)Parts of sliding surface are broken by the main shock, and then more and more strain energy concentrated in the locked segment. The rock mass in the locked segment starts a progressive failure.

(2)Once the locked segment is completely broken, the highly concentrated strain energy releases suddenly and triggers a landslide-quake. Under the coupling of the landslide-quake force and the gravity, there will be sudden departure of a landslide which may be the essential reason of the high-speed landslide.

Co-seismic landslides

For this kind of landslides, a landslide-quake is triggered by the main shock force, tectonic force and gravity before the main shock ends. So, main shock force, landslide-quake force and gravity are all important factors contributing on the sudden departure of a landslide.

As shown in Tab.2, the PGA in the epicentral area (Wolong and Mianzhu) is around 1.0 g. We here take the vertical and horizontal PGA as 0.8 g and take the landslide-quake PGA as 1.2 g, the same as what has been explained earlier in this paper. The join acceleration induced by main shock force, landslide-quake force and gravity will be 2.24 g, as shown in Fig. 5. The rock mass of the landslide will be projectile upward out of the slope with a perpendicular direction to the sliding surface at the locked segment. Niumiangou landslide was an example of this kind of landslides, which had a sudden departure by high-speed flying and then travelled 3.2 km after 4 direction changing due to hitting the hills. The PGA at Niumiangou landslide was 1.5 g (Yin, 2009).

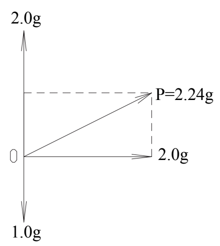

Fig.5 Force analysis for during-earthquake landslides

5 Conclusions

Many large landslides in Wenchuan earthquake have triggered landslide-quake which may be the essential reason for the sudden departure of a landslide. Landslide-quake, as well as the main shock has important effect on the characteristics and the sudden departure of a large landslide, basing on which large earthquake-induced landslides are classified into three categories including main-shock landslides, co-seismic landslides, and after-main-shock landslides. Main-shock landslides have not any locked segment and triggered by the combination of the main shock force and the gravity. It is the coupling of landslide-quake and gravity that ignites an after-main-shock landslide. For co-seismic landslides, a landslide-quake is triggered by the main shock force, tectonic force and gravity before the main shock ends. So, main shock force, landslide-quake force and gravity are all important factors contributing on the sudden departure of a landslide.

Our idea is still in the stage of working hypothesis. More investigations and studies should be carried out to show evidences for the idea.

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