Patterns and Mechanism of Rockslides Induced by Rainfall in China

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Abstract

Since 1980s, in southwestern China, especially in red-strata regions of Sichuan Basin, tens of thousands of landslides have been triggered by heavy rainfall, which include several large-scale deep-seated rockslides. For this kind of rockslides, based on field investigation, laboratory tests, physical model tests and numerical calculation, conclusions can be drawn in two aspects:

(1) the movement of deep-seated rockslides triggered by heavy rainfall can be grouped into two patterns, namely the single plane slide and the wedge block slide. For the former pattern, a landslide occurring in nearly horizontal rock strata is called translational rockslide, while that occurring along bedding plane with dip angle larger than 10° is called bedding rockslide. For the latter pattern, the symmetrical and asymmetrical wedge block rockslides are proposed based on the spatial configuration of two lateral sliding surfaces.

(2) the hydrostatic pressure in the rear edge and the uplift pressure on the bottom sliding surface both contribute to the occurrence of a rockslide. For the initiation of a translational rockslide, a critical water head in vertical cracks in the rear edge is established. The development of water pressure on the bottom sliding surface is time consuming, and the distribution mode along cracks also changes with time from triangle shape to trapezoid shape. Just because of this, the occurrence of a rockslide is always observed with lagging behind the rainfall event. This phenomenon is called hysteresis (or time delay). The present study is expected to provide basic work for the establishment of rainfall prediction model and the early warning of the deep-seated rockslides.

Keywords: rockslide, rainfall, slide pattern, formation mechanism

1. Introduction

Heavy rainfalls always cause geological disasters such as landslides and debris flows around the world, either in the tropic region or the arid region, and rainfall has become the most common triggering factor of landslides, other than earthquakes, volcanic eruptions, human activities and etc. (Keefer et al., 1987; Crosta, 1998; Wang et al., 2002). In recent years, the weather disorder due to global climate change is bringing about more and more extreme weather phenomena, which accelerates the occurrence of geological disasters. In China, one of the extreme phenomena is the rapid altering of flood and drought. For example, in 2011, before June, an extream drought not seen for sixty years hit the middle and lower reaches of the Yangtze River, causing the minimum water area since satellite records began in the Poyang Lake. After June, however, the rapid altering from drought into consecutive rainstorms not only triggered flood hazards in thirteen provinces, like Jiangxi, Hunan, Guizhou, Fujian and etc., but also triggered a number of landslides and debris flows occurring in groups. In Sichuan basin of western China, a special rock stratum is widely developed and is called red stratum due to the main apparent color of rocks (e.g. sandstone, mudstone). The rocks are extremely sensitive to water, and always cause severe landslide hazards occurring in groups in rainy season, including some well-recorded landslides like the Tiantai village landslide (Xu et al., 2006), the Kualiangzi landslide (Fan et al., 2009) and the Ermanshan landslide (Xu et al, 2012).

A wide scientific literatures reveal that short and intense rainfalls preferentially trigger soil slips, debris

(a) the colse - view of the Xingma Middle School landslide (b) crack in the rear edge (c) concrete rupture at the toe

Fig.1 The close-view of the Xingma Middle School landslide and the local deformation features.

flows and shallow landslides, while prolonged and less intense rainfalls preferentially trigger deep-seated landslides (Zêzere et al., 1999; Guzzetti et al., 2004). It should be noted that, compared to shallow landslides, the deep-seated landslides may be much less in number but responsible for the largest economic damge in a rainfall event. In spite of its importance, researches on deep-seated landslides caused by rainfall are still limited (Polemio and Sdao, 1999; Chigira, 2009; Fan et al., 2009; Tsou et al., 2011), and the specific patterns and the corresponding mechanisms of the deep-seated landslides are yet to be clearly understood.

Based on the long-term researches of rainfall-induced landslides in China, especially in Sichuan basin, where the geological and geomorphological conditions and rainfall characteristics are favorable for deep-seated rockslides, the purpose of this present paper is to show the typical patterns of this kind of rockslides and the genetic mechanisms. The research work involves multiple methods, including field investigation, laboratory tests, physical modeling tests and numerical calculation. As the ultimate goal, the early signs of sliding are expected to be identified and then the early warning can be implemented for the deep-seated rockslides.

2. Patterns of rainfall-induced rockslides

Other than the well-reported landslides, another two rockslides are herein introduced as case studies for the two failure patterns, and then the basic features of each failure pattern will be summarized.

2.1 Xingma Middle School Landslide, Sichuan

In 2007, a landslide occurred in the hillslope behind the Xingma Middle School, Xingma village, Nanjiang county, Sichuan province. The Xingma Middle School landslide is hereafter referred to as the XMS landslide. As shown in Fig.1, the landslide has a rectangle-like plan and the longitudinal length (parallel to the sliding direction) of only 15m is far smaller than the transverse length of 140 m, which makes a volume of 4.8×10^4 m^3.

The XMS landslide is restricted in the vicinty of a cliff. The slope angle is $65^o \sim 85^o$. The exposed strata of the cliff are the huge thickness of sandstones belonging to the Jianmenguan Formation of the middle Cretaceous System (K_{2j}), while a layer of silty mudstone is located in the lower part of the cliff. The strata have a a dip angle of only about 10^o. Besides, a set of nearly vertical structural planes are developed in the slope with their strikes parallel to the free surface of the cliff. They are long enough and, together with the bottom bedding planes, they cut the slope into several thin plates.

From the point of rock mechanics, although the slope has been disintegrated, the nearly horizontal rock strata will still keep the slope at a stable state. In fact, many signs of deformation indicate that the occurrence of the XMS landslide is much correlated to the rainfall. For example, Fig.1(b) shows the tension crack in the rear edge of the landslide, which was formed after the slope moved forwards 2 meters during the heavy rainfall on July 3~5 of 2007. The opening crack is 1~3 m long, 140 m wide, 17.5m deep, and becomes narrower from west to east. As the slope moved forwards, the pushing force was produced in the toe area of the landslide, and caused concrete rupture on the playground of the Xingma Middle School (Fig.1(c)). Another response to the landslide pushing is the disappearance of a 40-cm-wide drainage channel which was just next to the cliff. During the landslide process, the silty mudstone at the bottom was locally shattered, which made the sliding body sit down 0.5 m.

2.2 Chengkou Landslide, Chongqing

On the early morning of July 19th, 2010, a rockslide was caused by heavy rainfall in the Miaoba town, Chengkou county, Chongqing city. The landslide moved fast, blocked the road and the river at its toe, and formed a barrier lake with the storage reaching 6 million cube meters (Fig.2). As a result, the water level before the dam rised up quickly within half an hour and the Miaoba town in the upstream area (500 m far from the landslide) was submerged, causing about ten thousand inhabitants in emergency evacuation.

According to field survey, the rock strata in the landslide area are mainly composed of shale interbeded by sandstone which belong to the Reping Fomation of the middle Silurian System (S_2l), and the superfacial covering is composed of the Quaternary Holocene residuals (Q_4^{dl+el}). Because the landslide area is just located within the axial part of a syncline, the dip direction and dip angle of rock structural planes (1# and 2# planes in Fig.3) in the syncline's two limbs are different. Accordingly, together with another one set of steep cracks in the rear edge of the landslide, the sliding body finally presents a wedge block having two symmetric flanks, as shown in Figs.2 and 3.

A spring spot can be found at the crown of the landslide (Fig.3), and after the hazard took place, the flow quantity from the spot was measured to be 0.8L/s. A small trough also exists at the back of the landslide, which provides a natural channel for surface run-off into the slope. Beginning on July 16th of 2010, heavy rainfall continued in Chengkou town, and the total precipitation on July 19th when the landslide occurred reached about 200 mm. The spring water and the surface runoff due to rainfall entered into the trough, and then into the interior slope. This process produced water pressure around the boundaries of the sliding body and reduced the effective stress of soils, which is believed as the main cause of the landslide.

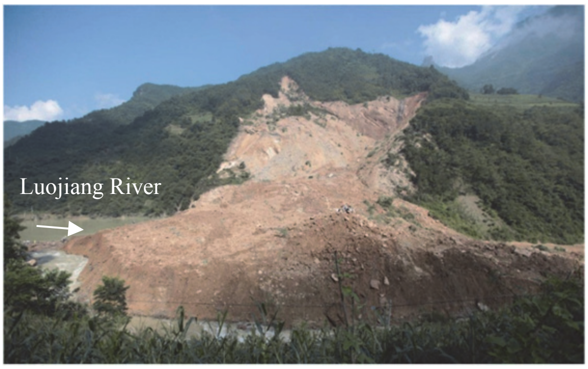


Fig. 2 The close-view of the Chengkou landslide

2.3 Typical patterns of rainfall-induced rockslides

Based on descriptions of the above two rockslides, the basic features of the single plane slide and the wedge block slide, two typical patterns caused by rainfall, are acquired. More detailed classification has been made for each failure pattern according to the dip angle (α) of rock stratum, as presented in Table 1.

Fig. 3 The V-shape trough and the spring water exposed in the rear edge of the Chengkou landslide

It can be seen that, the single plane slide is classified into two subtypes of movements. For $\alpha < 10^o$, mostly ranging between 3^o-5^o, a landslide occurs in nearly horizontal rock stratum and is called **translational rockslide**, while for $\alpha > 10^o$, a landslide occurs along the bedding planes of rocks and is called the **bedding rockslide**. In the latter subtype, if α is still smaller than 20^o, the slope will keep stable under natural condition, but fails in heavy rainfall along the bedding plane. This type of rockslide is commonly seen in red-strata regions of Sichuan Basin. If α exceeds 20^o, the steep rock strata is difficult to keep stable under natural condition, let alone subjected to other disturbances such like excavation or rainfall. Comparing the two subtypes of movements, the translational rockslide has attracted many attentions since long due to its unusual occurrence conditions and genetic mechanisms (Zhang et al., 1994). As an important part of this study, this will be stressed in the following section.

3. Genetic Mechanism of rainfall-induced rockslides

It is widely accepted that rainfall mainly produces two effects on the occurrence of a landslide (Chen et al.,2006; Tu et al., 2009). The first effect, namely the mechanical effect, is caused by increase of water pressure as the rainwater infiltrates into a slope. During the same process, the second effect, namely physical effect, is caused by the softening of slope materials. For a rock slope, water is limited to flow through cracks because of the impermeability of rocks. Due to space limit, only the mechanical effect is analyzed based on field monitoring and laboratory tests, and the emphasis will be put on the development of water pressure in cracks.

Table 1(1) Typical patterns of deep-seated rockslides triggered by heavy rainfall(First type of failure pattern)

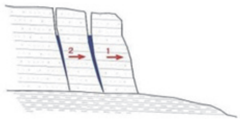
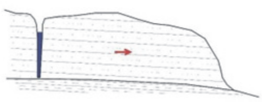
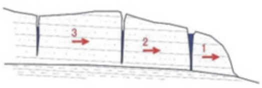
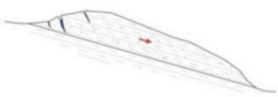
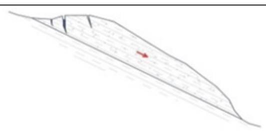
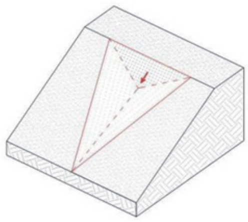
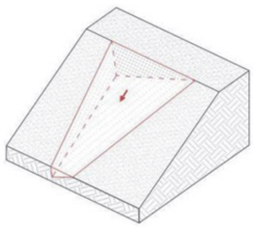
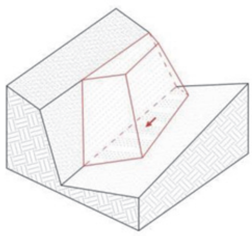
Subtype	Diagram	Main features and typical cases
First type of failure pattern: single plane rockslide		
Subtype Ⅰ: translational rockslides ($\alpha < 10^{o}$)	 (a) Plate-shaped rockslide	This type of rockslide has a rectangular slip plane, and the longitudinal length in sliding direction is far smaller than the transverse length. It usually occurs in rock strata with dip angle lower than 10^{o}, and a set of steep cracks develop parallel to the free surface, which cut the slope into thin plates. During heavy rainfall, the tension cracks are filled with water and water pressures are rapidly increased to a critical value for sliding. After that, the water pressures decrease and the slide stops. The rockslide often occurs in Sichuan basin composed of red-strata. The typical cases include the 2007 Xingma Middle School landslide and the Dahe Middle School landslide in Nanjiang county, Sichuan province (Xu et al., 2010).
	 (b) One-step rockslide	This type of rockslide usually occurs in a gentle slope with a gradient lower than 15^{o} and a dip angle of rock stratum lower than 10^{o}. A nearly vertical crack develop in the rear edge. During heavy rainfall, the initiation and cease conditions for the slide is the same with type (a). After sliding, a long and large tension trough was formed where the vertical crack develops, and spring spots or water flows occur at the toe, but the sliding body still looks intact without disintegration. The rockslide also often occurs in Sichuan basin composed of red-strata. The typical cases include the Kualiangzi landslide in Zhongjiang county, Sichuan province (Fan et al., 2009).
	 (c) Multi-step rockslide	This type of rockslide has the same geomorphological and geological conditions with type (b). The difference is the slope is cut by several sets of nearly vertical cracks. During heavy rainfall, 1# block is first pushed out by water pressure in crack, which makes the blocks at its back lose support and slide out successively from the front to the back and from the center to the sides. After sliding, several tension troughs will occur in the slope. The typical cases include the 2004 Tiantai village landslide in Xuanhan county, Sichuan province (Xu et al., 2006).
Subtype Ⅱ: bedding rockslides ($\alpha > 10^{o}$)	 (a) along the gentle bedding plane ($10^{o} < \alpha < 20^{o}$)	A bedding rockslide occurs along the bedding planes of rocks. When the dip angle (α) is smaller than 20^{o}, the slope will be kept stable under natural condition, but fails in heavy rainfall along the bedding plane. This type of rockslide is commonly seen in red-strata regions of Sichuan Basin. The typical cases include the 2010 Niumachang landslide in Fengyi village and the 2011 Shibangou landslide in Jiangying village, Nanjiang county, Sichuan province (Hu, 2013).
	 (b) along the steep bedding planes ($\alpha > 20^{o}$)	When the dip angle (α) exceeds 20^{o}, especially if the slope contains weak interlayers, the steep rock strata is hardly kept stable under natural condition, let alone subjected to other disturbances such like excavation or rainfall.

Table 1(2) Typical patterns of deep-seated rockslides triggered by heavy rainfall(Second type of failure pattern)

Second type of failure pattern: wedge block rockslide		
Subtype Ⅰ: symmetric wedge block rockslides		Differing from a bedding rockslide in which the sliding surfaces are controlled both by bedding plane and rock structure, the sliding surfaces of this type of rockslide are two sets of rock structural planes which have the same dip angle but totally reverse dip direction. Both of them intersect with the slope surface. In special cases, like the 2010 Chengkou landslide of Chongqing, the sliding surfaces just develop in two limbs of a syncline, and form a V-shaped spatial configuration. Another example is the 2010 Jinping Power Station landslide in Kangding county, Sichuan province (Sun et al., 2013).
Subtype Ⅱ: asymmetric wedge block rockslides	 (a) Ⅱ-1	This type of rockslide has the same slope structure with the symmetric type, but the two sliding surfaces have different dip angles. The slide is controlled by the gentler surface, but will be restricted by the steep surface during movement. That is to say, the steep surface acts not only as a sliding surface, but also as a lateral cutting surface. The typical case is the Shiaolin landslide in Taiwan (Tsou et al., 2011).
	 (b) Ⅱ-2	This type of rockslide often occurs in the prominent part of a valley slope. A set of gentle structural planes (mostly bedding planes) dip outwards, while another set of steep planes have strikes parallel to free surface. They together cut the slope into a sliding body. During heavy rainfall, the run-off infiltrates along the steep planes into the bottom of sliding surface, which causes soil softening and increase in water pressure. Due to the small contact area in sliding direction, once water infiltrates, the rockslide can easily occur. The typical case is the 2010 Ermanshan landslide in Sichuan province (Xu et al., 2012) and the 2010 Guanling rockslide in Guizhou province (Yin et al., 2010).

As mentioned in the previous section, the translational landslide is controlled by one set or several sets of nearly vertical cracks and a nearly horizontal bedding plane (dip angle < 10°) which afterwards forms the sliding surface. During rainfall, water infiltrates along those opening structures and generates hydrostatic water pressure on the vertical cracks and uplift pressure on the potential sliding surface. Fig.4 gives the concept model of one-step translational landslide as well as the water pressure distribution in cracks. Based on a limit equilibrium method, Zhang et al. (1994) proposed a critical height (h_{cr}) of water head in the vertical crack as the initiation criterion for one-step translation landslide and then built the estimation equation of h_{cr} as follows:

$$h_{cr} = \frac{1}{2\cos\alpha}[L^2 tg^2\phi + 8\frac{W}{\gamma_w}\cos\alpha tg\phi - \sin\alpha]^{1/2} \quad (1)$$

where h_{cr} is the critical water head value; W is the weight of a one-meter wide slide block (t/m); α is the dip angle of the sliding surface (a downslope dip gives a positive value, an upslope dip gives a negative value), $\alpha < 10°$; L is the length of the slide block; φ is the friction angle of the sliding surface; γ_w = the bulk density of water.

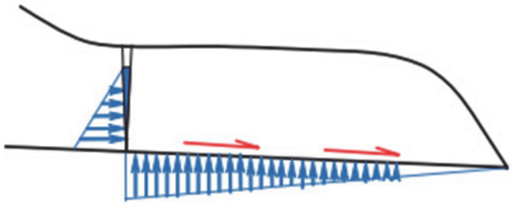


Fig.4 The concept model of translational landslide and the water pressure distribution

According to them, when the water head in the vertical crack exceeds h_{cr}, a translational landslide will occur. This opinion and the equation are further verified by Fan et al. (2009) who performed physical model test and numerical calculation for a one-step and a multi-step translational landslide in Sichuan basin. With this opinion, once the sliding body moves, the water in cracks will rapidly dissipate. As a result, the hydrostatic pressure and uplift pressure are both reduced, and the movement immediately stops as the water level drops to lower than h_{cr}. Actually, in the field, not large displacement can be observed for a translatonal rockslide, and even the maximum value is only from tens of meters to several meters. The above mechanism is simultaneously applicable to the plate-shaped translational landslide. More detailed analysis can be found in Xu et al. (2006) and Fan et al. (2009).

A serials of physical model tests have been conducted to study the developing process of water pressure and its correlationship with time and water head difference between cracks. The tests were based on the wedge block slide. As shown in Fig.5, the test system consists of model container, water pouring device and pressure monitoring device. The wedge block is designed to be symmetric and waterproof. The water pouring device is composed of water pouring holes and water box. Three pouring holes are designed at the back of container with gound-based height (H1 in Fig.5) of 71cm, 101cm and 131cm.

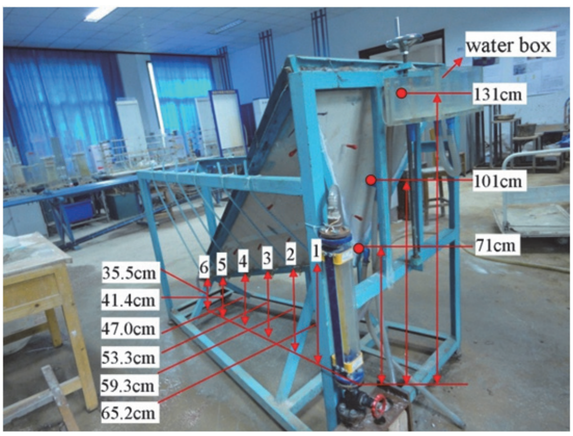
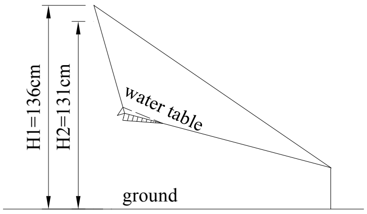
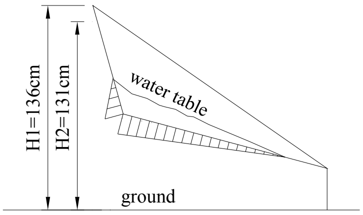


Fig.5 Physical model test of the wedge block landslide

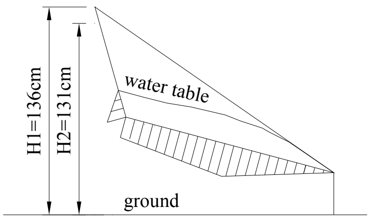
Each pouring height corrresponds to various water levels in the water box, which models different levels of water supply in the rear edge of the block. Besides those, Six piezometric tubes are installed along the sliding direction of each symmetric plane with different ground-based height (H2 in Fig.5) of 65.2cm, 59.3cm, 53.3cm, 47.0cm, 41.4cm and 35.5cm. With the design, when the water head at the rear edge changes, the water pressure along the two symmetric planes can be obtained.



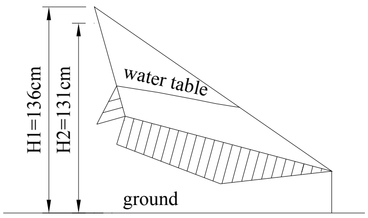
(a) 1minute after



(b) 10 minutes after



(c) 20 minutes after



(d) 40 minutes after

Fig. 6 Development of water pressure in cracks of the wedge block slide

Herein, due to space limit, only the water pressure development with time will be displayed when the water pouring height is 131cm and the water level in water box is 136cm. From Fig.6, it can be seen that, the water on the bottom plane is gradually flowing forwards and the water pressure is also increasing. Before 20 minutes has passed, the water pressure demonstrates a triangle distribution mode, but after 20 minutes, it keeps a trapezoid mode. The process indicates the development of water pressure on cracks is a time consuming process. For a deep-seated rockslide, just because it costs time to develop the uplift pressure on the bottom sliding surface, it always occurs behind the rainfall event, and this phenomenon is called the hysteresis effect.

4. Conclusions

In this study, the typical patterns are first summarized based on tens of deep-seated rockslides caused by rainfall in China. Then the genetic mechanisms of those rockslides are analyzed mainly based on field investigation, physical model tests and laboratory tests. The results can be concluded as follows:

(1) According to the spatial configuration of sliding surfaces, the rockslides can be classified into two patterns of movements, the single plane slide and the wedge block slide. For each pattern, deeper classification is made. For example, the single plane slide can be further divided into the translational rockslide and bedding rockslides. The wedge block slide can be further divided into the symmetric and asymmetric block rockslides. The basic features of each pattern of movement are described including the slope structures and rainfall conditions.

(2) for a translational landslide, it occurs once the water head in the vertical crack in the rear edge reaches a critical value (h_{cr}) and stops once the water head decreases bellow h_{cr}. Hence, in the field, large displacement can not be observed for a translational rockslide.

(3) The physical model test of the wedge block slide shows the development of water pressure around the sliding body is responsible for the occurrence of a rockslide in a rainfall event. As time goes, the water flows forwards and the uplift pressure along the bottom sliding surface gradually increases with the distribution mode changing from triangle to trapezoid.

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