Effects of rainwater softening on red mudstone of deep-seated landslide, Southwest China

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A R T I C L E   I N F O

Article history:
Received 18 September 2015
Received in revised form 19 January 2016
Accepted 22 January 2016
Available online 25 January 2016

Keywords:
Landslide
Slope stability
Rainfall
Red mudstone
Shear strength
Rock

A B S T R A C T

Red mudstone landslides are widespread in southwest of China. The development and distribution of deep-seated landslides with slow inclination are closely related to the special soft rock properties of the red mudstone layers. Most previous studies focused on the failure mechanisms of rain-induced shallow landslides. Studies on deep-seated landslides in red layer zones are still limited. In order to ascertain the basic failure mechanisms of red layer landslides with a gentle inclination, a fatal landslide named as Shibangou landslide, which occurred in Sichuan, China, was investigated. This paper aims to (1) conduct laboratory tests on the reduction in shear strength of a red layer to identify the water–rock coupling effect; (2) investigate variations in the microscopic structure of the soft rock found within a red layer after rainfall infiltration; (3) discuss the failure mechanisms of red layer landslides with slow inclination. Results from shear test of mudstone from the Shibangou landslide revealed that there is a tendency that behavior of soft rock can be transferred to soil in different days of immersion. The delineation threshold of shear strength of the red layer is determined as 6 days of immersion. Microstructures of clay minerals become loose and porous due to the contacts between the particles transferred from the face–edges, face–face associations into edge–face, and face–edge associations. Therefore, the intramolecular and cemented expansions of illite are the basic mechanisms which lead to structural damage, structural decay, and strength attenuation of soft rock in red layer under the condition of rainwater infiltration.

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1. Introduction

The red layer is composed of interbedded red mudstone and sandstone. Due to its weak resistance against weathering and impermeability, the red layer often suffers from high to complete weathering. Presence of the red layer makes overlying slopes prone to sliding easily along a bedding plane with slow inclination during rainy seasons. Red-layered landslides are widely distributed in Southwest of China. On 16 September 2011, a heavy rainfall triggered a deep-seated slow-inclination landslide, named Shibangou landslide, in Nanjiang County, Bazhong City in Sichuan (Fig. 1).

Most previous studies focused on the failure mechanisms of rain-induced shallow landslides. Studies on red-layer deep-seated landslides are still limited. It is necessary to explore deep into the mechanism of a slow-inclination red-layer landslide. According to an investigation conducted by Hutchinson (1961) on a slow inclination landslide that occurred in Norway, the sliding surface is a highly sensitive sandwich clay layer. Michael (2000) suggested that the failure process of a landslide occurs in the horizontally layered sedimentary rock with horizontal shear surface, which can be divided into five stages: unloading rebound, creep deformation of the weak layer, progressive deformation, mudding expansion, and gravity-induced differential settlement. Huang et al. (2008) studied the occurrence of large-scale landslides with gentle inclination, and proposed that the failure is mainly caused by wedging and tearing due to the influence of water pressure on the tectonic fissure fracture and the cushion effect of ground water.

However, even though these studies have considered the hydrostatic pressure at the trailing edge combined with uplift force acting on the slip surface, as the major cause that promotes the occurrence of translational landslide, they fall short of explaining the most essential failure mechanism of red-layer landslides especially for the deep-seated slope failure. In fact, the influence of rainfall infiltration on slope stability is not only mechanical but also physicochemical; in particular, the physicochemical aspect provides the main explanation for the reduction in shear strength. Shear strength reduction of mudstone caused by rainwater infiltration is associated with physicochemical interactions between the minerals in clay and water. Over tens of years in the past, a lot of attention has been placed on such interactions and their effects (e.g., Kenney, 1967; Rosenqvist, 1984; Skempton, 1985; Moore, 1991; Laurence and Simon, 2001; Dewoolkar and Huzjak, 2005; Rahardjo et al., 2005; Spagnoli et al., 2010; Xu et al., 2011; Wen and He, 2012; Miao et al., 2014). The development and distribution of deep-seated...
landsides with slow inclination are closely related to the special material properties of the red layers. According to our field investigations, most slope failures occur along the weak surface of the red layer in the study area.

In order to ascertain the basic failure mechanism of red layer landslides with a slow inclination, a deadly landslide known as the Shibangou landslide, was investigated (Fig. 1). This paper aims (1) to conduct laboratory tests on the reduction of shear strength of the red layer due to the water–rock coupling effect; (2) to investigate variations in microscopic structure of the soils after rainfall infiltration; and (3) to explore the fundamental failure mechanism of red layer landslides with slow inclination.

2. Study area and samples

The Shibangou landslide occurred in Nanjiang, Sichuan, which geographic coordinates are longitude 106°44′45″ and latitude 32°14′27″ (Fig. 1). The study area is underlain by mudstone in the Cretaceous Jianmenguan group (Fig. 2) with attitude of 170° and 12° (Fig. 3). From September 6 to 15, 2011, a total cumulative rainfall of 268.1 mm was recorded, and on September 17 and 18, a total rainfall of 250.4 mm and 179.1 mm was recorded respectively. According to local residents who witnessed the landslide, the slope failure began at about 10:20 on September 18. The landslide slid along the bedrock layer with an initial sliding direction of S10°E to a final direction of S45°E. Sliding surface of the landslide is a weak interlayer, which mainly consists of mudstone mixed with thin layer of silty mudstone (Fig. 3). Runout materials destroyed 487 buildings and carried a local resident away for approximately 300 m. The landslide resulted in 4 deaths and 8 people missing.

In order to explore the reduction of shear strength of the red layer due to the water–rock coupling effect, rock samples were taken from the belt area on the left side of the sliding zone at the back of the Shibangou landslides (Fig. 1b), which is defined as a lateral secondary sliding zone during the filed investigation. Due to the existence of vertical structural joints, rock mass in this zone was isolated from the main sliding body (Fig. 4a). Therefore, the sliding surface in this area kept at their original state, and the rock materials of the sliding surface haven’t been disturbed relatively (Fig. 4b).

3. Description of experiments

Water–rock physical and chemical effects are softening and chemical effects of water on the reduction of shear strength of rock layers, by decreasing cohesion, c, and friction angle, φ. It has an important potential for triggering landslides (i.e., rain; water level variation; earthquakes, etc.). Clay materials such as silty mudstone and mudstone that are distributed in the red layer are sensitive to water, especially during rainy seasons. With long-term exposure to water, the physical and mechanical strength of mudstone can be changed significantly by softening and mudding effect, which becomes a controlling factor of slope failure.

In the study area, strongly hydrophilic clay is distributed throughout the red layer, which can be easily softened, such as illite and chlorite. With effect of rainfall infiltration over a long period, drastic reductions in shear strength due to softening of soft rock become the main cause of deep-seated slope failure with slow inclination. In light of this, the experiments in this paper are conducted to test the variation of peak shear strength under various saturation rates and immersion conditions.

In order to simulate the long-term saturation with rainwater of red layer under the condition of various durations of rainfall, the samples were saturated with eight immersion periods, i.e. one day, two days, three days, five days, seven days, 10 days, 15 days, and 20 days.

3.1. Test equipment

Currently, direct shear test is used as a standard method in many places, such as UK, China, Japan, and the US (e.g., British Standard Institution (BSI), 1990; Standardization Administration of China (SAC) et al., 1999; Japanese Geotechnical Society (JGS), 2010; United States Army Corps of Engineers (USACE), 2011). In this study, due to low mechanical strength of the rock layer in this study, the soft rock of the red layer tends to disintegrate and soften in water. It is difficult to get a fully qualified specimen with regular shape during field sampling. Therefore, traditional direct shear test instruments are not suitable in this study since a regular specimen cannot be provided.

This test adopted a new shear instrument developed by the State Key Laboratory of Geological Disaster Prevention at the Chengdu University of Technology (Fig. 5), i.e., XJ-2 portable shear instrument. The apparatus is a new method to test the peak and residual shear strength of a weak rock layer. It is suitable for conducting the direct shear tests on the undisturbed rock samples with irregular shapes.

Details of the portable shear apparatus are shown in Fig. 5:

1. Because regular geometry is not required for the specimens, this test equipment is applicable to weak and soft rock samples taken from the structural surface of a landslide (e.g., bedding layer; fault fracture zone; sliding surface; soft interlayer; shale; phyllite;
schist; and strongly weathered rock, etc.). The irregular samples are wrapped in concrete and cast into specimens with fixed sizes and shapes initially.

(2) Direct shear test can be conducted after the regular shaped specimens are prepared and installed in the specific instrument with the same size (i.e., portable shear instrument). A series of

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**Fig. 2.** Characteristic of Shibangou landslide: (a) photo taken shortly after the event; (b) tectonic joint surfaces occurred at the scar of landslide; ① and ② represents two groups of tectonic joints exposed at the rock surface; (c) shale sandwich caused by water–rock interaction at the scar of landslide.

**Fig. 3.** Cross-section of Shibangou landslide, before and after the slope failure.
shearing tests and data compilation can be fulfilled according to Coulomb Formula.

3.2. Rock sample preparation

Rock samples were taken from the Shibangou landslide site for investigation on their shear strength and microstructure (Figs. 1b and 4), where the rock materials of the sliding surface kept at their original state without disturbance. Before the preparation of the rock samples, initially, threshold of saturation is determined as 5 immersion days by conducting submerging tests. All the rock samples are cemented with concrete before saturation. According to the threshold of saturation, these rock samples in waters for zero, one, two, three days, five days, seven days, 10 days, 15 days, and 20 days are classified as unsaturated samples, which can be used to analyze the degree of saturation effect. The rest samples in five, seven, 10, 15 and 20 days are classified as fully saturated samples, which are used to analyze the saturation aging effect. The procedures of rock sample preparation are following four steps:

(1) Measurement of shear area, $S_j'$, before the specimen is cast;
(2) Preparation of the half specimen. Brush the inner box with engine oil and put a piece of paper inside, which allows an easy retrieval of the specimen. The sample is placed in the middle of the box and enabled the proposed shear surface fix at 0.5 cm above the box frame. Add the concrete at the ratio of cement, dry sand to water being 1: 2: 0.5. In order to stabilize the rock samples, concrete is filled and tamped into the sample box, as shown in Fig. 6;
(3) Preparation of the entire specimen. Around 24 h later, remove the specimen when the concrete is cemented (Fig. 6a). Then brush a little oil on the inside of box, put a gasket strip (1 cm) in the box and filled the crack with concrete. After another 24 h, remove the box and pick up the specimen. Finally get rid of the gasket strip;
(4) When the concrete has reached sufficient strength (around 7 days), put them into water for zero day (natural state), one day, two days, three days, five days, seven days, 10 days, 15 days, and 20 days, respectively. Then the shear test can be started (Fig. 6b).

3.3. Test procedures

(1) Installation
a. The specimen was placed inside the shear box;
b. Apply vertical load gradually to straighten the vertical rope. Record the initial value of the vertical load from the pressure gauge, $I_{\sigma_0}$. Then cut the thin wire to release the specimen through the crack gaps;
c. Apply shear load gradually to straighten the horizontal rope. Record the initial value of the shear load, $I_{\tau_0}$; Set up a shear displacement indicator.

(2) Shear test
a. Apply the vertical load to a predetermined normal stress, the predetermined normal stress should be transferred to the gauge readings according to the following formula:

$$I_{\sigma} = \frac{\sigma \times S_j' - G}{Sw} + I_{\sigma_0} (1)$$

where $I_{\sigma}$ is the vertical pressure (Mpa); $I_{\sigma_0}$ is the initial value of vertical pressure (Mpa); $\sigma'$ is the predetermined positive stress (Mpa); $S_j'$ is the shear surface area (m² or cm²); $G$ is the sum of the weight of the shear box, the vertical jacks and the upper part of the concrete specimen (MN); and $S_p$ is the piston area of the vertical jack (m² or cm²);
b. Record the initial reading of each dial indicator;
c. Quick shear method is adopted through the test. Shear stress is controlled by adopting stress control method. Positive stress is kept constant at a certain time interval (30 s), and the shear stress is applied step by step. When the second shear displacement is more than twice as the previous level, apply the next shear loading, $I_{\tau_0}$, by half, until the specimen is sheared and the shearing displacement of the structure surface reaches 1 cm (the duration is around 5 to 10 min). When the reading of the horizontal pressure gauge becomes constant, or shear displacement speeds up, the shear stress (each grade) of the rock sample can be calculated based on the 5% to 10% of normal stress, weak structure plane is 2% to 5% of normal stress. After applying the shear stress, the shear displacement, $L_{\tau}$, and vertical displacement, $L_{\sigma}$, should be recorded;
Fig. 5. Details of the portable shear apparatus.


Fig. 6. Preparation of the rock samples: (a) specimen under shaping; (b) immersion of specimen; (c) and (d) conduction of the test.
d. Remove the specimen, measure the shear surface area, and describe the characteristics of the shear surface after completing all shear tests. Cellophane can be used to outline the shear surface. Then the exact shear surface area, $S_j$, can be measured using a planimeter.

4. Test results

After the test, the normal stress and shear stress can be calculated using Eqs. (2) and (3):

$$\sigma = \frac{(I_\sigma - I_{\sigma 0}) \times S_h + G}{S_j} \quad (2)$$

$$\tau = \frac{(I_\tau - I_{\tau 0}) \times S_h}{S_j} \quad (3)$$

where $\sigma$ is the normal stress (Mpa); $\tau$ is the shear stress (Mpa); $I_\tau$ is the shear load pressure (Mpa); $I_{\sigma 0}$ is the initial shear load pressure (Mpa); $S_j$ is the shear surface area ($m^2$ or $cm^2$); and $S_h$ is the piston area of the horizontal jack ($m^2$ or $cm^2$).

A shear-displacement, $\tau$-Lh curve, under different normal stress can be developed with the shear stress taken as the vertical axis and shear displacement as the horizontal axis. Another curve, $\tau - \sigma$, which reflects the relationship between peak shear stress and normal stress, can be developed taking the shear stress as the vertical axis and normal stress as the horizontal axis. $\varphi$ and $c$ can be calculated using the least square method.

4.1. Immersion aging time effect

Experimental observations have revealed that the shear displacement curve of the rock samples without immersion is characterized by typical elastic–plastic features (Fig. 7a). The shear displacement of the sample is small before the peak shear stress is reached. The peak mostly occurs at a displacement of 1−2 mm. However, the shear displacement curve of the rock sample aged for 10 days in water reveals that there is a tendency for the shear deformation characteristics of the rock to transform into those of soil (Fig. 7b). The increments of shear stress and shear displacement are similar before the peak point is reached. Peak shear strength occurs mostly between the shear displacements of 2.5−3 mm. The immersion aging effect on the reduction of shear strength of the red layer is directly reflected through the shear strength envelope curve (Fig. 8a). After immersion for varied days (from 1 to 20 days), the shear strength of rock sample is decreased gradually. Meanwhile, cohesion and the internal angle of friction decrease as the duration of immersion increases. As shown in Fig. 8b, during the first 10 days of immersing the samples, cohesion and the internal friction angle reduce to 61.3% and 63.3% respectively; afterwards, between 10

- Fig. 7. Shear stress-displacement curve: (a) in the natural condition; (b) 10 days of immersion.
- Fig. 8. Immersion aging time effects on: (a) shear strength envelope curves; (b) variation of shear strength parameters.
and 20 days of immersion, they are reduced to 76.6% and 69.3%. Comparing the two periods shows that the curve tends to be flat, with amplitude of cohesion and internal friction angle attenuating at 15.3% and 6.0% between days 10 and 20.

4.2. Degree of saturation effect

The specimen gradually becomes saturated during immersion processes, and the water content of the rock sample increases from 7.4% to 15.3%. According to Table 1, the internal friction angle of the sample shows a decrease in the form of a negative power function as saturation increases. The internal friction angle is 28.3° at saturation degree of 48.4%. In 5 days immersion, the internal friction angle is 13.7° at saturation degree of 100%. The cohesion of the sample exhibits an exponential decay trend as saturation increases. Cohesion is at 56.1 Kpa when saturation degree is 48.4%. In 5 days immersion, the internal friction angle is 13.7° at saturation degree of 100%. The cohesion of the sample exhibits an exponential decay trend as saturation increases. Cohesion is at 56.1 Kpa when saturation degree is 48.4%. As the degree of saturation varies further, the declinations in cohesion and internal friction angle exhibit incompatibility, cohesion is reduced by 26%, which is much smaller than the 51.6% decrease in inertial friction angle.

4.3. Saturation aging effect

In order to assess the aging effects of saturation, analysis of the reduction of shear strength varied with the days of saturation is conducted. As the number of days of saturation increases, both the internal friction angle and cohesion show logarithmic decrease, the decay rate and amplitude decrease gradually. After immersion of 16 saturation days, the cohesion and internal friction angle of the rock sample decreased by 28.4 kpa and 5° respectively (Table 2).

As shown in Table 2, cohesion and the internal friction angle of the red mudstone decrease rapidly at the first six immersion days at a rate of 47.7% and 24.1%, respectively. However, both their rates of decline slow down significantly after the 7th immersion day. According to the characteristics of the attenuation of shear strength parameters, six days of immersion is the critical amount of time for the reduction of shear strength of the rock sample from red layer. Experiments reveal that the softening effect caused by rainwater is expressed fundamentally through changes in such physical properties as the mass and surface structure of the rock. The plastic state of a rock’s structural surface transferred to liquid state with the variation of water content and duration of immersion.

5. Changes of microstructure of red-layer during water softening

Interaction between groundwater and the soft rock of the red layer can change the soil mineral and chemical compositions, as well as decrease the coupling forces between particles and the shear strength of soft rock. Eventually, a landslide slip surface can be developed. In order to reveal the fundamental failure mechanism of the landslides in red layer zone, this study test the changes of mineral composition and microstructure of rock samples from the sliding surface, the main body, and the lateral secondary sliding zone of the Shibangou landslide, using X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) in a micro perspective.

5.1. Microstructure of red layer under natural conditions

5.1.1. Mineral composition of red layer

Results from the XRD analysis of the rock samples are listed in Table 3 and Fig. 9. Fig. 9 presented X-ray diffraction spectrum of rock samples taken from sliding surface (Fig. 9a), main body (Fig. 9b), and lateral zone (Fig. 9c) of Shibangou landslide. X axis in X-ray diffraction pattern graph represents Bragg angle, which is grazing angle of X-ray incident to crystal; Y axis represents peak intensity of crystal diffraction. The test equipment is DMAX-3C diffractometer using CuKα, Ni filter. Based on the analysis of the diagram as shown in Fig. 9, the mineral compositions of each sample taken from different parts of the landslide are determined (Table 3). The argillaceous siltstone at the main body of the Shibangou landslide is mainly composed of clay minerals, which accounts for 52% to 63% of the entire mineral compositions. While the main components of the clay minerals is dominated by illite and chlorite, followed by montmorillonite. As shown in Fig. 10 the amounts of clay minerals at the main body, lateral secondary sliding zone, and sliding surface of the landslide are increased, especially the amounts of illite and chlorite.

Results of the X-ray full mineral analysis show no potassium feldspar in the lateral secondary sliding zone or sliding surface of the landslide is detected, but the material does appear in the main body of landslide with a content of 6%. Such an unusual phenomenon can be explained by the local geological conditions and the effect of water–rock interaction.

Rainwater infiltrates rapidly along the vertical fractures and slow down when reach to the horizontal soft muddy rock surface. Because poor water permeability of the red layer, a belt with rich water activity

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample location</th>
<th>Description of lithology</th>
<th>Percentage (%)</th>
</tr>
</thead>
</table>
|     |                       |蒙脱石|伊利石|粘土石|石英|钾长石|含铁长石|钙
| X1-1| Sliding surface       | Mudstone                  | 8  | 35  | 20  | 26 | N/A | 7  | 2  | 2  |
| X1-2| Main body             | Mudstone interlayer       | 6  | 13  | 5   | 61 | 6   | 9  | N/A| N/A|
| X1-3| Lateral secondary sliding zone | Mudstone               | 8  | 29  | 15  | 30 | N/A | 8  | 7  | 2  |
is developed, which promotes long-term interactions between groundwater and the soft rock at sliding surface. It can also explain why the initiation zone of the sliding surface is an activity area of groundwater. Due to the effect of water–rock interaction, the potassium feldspar has been converted to clay after a long weathering process. In other words, feldspar dissolves into illite by following Eq. (4):

$$3K[AlSi_3O_8] + 2H^+ + 12H_2O = 6H_4SiO_4 + KAl_3Si_3O_10(OH)_2 + 2K^+ \quad (4)$$
The above chemical transition process leads to the formation of clay minerals by argillization and hydrolysis. With time goes by, potassium feldspar disappear and transformation of clay minerals at the locations of sliding surface and lateral secondary sliding zone with active water–rock interaction, and eventually evolved into the slide belt.

5.1.2. Microscopic structure of red layer
The microscopic structure of the minerals in red layer under natural condition is observed by Scanning Electron Microscopy (SEM), S-3000 N. When the SEM enlarged to 100 times, it can be seen that the surface minerals are tightly and directionally arranged with sharp edges. When the SEM enlarged to 3000 times, it can be seen that the clay minerals constitute a larger part of the layer, and a coarse grain skeleton is built up by the coarse particulate mixed with clay minerals with fine cementation (Fig. 11a and b).

Fig. 11c and d reflects the fracture characteristics of the mudstone layer. When the rock structure is enlarged to 800 times, small clay particles can be observed from the lateral view, which exhibit a flocculent structure with mixed layers of illite and illite–smectite. When enlarged to 3000 times, lamellar structure can be observed in the illite crystal particles with a maximum pore diameter of 3 km. Under the long-term gravity effect from the overlying hard sandstone, the structures are dominated in the form of face–face and face–edge associations. Interaction between water and rock tends to destroy the clay minerals' microstructure, and causes the dislocation within the interlayer clay.

5.2. Microstructure of red layer in water
5.2.1. Changes of mineral compositions
As found in the X-ray diffraction analysis of rock samples after 20 days of immersion (Table 4), taken from the lateral secondary sliding zone of the Shibangou landslides (Figs. 1b & 4), the contents of illite, chlorite, and pyrite have increased while all other minerals have decreased by comparing with the samples under natural conditions. Therefore, the composition and content of the minerals in the red layer are considered as constant except the deviation in test samples itself.

During the immersion process, the crystal lattice of the clay minerals is destroyed and edges of the crystal grain changed from a clear zigzag shape into a round shape. Such declination is resulted from the destruction of the crystal lattice of the clay minerals in water. The peak

Fig. 10. The variation of clay minerals at varied sample points, X1-1 represents rock sample taken at sliding surface; X1-2 represents rock sample taken at main body of landslides; X1-3 represents rock sample taken at lateral zone, where secondary sliding occurred.

Fig. 11. Microstructure characteristics of mineral surface: (a) ×100 times; (b) ×3000 times; and of fracture; (c) ×800 times; (d) ×3000 times under natural condition.
The diffraction value of the clay minerals decreased and fluctuated around the peak region after the immersion (Fig. 12). The change of the crystal edges can be observed in SEM tests by making a comparison of the microstructure of clay minerals after varied immersion time (Fig. 13a and e).

5.2.2. Changes of microstructure

To find out the inherent mechanism of the reduction of shear strength due to water–rock interaction, a series of SEM tests were conducted on the rock sample with varied numbers of immersion days. A large amount of water is required by the immersion test. However, it is difficult to obtain the original ground water due to the limited water discharge in the field. In order to exclude unexpected chemical reaction, distilled water was adopted for the rock sample immersion.

The microstructure of the mudstone samples after 12 h of immersion is shown in Fig. 13a and b. Comparison between Fig. 11a and b indicates that the micro-pores in the clay minerals expanded after the water immersion, which contributes to the loss of coupling strength between the grains within the larger framework. Thus, a few of the quartz, feldspar and other skeletal particles was detached and suspended from the surface.

The microstructure suffered further destructions after 24 h of immersion (Fig. 13c and d). As the duration of immersion increased, the water film thickness of the original skeleton of coarse particles increased, which was accompanied by the decrease of the binding force between molecules. Thus, the cementation between the coarse grain skeleton is further deteriorated. With immersion duration increased (e.g., 120 h), the degree of cementation within the coarse grain skeleton is further reduced (Fig. 13e and f). Due to the loss of cementation force, the quartz, feldspar and other mineral particles detached from the original skeleton and distributed. The sheets of illite at the surface are further softened and disassembled with small particles filling into the large pores. The clay minerals gradually fragmented and the largest width of fracture reached 5 um after 240 h of immersion (e.g., 10 days). As shown in Fig. 14a and b, the voids of the microstructure are filled by the peeled softening materials immediately, which in turn decreased the porosity. After 480 h of immersion (i.e., 20 days), there is no obvious differences of the microstructure from the one in 240 h (Fig. 14c and d). Porosity did not change a lot even under constant water–rock interaction.

When the SEM of the clay minerals in each sample is enlarged to 3000 times (Figs. 13b, d, f and 14b, d), it can be observed that the softened coarse grain flakes are imbricated arranged, and the left pores are filled by the softened fine grain flakes. Such phenomena imply that the interlayer binding force of clay crystal can be decreased.

From the microstructure’s perspective, firstly, the large pores are expanded and filled with water, then softening occurred from the edge to the middle of the large particles. Water–rock interaction causes the decrease of strength at the part of the grain skeleton where poor cementation exists. Due to the aging effect of immersion, the small gaps are gradually filled with water, and the small particles peeling off from the larger particles filled the pores, which enable a uniform distribution of pores. Such changes contribute to the reduction of large pores and increase of small gaps. Thus, the structures of clay minerals tend to be loose and porous due to the contacts between the particles transferred from the face–edge, face–face into edge–edge, and face–edge associations (Sridharan and Jayadeva, 1982).

### Table 4
Comparison of mineral compositions of the rock samples taken from the lateral secondary sliding zone of Shibangou landslide under natural and water immersion.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample type</th>
<th>Percentage (%)</th>
<th>Montmorillonite</th>
<th>Illite</th>
<th>Chlorite</th>
<th>Quartz</th>
<th>Potash feldspar</th>
<th>Anorthose</th>
<th>Calcite</th>
<th>Pyrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1-3</td>
<td>Natural condition</td>
<td>8</td>
<td>29</td>
<td>15</td>
<td>30</td>
<td>N/A</td>
<td>8</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>X1-4</td>
<td>20 days of immersion</td>
<td>5</td>
<td>35</td>
<td>17</td>
<td>26</td>
<td>N/A</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Fig. 12. X-ray diffraction spectrum of rock sample taken from lateral zone of Shibangou landslide (20 days of immersion).
6. Fundamental failure mechanisms of red layered landslides

The reduction of shear strength of the red layer is substantially caused by the decay of inherent microstructure of the clay minerals. Since the red layer contains a lot of clay minerals, such as montmorillonite, illite, kaolinite etc., which are easy to swell or shrink during the wetting or drying process.

Two expansions resulting in the damage of the soft rock in red layer have been identified: cementing expansion and internal expansion. The clay particles in the study area have atoms and ions at free states with strong electrostatic attraction. The electrostatic gravitational field formed at the clay surface enables the increase of clay water film thickness by attracting water molecules, which lowered the binding force between the molecules and resulted in the deterioration of mechanical properties of the clay materials. This phenomenon is called the "water film effect" on the surface of the clay minerals, which is a cementing expansion process (Fig. 15). In addition, the clay mineral of the red layer in the study area is dominated by illite, which is classified as a non-expanded clay mineral. It is necessary to further discuss the hydration mechanism of the red soft rock in the study area. Crystal unit of illite is composed of a layer of aluminum sandwiched between two layers of silicon with a number of counter ions. When the water infiltrates, the binding force is reduced due to the counter ions escaping from the inter-layers. In this way the water molecules squeeze into the inter-layers; this explains the molecular mechanisms of internal expansion (Fig. 16).

The above two expansion mechanisms illustrate that water will gradually undermine the cohesiveness between the mineral particles of mudstone in a saturated state and enter the pores between the chip-shaped particles. Subsequently, it will result in uneven inner-stress and a lot of micropores in the mudstone and induce softening and degradation (Huang and Che, 2007). Finally, the microstructure of softening clay minerals transferred from the face-face association into face–edge, edge–edge, and edge–corner associations (Fig. 17), which not only led to the reduction of mechanical strength due to the loss of binding force, but also increases the effective contact area between...
the clay particles and water. The capacity of absorption of water will be further enhanced and a wedging force will be developed into the pores, which contribute to further reduction of shear strength. Thus, surface porosity of the mudstone is unchanged while shear strength is reduced.

7. Conclusions

Under the condition of rainwater infiltrates, the reduction of shear strength of the red layer reflects substantially the external appearance of attenuation of microstructure of soft rock. The significant softening of the red layer occurred on its clay minerals, such as montmorillonite, illite, and kaolinite. With the clay minerals swell and shrink under the natural dry and the water immersion conditions, the structure of the soft rock changed which contributes to the degradation of strength. The results of shear test of mudstone from the Shibangou landslide revealed that there is a tendency that soft rock transferred to soil in different days of immersion. The internal friction angle and cohesion...
decreased from fast to slow and tend to be constant eventually. The delineation threshold of shear strength of the red layer is determined as six days of immersion. Based on the perspectives of microscopic mineral components, the mineral components are kept as constant before and after the immersion. Illite is identified as the major clay mineral of the soft rock in red layer. Based on the perspectives of microstructure, the pores tend to be distributed uniformly with the growth of the immersion time. The structures of clay minerals become loose and porous due to the contacts between the particles transferred from the face-edges, face-into edge-edge, and face-edge associations. Therefore, the intramolecular and cemented expansions of illite are the basic mechanisms which lead to the structure damage, structural decay, and strength attenuation of soft rock in red layer under the condition of rainwater infiltration.

Acknowledgement

A substantial part of this research was supported by the National Science Fund for Distinguished Young Scholars of China (Grant No. 41225011), State Key Development Program for Basic Research of China (Grant No. 2013CB733200) and Geological Survey Projects of Geological Survey of China (Grant No. 1210113010100).

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