

## The 2 September 2014 Shanshucao landslide, Three Gorges Reservoir, China

**Abstract** A Shanshucao landslide, large displacement landslide, took place on 2 September 2014, at 13:19 in Zigui County, Hubei Province, central China, which was about 42 km from the Three Gorges Dam. It was located on the left bank of Luogudong River, which was a secondary tributary of the Yangtze River. Just as the well-known Qianjiangping landslide, this landslide was considered to be one of the longest displacement consequent slope failures, which was characterized by red layer rock landslide. This event has become an outstanding and valuable reference for landslide study and is of particular importance for understanding the influence of the stability of the slope in the Three Gorges Reservoir Area. The geomorphological and geological conditions of the landslide were investigated to identify and characterize previously discontinuous and slide stratum bed. The hydrogeological and geomechanical features were also analyzed. It was found that the landslide was triggered by both the long and heavy rainfall and the rising water level of the reservoir at high speed.

**Keywords** Landslide · Three Gorges Reservoir · Consequent slope · Rainfall · Rising water level

### Introduction

On 2 September 2014, at 13:19 pm, a large displacement rock landslide occurred in the town of Shazhenxi, on the left bank of the Luogudong River, a secondary tributary of the Yangtze River in Zigui County, Hubei Province, central China (Fig. 1). The Qianjiangping landslide (Wang et al. 2004; Jian et al. 2014; Xiao 2007), which lasted a distance of 0.75 km, separated by Qinggan River, which is a tributary of the Yangtze, was closed in proximity to this event site. The distance from the Shanshucao landslide to the Three Gorges Dam is approximately 42 km.

The Daling Hydropower Station (installed capacity of 1000 kW), situated on the lower part of slope, was completely destroyed and slipped underwater, and three five-storey apartments were completely demolished and broken to pieces. The power supply for the town was interrupted due to the crooked transmission pole. Additionally, the national road (G348), a country road, houses, and around  $20 \times 10^4$  m<sup>2</sup> area of orange planting were seriously damaged. A direct economic loss of nearly 32 million RMB was caused by the geohazard. Fortunately, there were no fatalities in this event, primarily due to the accurate prediction, good decision making, and timely evacuation of the residents. The event is of special focused not only because a whole hydropower station has been firstly destroyed by the landslide but also because the stability of the consequent slope is of significantly important under the rainfall effect and the influence of the alternated filling-drawdown cycles in the Three Gorges Reservoir Area (Xu et al. 2013; Jian et al. 2014).

This report outlines the event of Shanshucao landslide, which occurred on 2 September 2014 in Three Gorges Reservoir. The geology background in Three Gorges Reservoir, generating process and features of the landslide are presented. Triggering factors, i.e.,

raining and rising water level of reservoir, and failure mechanism are preliminarily analyzed.

### Geomorphological and geological condition

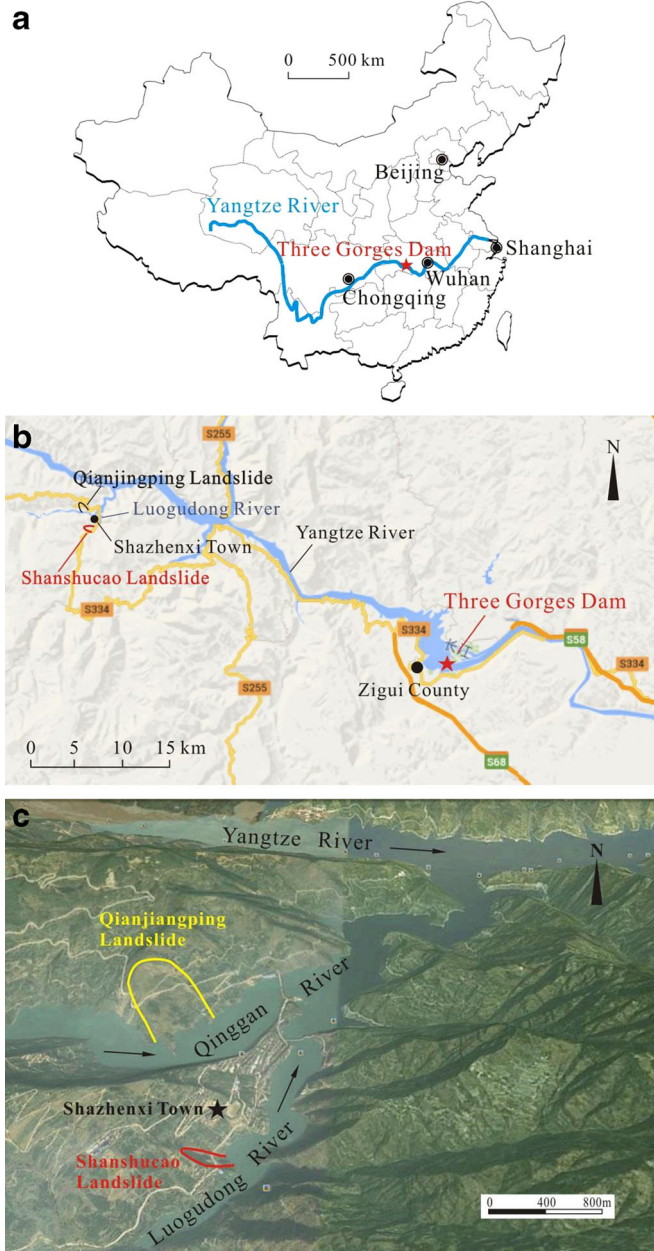
The town of Shazhenxi, Zigui County, is located at the southwest limb of the Zigui syncline, ExiFold tectonic zone, resulting in from middle to high mountains and steep valleys. The average elevation is greater than 1000 m with a topographic height difference of 300–1000 m. The mountain in this region is in the formation of asymmetrical slopes according to the attitude of sediments. For the consequent slope, it is usually in the formation of cuesta with the slope angle of 15–30°, while for the reverse slope, it has a steep slope with an angle of 35–45°.

The Shanshucao landslide occurred at the consequent slope, left bank of the Luogudong River, a secondary tributary of the Yangtze River (Fig. 2). The river here curves as “W” shape and flows from south to north. The morphology at the south boundary looks like a tongue protruding to the eastern. The elevations of the ridge and riverbed are 440 and 140–145 m, respectively. The topographic height difference between the ridge and riverbed is about 300 m. The slope angle varies from 18 to 25°. The most distinguished geomorphology is that there had been an overhanging rock cliff with the height of 20–30 m before the slide occurred (Fig. 2a). The overhanging rock cliff precisely forms the north boundary of the main rock sliding area (I) (Fig. 2b and see Fig. 5).

The geological strata within the site are feldspathic quartz sandstone, siltstone with mudstone, sandy shale, and their interbedded strata deposited in the Middle Jurassic Qianfoya formation ( $J_{2q}$ ). The altitude of the layer varies from 120 to 125°  $\angle$  19–21°. The Quaternary strata include an eluvial layer ( $Q_4^{el+dl}$ ), which mostly consists of sandy clay with sandstone debris, colluvial deposits ( $Q_4^{col+dl}$ ) which consists of sandy clay, rock debris originated from sedimentary rock, and an accumulation of landslide ( $Q_4^{del}$ ).

According to the results of the laboratory shear testing, the shear strength of feldspathic quartz sandstone, thick layer with pale green color, has cohesion ( $c$ )=9.3–13.5 MPa and internal friction angle ( $\phi$ )=42.5–47.2°; the shear strength of siltstone with mudstone, middle to thin layer with amaranth color, has  $c$ =3.9–5.7 MPa and  $\phi$ =35.8–39.5°; and the shear strength of sandy shale, thin layer with green-brown color, has  $c$ =0.8–1.2 MPa and  $\phi$ =28.5–32.5° when they are in natural water content state (Liao and Lei 2014). It can be seen that the intact rocks have quite high shear strength. However, unfortunately, there is a thin and weak muddy intermediate layer between feldspathic quartz sandstone and sandy shale at certain depth. The argillation layer is formed at the interface with thickness of 5–10 cm. The strength at natural state (samples taken from an exploratory trench at the central part after sliding) and saturated state is  $c$ =23–36 kPa,  $\phi$ =14–18° and  $c$ =20–28 kPa,  $\phi$ =12.5–17°, respectively (Liao and Lei 2014).

As a matter of fact, the Jurassic formation, from the lower Tongzhuyuan formation ( $J_{1t}$ )—middle Qianfoya formation ( $J_{2q}$ )



**Fig. 1** Location of the Shanshucao landslide in Shazhenxi Town, Zigui County, Hubei Province, central China

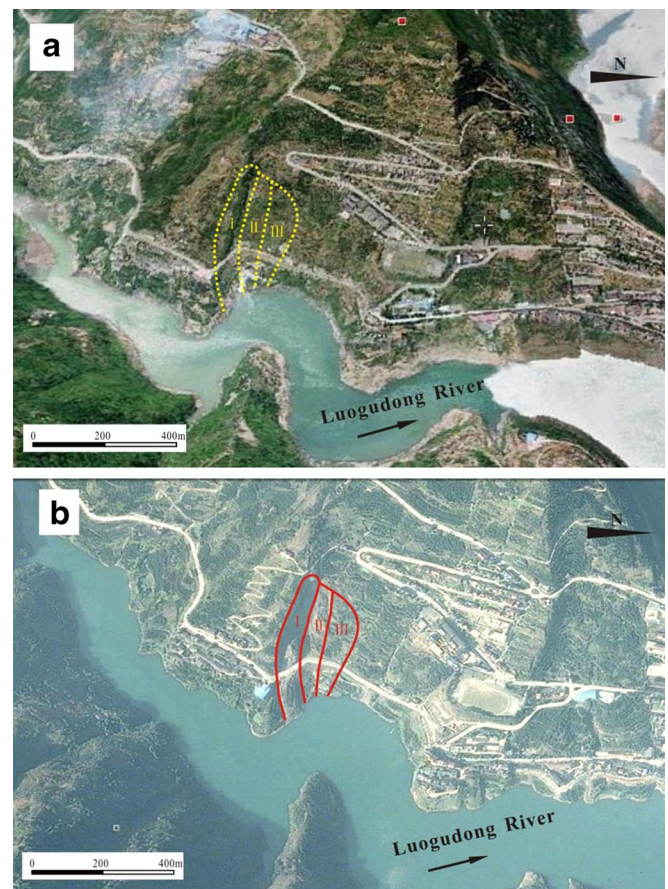
to the upper Jiuligang formation ( $J_{3j}$ )—covers the whole Three Gorges region from Zigui County to Chongqing city. It is mainly composed of siltstone with mudstone and its red color, and the Jurassic formation is called *red layer*. Because red layer is characterized by the dominant argillation layer, landslide often occurs in the Jurassic formation especially in the consequent slope, such as Qianjiangping landslide and Shanshucao landslide. Some researchers name this kind of landslide as *Zigui type landslide* (Chen et al. 2006).

#### Rock mass structure of slope

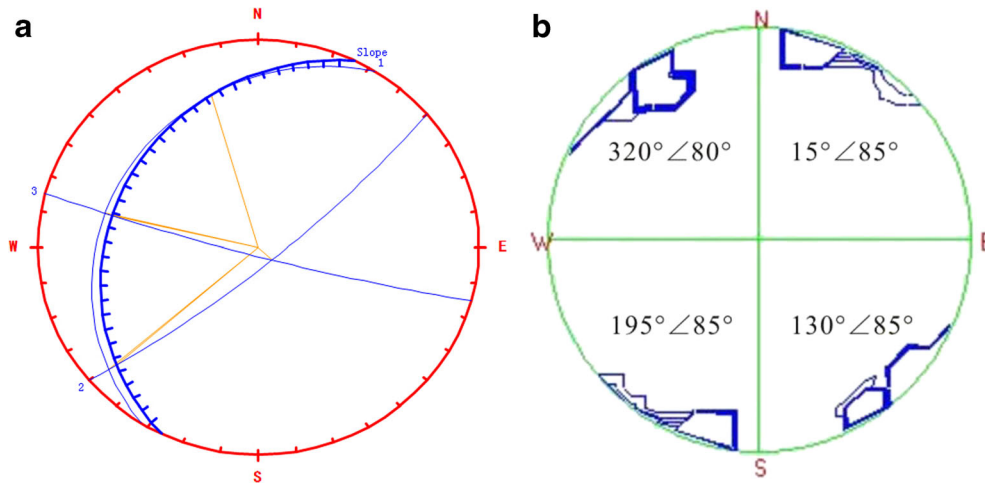
The slope consists of feldspathic quartz sandstone, siltstone with mudstone, sandy shale, and their interbedded strata in the Middle

Jurassic Qianfoya formation ( $J_{2q}$ ). The thickness of the strata varies from thick to thin layer. The strength varies from hard rock to soft rock. The unconfined compressive strength of unweathered feldspathic quartz sandstone varies from 71.6 to 98.4 MPa with average value of 82.5 MPa. The unweathered siltstone and sandy shale are hard rock, having the unconfined compressive strength of 31.5–43.3 MPa and average value of 40.2 MPa (Liao and Lei 2014), while they are easily weathered and degraded into soft rock. The altitude of the Red Layer is of  $122^{\circ}\angle 20^{\circ}$ , and the slope angle is of  $116^{\circ}\angle 22^{\circ}$ . Hence, the slope belongs to consequent slope (Fig. 3), and the rock mass structure of slope is classified into type III (GB 50330-2013).

There are mainly three sets of discontinuities in the slope (Fig. 3, also see Fig. 11). The sedimentary bed (set 1) is key discontinuities, which has smooth plane and good elongation. Especially, the intermediate argillation layer is the crucial sliding plane for the landslide. Besides the sedimentary bed plane (Xu et al. 1993), there are two tectonic fractures. Set 2 of tectonic fractures, controlling the side boundary for landslide, has strike  $N 40^{\circ} E/dip 80^{\circ}$ , i.e.,  $320^{\circ}\angle 80^{\circ}$  or  $130^{\circ}\angle 85^{\circ}$ , has fracture density of 3–5/m and trace length of 0.5–5 m. Some are filled by clay with debris and some are not. Set 3 of tectonic fractures, controlling the scarp for landslide, has strike  $N 75^{\circ} W/dip 85^{\circ}$ , i.e.,  $15^{\circ}\angle 85^{\circ}$  or  $195^{\circ}\angle 85^{\circ}$ , has density of 1–3 /m and trace length of 0.5–2 m.



**Fig. 2** Comparison prior to and after failure. a The satellite imaging taken in the year 2009, water level at 150 m. b The satellite imaging taken in the year 2014, December, water level at 175 m

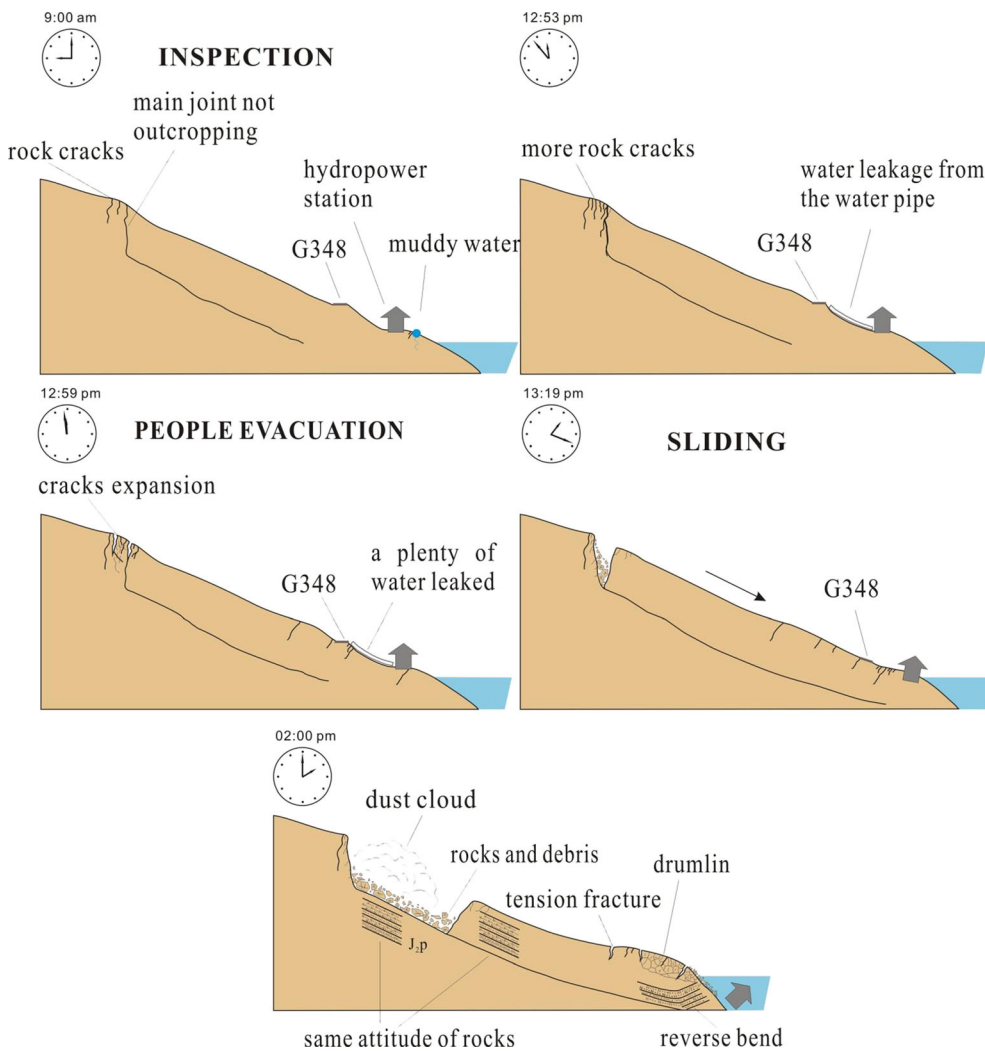


**Fig. 3** Discontinuities in the slope. **a** Stereographic projection of the slope. **b** Schmidt projection net for fractures

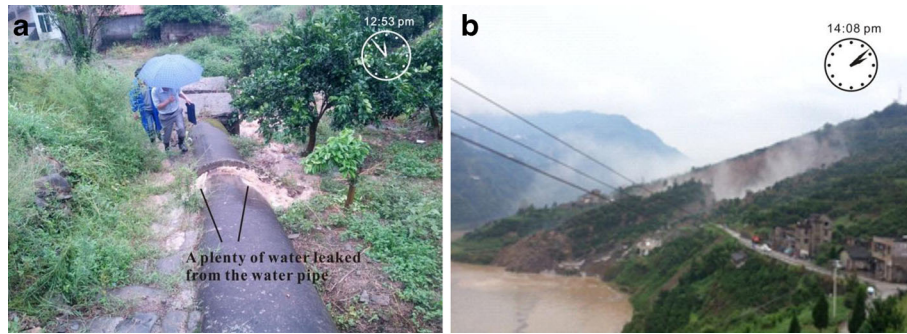
**Generating process and loss of the event**

A week of intense rainfall did not stop until the event occurred on 2 September 2014. According to the local interview survey at

9:00 am, some muddy water overflows at the lower part of the slope close to the river, and some rock cracks outside the back scarp were found. Figure 4 displays the time evolution process of



**Fig. 4** The time evolution process of the Shanshucao landslide



**Fig. 5** Photos of the day's event. **a** Water leaked from the water pipe prior to large displacement failure. The man with umbrella is the commander of this event, Yu Zuzhan. **b** The sliding mass slipped with dust cloud

the Shanshucao landslide. At 12:53 pm, a few cracks appeared on one side (close to the landslide) of pressure pipeline below the national road, with water leakage. Approximately 6 min later, a large water leak from both sides of the pipe (Fig. 5a) was observed. After that, a blast of turbid water gushed out of the ground at the right boundary (164 m). All people, including local inhabitants and staves who worked in the Daling Hydropower Station, were informed to emergency escape and evacuated out of the sliding mass at 13:00 pm. Afterwards, the large-scale rock mass began to slip at 13:19 pm and completed at 14:08 pm except small block of rockfall that occurred from the newborn overhanging cliffs, the south boundary of the main rock sliding area (I) and scarp. The commander of this event and witness, Yu Zuzhan (the Director of Bureau of Land and Resources in Zigui County), stated that he could hear a loud roar at the distance of 400 m from the landslide, then see a great deal of dust cloud rose from the rear area of the landslide (Fig. 5b). There were still small rock blocks intermittently till 17:18 pm.

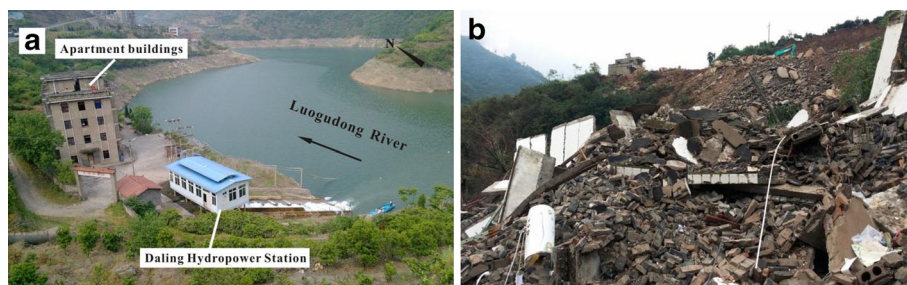
Owe to brilliant decision and decisive evacuation, no one was injured. However, there was still serious economic loss caused by the Shanshucao landslide. The direct economic loss was incurred to 32 million RMB. It was the first time that a hydropower station was completely destroyed and disappeared into the water. Three five-storey apartments on the lower part of slope near the hydropower station were shattered (Figs. 6 and 7). Two hundred meters of the national road (G348) was moved 5–100 m displacement, the maximum displacement occurred in the main rock sliding area (I) and reached 100 m and the relatively small displacement occurred in the tractive area (III) (Fig. 7). Twenty hectares of orange

planting was destroyed or affected. In addition to these, the power supply for the town of Shazhenxi was cut for 3 days. A huge loss induced by a landslide is unthinkable before the final failure of the slope with great displacement (Xu et al. 2014).

#### Landslide features

Figures 8 and 9 illustrate the extent of the Shanshucao landslide and subzones. The landslide had an irregular rectangular shape, with a length of 350 m and a maximum width of 140 m. The highest elevation of the main scarp was about 283 m. The national road (G348) was situated in the middle part of the slope (elevation 204 m), and the hydropower station was located in the lower part of the slope (about 160 m elevation) prior to sliding. The remains of the apartments and concrete pavements were in the lower part of the landslide (Fig. 8). The gradient of the upper part of landslide was basically the same as the original slope angle of 18–20°, although it changed the direction (to 40–65°) below the national road (G348). The elevation of the water level was 162.31 m on the day of the event, so some lower part of the landslide was buried under the water. Based on the sliding distance and substance of sliding mass, the Shanshucao landslide was divided into three subzones (Fig. 9): the main rock sliding zone (I) and two separated slipped zones (II and III).

The maximum length and width of the main rock sliding mass (I) were 350 and 40 m, respectively, for an area of 1.4 ha. The sliding was initially in a S 64° E direction, which then turned to S 83° E due to the resistance of the tongue-protruding slope at the lower part of south side. The maximum depth of the sliding mass reached 27 m, so it was a deep-seated landslide (DZ /To218-2006).



**Fig. 6** View of the lower part of the Shanshucao landslide. **a** Daling Hydropower Station and three five-storey apartments prior to slope failure (taken on April 30, 2013). **b** Daling Hydropower Station disappeared and three five-storey apartments rubble (taken on September 17, 2014)



**Fig. 7** View of the lower part of the Shanshucao landslide, road G348 was moved at great differential displacements, and the concrete pavement broken into pieces

The estimated sliding mass volume was 0.37 million  $m^3$ . It dove towards the river like a submarine, moving about 160 m measured by laser geodimeter. Due to the long displacement of the main rock sliding mass (I), an unloading zone area about 1700  $m^2$  was induced along the new-born overhanging rock cliff on the right side. On the left side of the main rock sliding mass (I), two tractive zones (II and III) were developed. The average thickness of the zones was about 6.5 m, and its length and width were approximately 260 and 90 m, respectively, with an estimated volume of 0.15 million  $m^3$ . The landslide was considered as a medium-scale failure (DZ /To218-2006), with an area of 0.038  $km^2$  and a volume of 0.52 million  $m^3$  in total.

The slip displacements of landslide, which were measured by laser geodimeter or estimated by landmark or symbolic points such as national road, guardrail, and apartment, varied with the location. It gradually decreased from south to north. The displacement in zone I, an active zone located in the south side, was the largest movement about 60–120 m. While the displacement in zone III, a passive tractive zone located in the north side, was

the smallest movement about 5–20 m. The displacement in zone II, another passive tractive zone located in the middle, was among of those in zone I and zone III about 20–60 m. It also varies from the upper to lower part of the landslide. For example, the displacement in zone I at upper part was 120 m, while at the lower part, it was 5–60 m because the riverbed hindered the movement of rock mass.

Figure 10 is a longitudinal section of the main rock sliding block (zone I) of the Shanshucao landslide. It shows that the slope angle is around  $22^\circ$ . The bedrock is feldspathic quartz sandstone, silty mudstone, and sandy shale of the Middle Jurassic Qianfoya formation ( $J_{2q}$ ), with the dip direction of  $120^\circ$  and dip angle of  $20^\circ$ . The landslide, obviously, occurs in the consequent slope, which is the facility-sliding stratum for landslide in Three Gorges Reservoir.

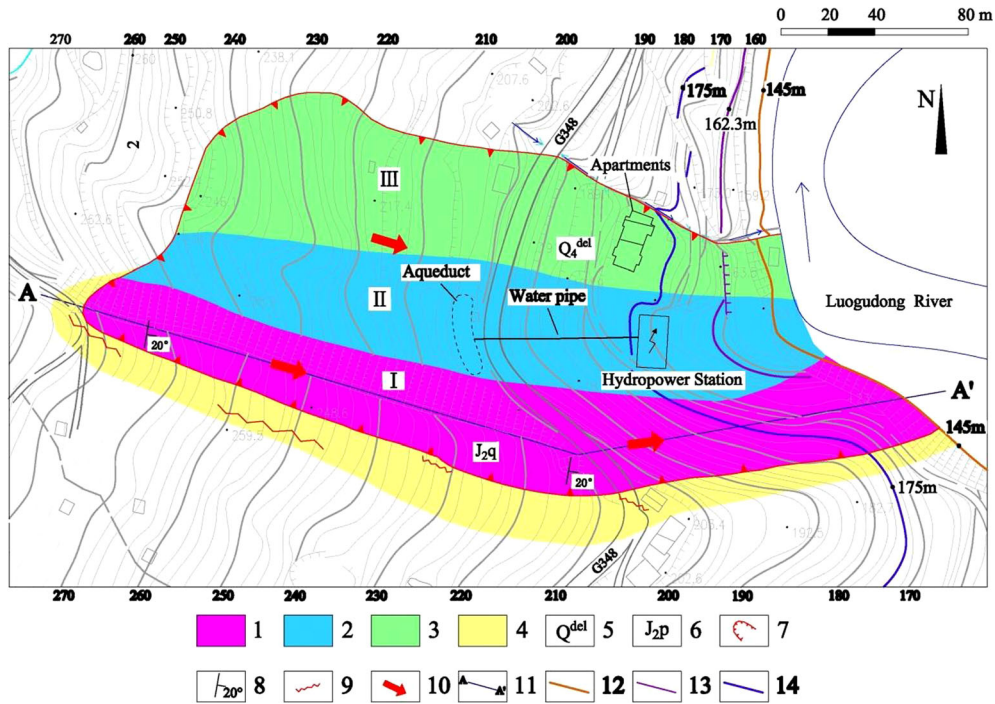
#### Structure and deformation characteristics

The very interesting special boundary conditions of Shanshucao landslide were two free boundaries and two separating planes (Fig. 11). Two free boundaries are the following: one is the overhanging rock cliff, which is composed of the left boundary (north boundary) for the main rock sliding mass (I); and the other is river valley, which is the free space (east boundary) of sliding for landslide zones I, II and III. Two separating planes are the following: one is an assembly discontinues through set 2 fractures with strike  $N 40^\circ E \angle 80^\circ$ , which forms the right side boundary (south boundary) and incises rock mass and bed from the slope for the main rock sliding mass (I); and the other, an assembly discontinues through set 3 with strike  $N 75^\circ W \angle 85^\circ$ , which makes up the scarp boundary (west boundary) and incises rock mass and bed from the vertical slope and connected plane of back scarp (on the west). The north and east boundaries of slope are free, resulting in no friction to resist sliding, which is similar to that of Qianjiangping landslide (Liao et al. 2005).

The sliding mass at upper part of zone I, rock blocks with different sizes (Fig. 11a, b), is lithologically and structurally the same with the bedrock. The remaining mass at the middle part of zone I as shown in Fig. 11c, not only the occurrence of stratum but also the attitude, is just the same as the original sedimentary and overhanging rock cliff on the right boundary of the landslide. It indicates that the main rockslide zone I was an integral



**Fig. 8** View of the Shanshucao landslide and landslide subzones

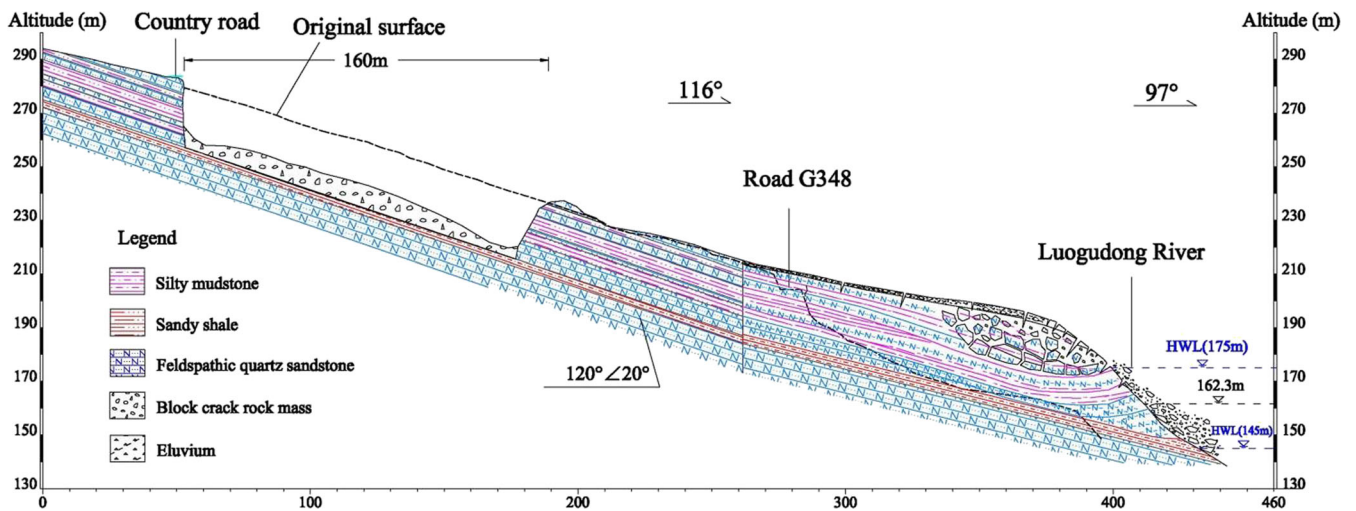


**Fig. 9** Layout of the landslide. 1 The main rock sliding zone (I), 2 tractive zone (II), 3 tractive zone (III), 4 unloading area, 5 landslide formation, 6 Middle Jurassic Qianfoya formation, 7 boundary of the landslide, 8 attitude of strata, 9 fractures, 10 sliding direction, 11 longitudinal section trace, 12 the lowest water level, 13 water level on the day of the event, and 14 the highest water level

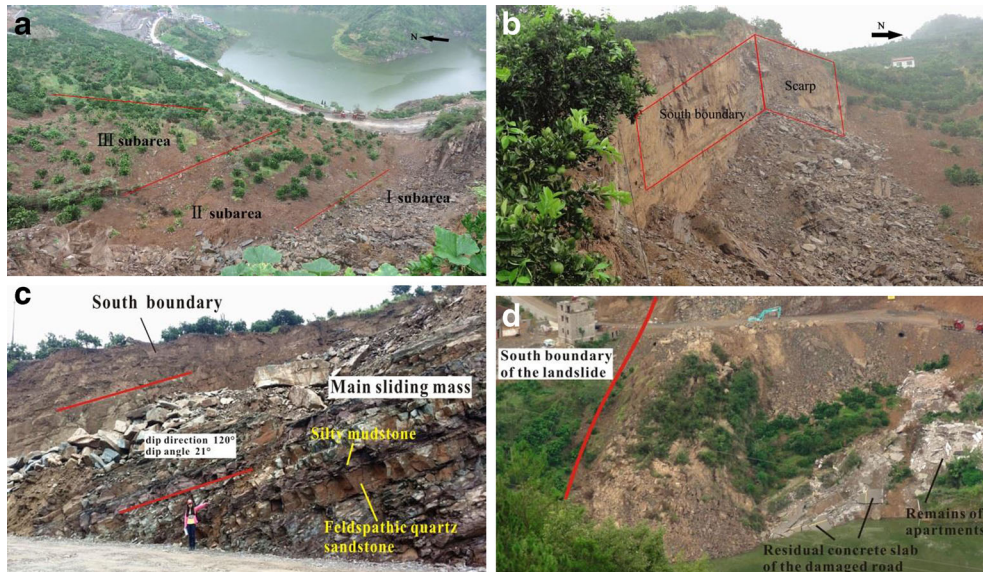
translational motion. However, the sliding rock blocks at the lower part of zone I are chaotic, turned, and squeezed since the sliding mass was resisted by the riverbed and pushed by upper sliding mass. This resulted in the formation of a drumlin at slope toe, which elevated about 15 m (height)×65 m (width) above the ground (Fig. 11d).

The sliding mass of zones II and III consists of the residual deposit of Quaternary and rock debris originated in sedimentary of the Middle Jurassic Qianfoya formation ( $J_{2q}$ ) (Fig. 11a).

Some changes had taken place in topography after this failure event. Figure 12a shows a great deal of rocks and debris in disorder in the upper part of zone I, due to the second collapse of scarp and new-born overhanging rock cliff induced by unloading. The rock layer was nearly vertical with scratches on it for squeezing between I and II subareas (Fig. 12b). Citrus tree on surface land of zone II and zone III, exhibiting slanting and falling, behaves as drunkard, which is a typical displacement feature of landslides. Cracks



**Fig. 10** Geological longitudinal section (line A-A in Fig. 9) of the landslide



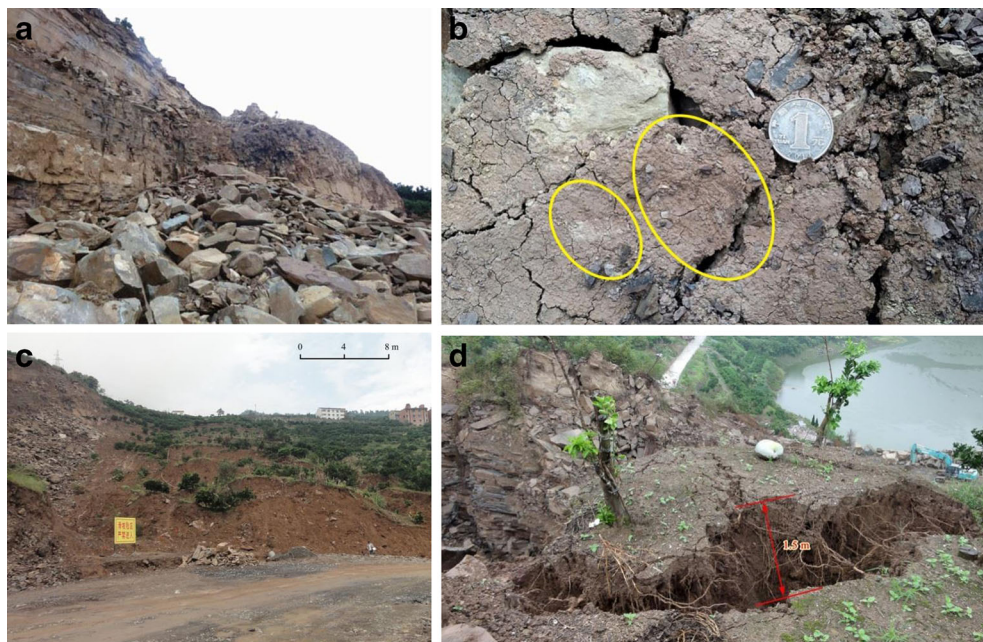
**Fig. 11** Photographs showing structure characteristics of the landslide. **a** The landslide was divided into three subzones. **b** The south boundary at the upper part of the landslide. **c** Main sliding mass in the upper part of the landslide. **d** The sliding mass in the anterior part of the landslide

in these zones distribute widely in the step shaped (Fig. 12c). Besides these, there is an unloading area nearby the south overhanging rock cliff, where it develops an amount of cracks with different extent sizes ranging from 0.03 to 1.5 m. The closer the crack to the edge of the new-born cliff, the longer and more open it becomes. Figure 12d shows a deep and large crack opening along the edge of the cliff, with the approximate width of 1.5 m resulting from the unloading effect.

### Triggering factors and failure mechanism

#### Rainfall

It is assumed that there is an association between rainfall and landslide due to the week of intense rainfall. Precipitation from 1 August 2014 to 2 September 2014, monitored in Shazhenxi meteorological station, is depicted in Fig. 13. It is clear that high intensity and duration of rainfall was clustered into the last 6 days. The



**Fig. 12** Photographs showing the deformation characteristics of the landslide. **a** A great deal of rock blocks and debris in disorder in the upper part of zone I. **b** Scratches on the rock layer between zone I and zone II. **c** Cracks in zone II widely distributed in step-shaped. **d** A big crack along the edge of the south overhanging cliff

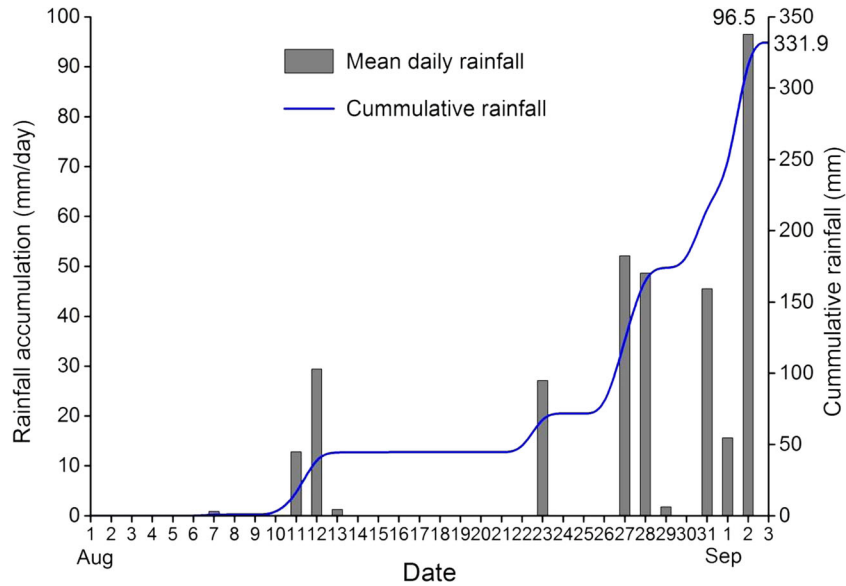


Fig. 13 Precipitation monitored and the cumulative rainfall (from 1 August 2014 to 2 September 2014) in Shazhenxi Station

rainfall on 2 September 2014 (the day of landslide event) was significantly larger than other daily rainfall amounts, reaching up to 96.5 mm. Total rainfall accumulated for 33 days before the event reached as 331.9 mm, which was a very large value in this area.

According to the historic records, the rainfall in the landslide area mainly occurs from May to September, with the maximum mean monthly rainfall being 175.2 mm in July and the second being 149 mm in August (Fig. 14). However, the total rainfall in August 2014 reached up to 219.8 mm, which is 1.48 times of the mean monthly rainfall.

Furthermore, the permeable rocks (the feldspathic quartz sand stone and siltstone) and impermeable rocks (sandy shale) are interbedded, which easily affects the strength of the impermeable rock by water, especially for the argillation layer. The sandy shale and argillation layer are alternated by the groundwater, and the argillation layer finally becomes the potential sliding surface due to greatly reduce the shear strength (Li and Yang 1994). This infers that

the instability of the slope was initiated by increasing of the pore water pressure and softening of strength by the rising groundwater level from long and heavy rainfall. Hence, long-intense rainfall is one of the most important triggers of the deep-seated slope failure.

**Change of the water level**

The Shanshucao landslide occurred during the period of impoundment of the Three Gorges Reservoir, when the water level changed from the lowest water level (LWL, 145 m) to the highest water level (HWL, 175 m). The change of the annual water level of Three Gorges Reservoir is shown in Fig. 15. Figure 16 demonstrates that the amplitude of water level fluctuation is around 1 m except on September 2, reaching up to 3.8 m dramatically. The rapid rising level has a big impact on the lower part of the slope, where the water content of rock and soil changes suddenly. Firstly, the strength of rock mass in the lower part reduces greatly by soaking in the reservoir water and underground water. Secondly, the uplift

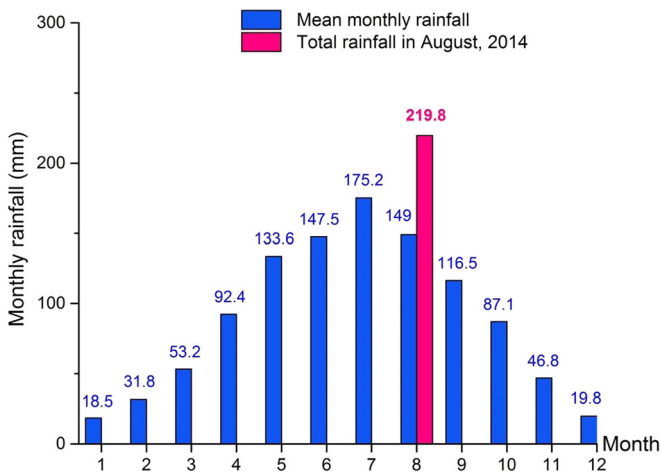


Fig. 14 Mean monthly rainfall of the landslide area over the years

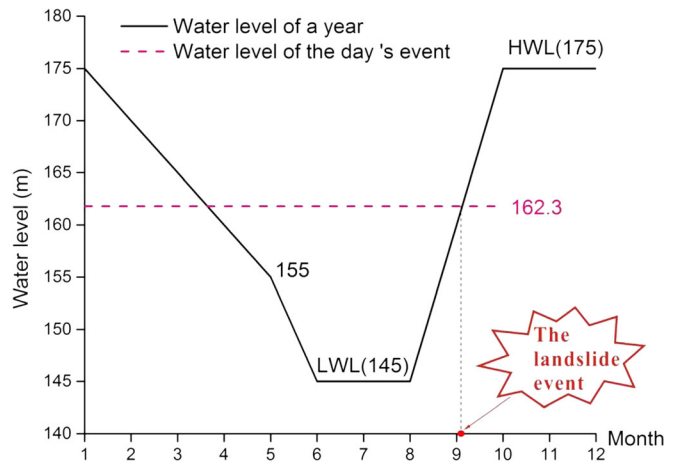
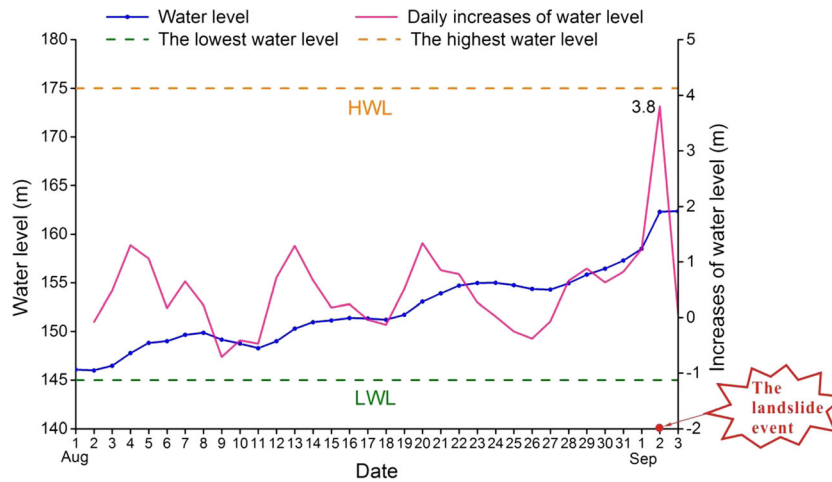


Fig. 15 The annual change of the water level of the Three Gorges Reservoir





**Fig. 16** Changes of the water level from 1 August 2014 to 2 September 2014 (according to the information of China Three Gorges Corporation)

pressure above the impermeable layer is evidently increased by the quick rising of water level. Finally, the rock mass of the lower part will launch by reducing resistance when the sliding mass of the upper part slips down.

#### Failure mechanism

Figure 17 shows the mechanism sketch of the Shanshucao landslide. It is deemed that there are two start-sliding sources in the event: one is at the top of the landslide, and the other is at the foot of the landslide. The cracks and argillation layer in the slope were filled up by infiltration water because of the long rain in August and heavy rain on 2 September 2014, which caused the fracture propagating, pore water pressure growing, and shear strength decreasing of the slope. The fracturing and underground water pressure in the scarp and head push the mass sliding due to the heavy and prolonged rainfall. The groundwater level is rapidly increased by the rising of the reservoir water level that forms larger hydrostatic pressure at the potential sliding surface. Thus, the uplift pressure at the foot, where the mass is submerged, is greatly increased at extreme rapid rate on 2 September 2014, and the normal stress is reduced. In other words, the anti-sliding force is minified, and the sliding force is increased due to the uplift

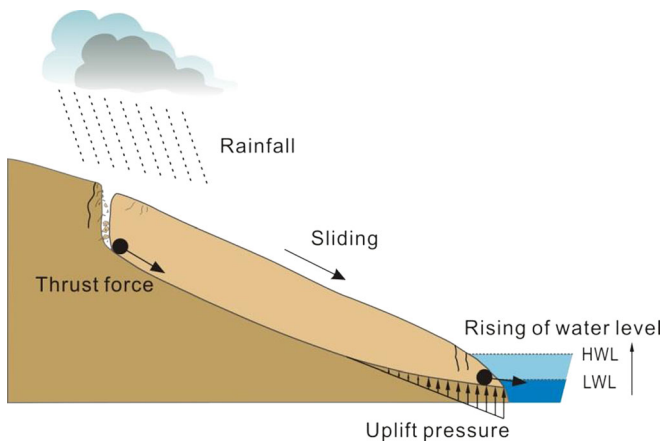
pressure (Tang et al. 2014; Wang et al. 2014). It can be concluded that the Shanshucao landslide is initiated by two start-sliding sources and deduced that the landslide will not occur only by heavy raining or only by reservoir water level rising factor.

Further analysis on 2 September 2014 landslide sliding mechanism using numerical modeling is in progress.

According to the mechanism of landslide in reservoir area, it is classified into four types: uplift pressure induced (failure is initiated by the uplift pressure at foot when reservoir impoundment and water level is rising), uplift pressure+heavy raining induced, hydrodynamic pressure induced (failure is initiated by the seepage pressure at lower part of slope when reservoir drawdown and water level is decreasing), and hydrodynamic pressure+heavy raining induced (Xu et al. 2013). As mentioned, the Shanshucao landslide belongs to the uplift pressure+heavy raining induced type, which usually occurs for consequent slope in Three Gorges Reservoir region, such as the well-known Qianjiangping landslide.

#### Conclusions

The Shanshucao landslide is one of the longest displacement slope failures and is an outstanding and valuable reference for Red Layer landslides in Three Gorges Reservoir region. Based on investigation and analyses, the following conclusions were made.



**Fig. 17** The failure mechanism of the Shanshucao landslide

1. Shanshucao landslide occurred on 2 September 2014, in Three Gorges Reservoir region, with an area of 0.038 km<sup>2</sup> and a volume of 0.52 million m<sup>3</sup> in total. It could be divided into three zones: zone I was the main rockslide with a very large displacement of 160 m, zone II and zone III were tractive zones induced by rock slope failure (zone I) and had differential displacement varying from 60 to 5 m. A huge loss was suffered from the great displacement.
2. The special overhanging rock cliff-one free boundary, two separating planes (assembly discontinues through sets 2 and 3), and strata bed of consequent slope formed the main rock sliding mass (I). Moreover, the bedrock consisted of feldspathic quartz sandstone and siltstone, alternating sandy shale and interbedded argillation layer, which was the potential sliding surface.
3. Both the long and heavy rain and the rapid rising of water level were thought to be the main triggering factors. Due to the

heavy and prolonged rainfall, the underground water pressure in the scarp and head pushed the mass sliding. Meanwhile, the uplift pressure in the foot greatly increased the sliding force due to rapidly rising of the reservoir water level. According to the mechanism of landslide in reservoir area, the Shanshucao landslide was an uplift pressure+heavy raining induced landslide.

### Acknowledgments

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