Analysis on the mechanism of landslides triggered by impoundment of water reservoir and development on the deformation prediction method

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貯水池水位変動による地すべり発生機構の解明及び予測手法の開発

要　旨

中国の揚子江における三峡ダム工事は世界一大きい水力電力プロジェクトである。2003 年 6 月に最初の湛水により、貯水池地域では、多くの斜面に変形が発生し、また再活動性地すべりも数多く移動し始めた。本プロジェクトにおいて、2003 年 7 月に発生した千将坪地すべりに対して、地すべりの発生機構について現地調査を行い、湛水による地すべりの誘起機構について検討を行なった。また、湛水により活発に変動している樹坪地すべりに対して、伸縮計による観測システムを設立し、それに警報機をつけて、斜面変形に基づいた地すべりの早期警戒態勢も立てた。また、地下水による当地すべりの変形への影響を解明するために、1 m 深地温探査を行い、地すべり末端付近の地下水分布を調査した。さらに、斜面内部構造を探査するためのボーリング調査も実施し、地下水分布とすべり面の確認を行なった。

樹坪地すべりの観測結果より、当地すべりの変形が貯水池湛水に敏感に反応していることが分かった。本研究計画実施する前の GPS 観測結果と合わせて解析すると、樹坪地すべりの湛水による変形挙動は明らかになっている。貯水直後、末端部は先に下方へ移動し、その後、地すべり頭部が着いていく。 現段階では、最初湛水してから約２年間を過ぎたところ、斜面変形バターンが変化した。末端部の変形量が小さくなったため、地すべり頭部の変形より、末端部が圧縮されている。

従来から、貯水池において、貯水する時に、斜面の安定性が低下しなく、放水するときに、斜面が不安定になるという理論が立てられている。しかし、千将坪地すべりは貯水した直後の一ヶ月に発生し、樹坪地すべりも貯水行為に影響され、貯水直後の変形が激しく、その後段々と安定している。水位変動に対する反応が明瞭に観察される。本研究は貯水池の水位変動による斜面変形・安定問題を予測する方法の開発を目指しているが、現段階では、一回のみの湛水を観測しかできず、今後も観測を継続させ、2006 年と 2008 年に予定している湛水の観測を行なってから、予測方法のまとめにかかりたい。

Abstract

The Three Gorges Dam construction on the Yangtze River in China is the largest hydro-electricity project in the world. The first impoundment started from 95 m on June 1st, 2003, and reached 135 m on June 15th, 2003. Shortly after the water level reached 135 m, many slopes began to deform and some landslides were reactivated. In this research project, field investigation was conducted on the Qianjiangping landslide that occurred in July 2003, and the mechanism of landslide triggered by water-reservoir impoundment was examined. On the reactivated Shuping landslide, through establishing a deformation monitoring system, the deformation behavior of the Shuping landslide after the water impoundment was monitored. Also, to clarify the effect of groundwater on the landslide deformation, geophysical exploration with the method to measure the 1 m ground temperature was conducted to understand the groundwater distribution. Also, boring exploration was conducted to confirm the groundwater level and confirm the sliding surface of the landslide. The following are the main results.

(1) In this report, the investigation results on the Qianjiangping landslide was presented to show the possible mechanism of the landslide triggered by the impoundment of water reservoir. It shows that, the Qianjiangping landslide occurred along a pre-existing shear surface along the strata layer of sandstone and siltstone with mudstone. Quarrying of mudstone for brick manufacture from the toe of the slope, and intense rainfall before the landslide put the slope in a critical state. It is clear that the high water level in Qinggan-he River through impoundment of the reservoir was the trigger for the landslide occurrence. Brittle fracture of crystalline calcite caused a quick loss of shear strength along the sliding surface, which is the main reason for the rapid movement of the landslide after the slope failure.

(2) The monitored results show that the deformation of the Shuping landslide became very active after the impoundment. Through the GPS monitoring, crack displacement measurements, extensometer monitoring along the longitudinal section of Block-1, the deformation style of the Block-1 of Shuping landslide was analyzed. Sooner after the impoundment of the water reservoir, the toe part displaced downward faster than the upper part. In the current stage, two years after the first impoundment, the slope deformation style changed. The displacement of the lower part almost terminated while the upper part displaced downward gradually, and compressed the toe part. For the Shuping landslide reactivating from an old landslide, and with rich groundwater in it, the influencing factors on the slope deformation is complicated. From one year monitoring with the extensometers, it is very clear that the slope displaced soon after the impoundment of the water reservoir. It is very important to keep the monitoring continued especially during the next stage of impoundment which will be conducted in June 2006 (Water level will be raised from 139 m to 156 m).

1. Introduction

The Three Gorges Dam construction on the Yangtze River in China is the largest hydro-electricity project in the world. The dam site is located at Sandouping village near Maoping, the capital of Zigui County, Hubei Province. The designed final dam height is 185 m, the final length 2309.5 m, and the designed final highest water level 175 m. When dam construction is finished, the Three Gorges Reservoir will reach Chongqing City, about 660 km upstream from the dam. The first impoundment started from 95 m on June 1st, 2003, and reached 135 m on June 15th, 2003. Shortly after the water reached 135 m, many slopes began to deform and some landslides occurred.

In this report, the investigation results on the Qianjiangping landslide and the monitoring results on the Shuping landslide are reported.

2. Features of the Qianjiangping landslide

In the early morning, at 00:20 July 14, 2003, the Qianjiangping landslide occurred at Shazhenxi Town (Fig. 1) beside Qinggan-he River, a tributary of the Yangtze. The Qianjiangping landslide was located on the western side of Qinggan-he River. On the opposite side of the river is the main street of Shazhenxi (Wang et al. 2004). The distance from the landslide to the junction of the Qinggan-he River with the Yangtze is about 3 km, and the distance along the Yangtze River from the junction to the Three Gorges Dam is about 50 km (the direct distance is about 40 km).

Fig. 1 Location map of the Qianjiangping landslide in the Three Gorges Reservoir area, Hubei Province, China

Figs. 2 and 3 are photographs of the landslide taken from the upstream side and front of the landslide. The landslide had a tongue-shaped plan, with a length of 1,200 m, and a width of 1,000 m. It moved about 250 m in the main sliding direction of S45°E. The average thickness of the sliding mass was about 20 m, thinner in the upper part and thicker at the lower part. The total volume was estimated to be more than 20 million cubic meters. The elevation of the main scarp was 450 m, and the elevation of the Qinggan-he River water level was 135 m when the landslide occurred. The landslide release surface was along a bedding plane in the bedrock (Fig. 2). Factory buildings on the sliding mass still remained standing after sliding for about 250 m (Fig. 3). However, because serious cracks developed in the buildings, they could not be used any more and were demolished and the building materials were recycled (compare with Fig. 2). Standing trees on the sliding mass in the middle of the landslide (Fig. 4) indicate that the angle of the sliding surface remained constant and no rotation occurred. The exposed sliding surface at the upper part was very planar, and sub-parallel to the sandstone bedrock strata (Fig. 5). All of these phenomena show that the sliding mass slid along a planar sliding surface. When the sliding mass entered Qinggan-he River, the dip direction of the strata was changed to N45°W, which is opposite to the original dip direction of S45°E. The dip angle is about 5° in the bed of Qinggan-he River (Fig. 6). The deposits at the distal landslide margin contain white gravel with clasts up to 100-mm-or-so in diameter. The dip angle of the sandstone bedding at the distal margin is steeper than 30° (Fig. 7).

Fig. 2 View of the Qianjiangping landslide from the upstream side of Qinggan-he River (Taken by F.W. Wang, March 15, 2004)

Fig. 3 Front-on view of the Qianjiangping landslide (Taken by Y.M. Zhang, July 15, 2003)

Fig.4 View of the unrotated trees on the sliding mass in the middle of the Qianjiangping landslide

Fig.5 The exposed planar sliding surface, which is also a sandstone-bedding plane (there is a damaged rice paddy in front of the person)

Fig. 6 View of the reversed dip direction of the sandstone beside Qinggan-he River (Taken by F.W. Wang, March 16, 2004)

Fig. 7 Gravels displaced from the bed of Qinggan-he River and deposited in the toe of the landslide deposit (circled in photograph). Note that the sandstone dip direction is reversed and the dip angle has become steeper compared with Figs. 4 and 5)

2.1 Geological conditions

The geological strata at the site are beds of quartzo-feldspathic sandstone, fine sandstone with carbonaceous siltstone, siltstone with mudstone, and silty mudstone of the Shazhenxi group of Late Triassic age. Before the landslide occurred, the geology was thought to be very simple, and the slope was considered safe because no landslide trace on the slope was observed during the field investigation for the Three Gorges Dam construction. It looked like a simple slope with a dip structure. However, scratches (slickensides) on the sliding surface exposed after the sliding suggest a reasonable explanation for the sliding mechanism of the rapid, long-runout landslide (see below).

2.2 Scratches on the failure surface

Fig. 8 shows a sequence of two photographs of scratches on the sliding surface at the upper part of the landslide. Fig. 8a shows the original situation, while in Fig. 8b a slice of sandstone has been stripped away from the plane to reveal more scratches. This shows that the scratches were present beneath the landslide sliding surface before the landslide occurred. The scratch strike direction is S15°W (red arrow). The sliding direction (S45°E) of the July 2003 event (blue arrow) is also shown by the water dribble trace in Fig. 8b). The angle between the sliding direction and the scratches is about 60°. Comparison of the two photographs shows that the scratches were not formed by the event of July 2003. They must have formed earlier, probably in a much older geological event, because calcite veinstone is widely distributed along them. This site lies between the Zigui syncline and Baifulai-Liulaiguan anticline that were folded during the Cretaceous period (Wang et al. 2002) and so the scratches can be interpreted as slickensides along bedding-plane shears.

Fig.8 A pair of photographs at the same site showing the pre-existing scratches that underlie the sliding surface of the July 2003 event (Blue arrow shows the sliding direction, red arrows show the strike direction of the pre-existing scratches). The scratches are inferred to be slickensides formed by bedding-plane shear during folding of the rocks in the Cretaceous period

2.3 Possible triggering factors and sliding mechanism

The high water level within the landslide toe caused by impounding of the Three Gorges Reservoir was naturally considered to be the trigger. Impoundment started from June 1st, 2003, and the reservoir water level reached 135 m on June 15th, 2003. The first cracks due to the slope deformation, however, were observed on October 22nd, 2002 near the present main scarp. This means that the slope was in a critical state even before impoundment of the reservoir. With the slope in such a critical state, failure probably was triggered by the direct reduction in normal load within the toe of the slope caused by the rising water level.

According to local people, sandstone and mudstone were exposed in the Qinggan-he River bank before the reservoir was impounded. The dip angle of the sliding surface, which is also a bedding plane, was measured as 32° at the upper part. Zhang et al. (2004a) observed two sets of large transversal cracks crossing the upper and middle parts of the slope. Although some rice paddies were located on the upper part of the landslide (Fig. 3), the associated high water table from irrigation should have been kept perched by the impervious weathered mudstone. The rice paddy was started ten years ago, and a pond for water supply was built near the paddy. So, for landslide stability analysis, the boundary conditions for the landslide are very clear. There was little volume of landslide in the uppermost part. The right lateral boundary was open, and so had no friction to resist sliding. As shown in Fig.8, the sliding surface was a pre-existing structural shear-plane.

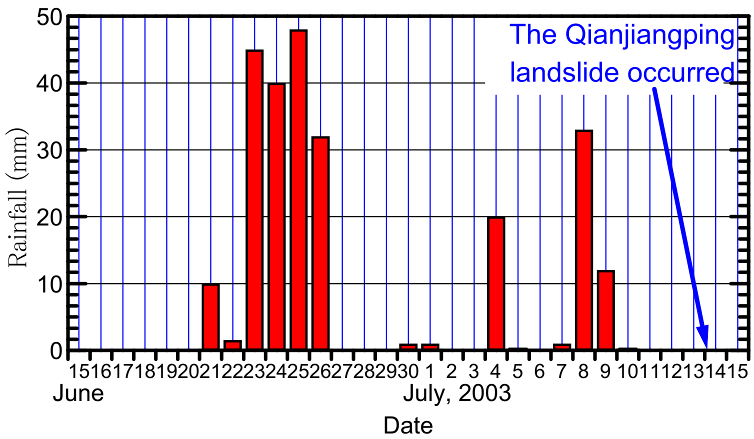

Fig. 9 Precipitation data monitored in Yichang City, 70 km from the landslide

Precipitation is monitored in Yichang City (Fig. 1), about 70 km from the landslide site. Intense rain from June 21st to 26th, and rain from July 4th to July 9th (Fig. 9) may have saturated the sliding mass, and increased its unit weight. However, considering the high permeability of the slickensided sandstone, and the transverse cracks crossing the sliding mass, it is not likely that high pore pressure would have resulted.

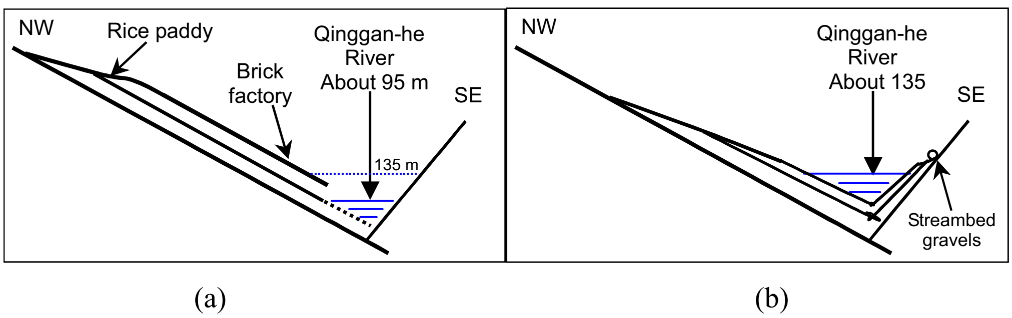

Fig. 10 Structural model of the Qianjiangping slope (a) and a sketch of the landslide after failure (b)

The landslide toe had been eroded by the Qinggan-he River long ago, and offered little resistance to sliding. Only the left lateral boundary offered side friction and tension resistance from the neighboring rock mass. For such a huge landslide, the mechanical model can be simplified as a two-dimensional longitudinal section as shown in Fig. 10(a). The situation of the landslide after failure is sketched in Fig. 10(b).

With the slope in a critical state (Fig. 10a), an increase in water level in the river would decrease the effective normal stress in the toe of the slope, and the shear resistance would decrease at the same time. These changes in the mechanical balance resulted in the slope failure.

For additional factors contributing to the failure, some attention should be paid to the factories on the lower slope before the landslide occurred. The brick factory had been quarrying mudstone in the lower part of the slope as raw material for brick making from 1997. Some 2-3 million bricks (each about 250 x 120 x 50 mm) had been produced during the six years. Such removal of mass from the toe of a landslide is a very dangerous action that leads to slope instability (but the presence of the landslide was unrecognized by experts until the cracks appeared in 2002).

When the existence of the widely distributed scratches on the sliding surface is considered, it is easy to assume that the shear strength between the sliding mass and the sliding surface was at residual strength. If this assumption were true, the rapid, long-runout sliding would be difficult to explain, because a rapid loss of shear strength is necessary to achieve the high rate of acceleration. As mentioned previously, the scratches probably were formed in the Cretaceous period, and the beds on either side of the scratched surface were bonded together with calcite cement. After the occurrence of the landslide, Zhang et al. (2004a) observed crushed crystalline calcite, some 20 to 30 mm thick, widely distributed on the exposed sliding surface on the upper part of the landslide. Fig. 11 shows a sample of the calcite. Generally, failure of crystalline calcite is characterized by brittle fracture. After a certain small distance of shearing, the cement bonding would have been destroyed. The quick loss of adhesion of the crystalline calcite could be the main reason for the rapid landslide acceleration after the initial failure of the slope.

Fig. 11 Photograph of a crystalline calcite sample taken from the sliding surface at the upper part (The white color is crystalline calcite)

2.4 Discussions

A detailed field investigation was made of the Qianjiangping landslide that occurred after the first impoundment of the Three Gorges Reservoir. The mechanisms of the landslide, especially the factors affecting slope failure were studied, and reasons for the rapid and long distance movement of the landslide were considered. Based on fieldwork and analyses, the following conclusions were reached:

(1) The Qianjiangping landslide is a landslide with dip structure. The sliding surface was along a pre-existing structural plane of weakness (a bedding-plane shear).

(2) Quarrying of mudstone for brick manufacture from the toe of the slope, and intense rainfall before the landslide put the slope in a critical state. This is not to assign blame for the landslide on the operators of the brick factory. Although quarrying of rock from the toe of a landslide is not good practice, there was no information to indicate that it was bad practice until the landslide was recognized. Prior to the cracks appearing, there appears to have been no reason to expect that the slope was unstable, and hence little reason to exercise caution.

(3) The high water level in Qinggan-he River through impoundment of the reservoir was the trigger for the landslide occurrence.

(4) Brittle fracture of crystalline calcite caused a quick loss of shear strength along the sliding surface, which is the main reason for the rapid movement of the landslide after the slope failure.

(5) Because the landslide has a tectonic background, and there are many similar slopes in the nearby area, detailed evaluations for those slopes are very important for the future stability of the Three Gorges reservoir when it is raised to its final operating level.

3. The Shuping landslide in the main stream of the Yangtze River

Fig. 12 Shuping landslide consisting of two blocks at the main stream of the Three Gorges Water Reservoir

Shuping landslide is located at the main stream of the Yangtze River (Fig. 1) in Shazhenxi Town, just about 3.5 km from the Qianjiangping landslide. The deformation became active after the first impoundment of the reservoir. Fig. 12 is an oblique photograph of the Shuping landslide, and Fig. 13 is the plane of the landslide. The landslide ranged its elevation from 65 m to 500 m. Its width was about 650 m, the estimated thickness of the sliding mass was 40 m to 70 m according to the bore hole data, and the total volume was estimated as 2.0×10^7 m^3. The toe part of the landslide was under the water level of the Yangtze River. The slope is gentle at the upper part and steep at the lower part with a slope angle of 22 degrees and 35 degrees respectively.

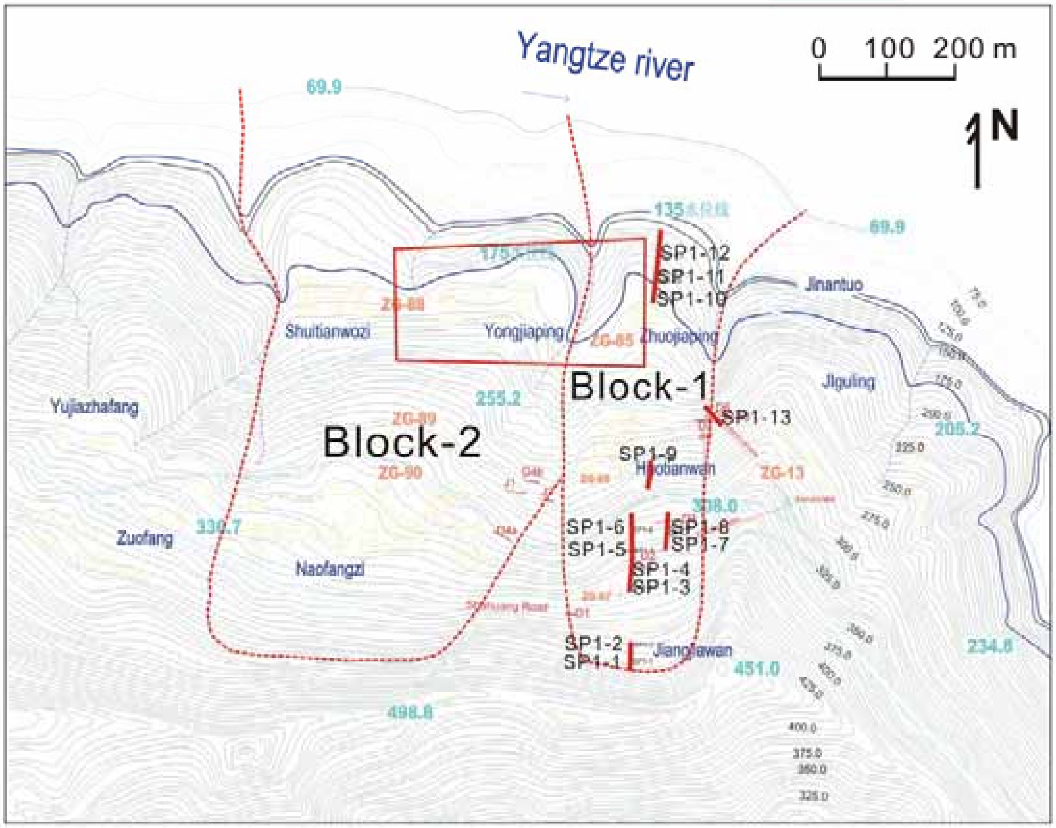

Fig. 13 Plane of the Shuping landslide and locations of monitoring and measurement works (locations of extensometers and measurement area of 1m-depth ground temperature are shown)

3.1 Features of the Shuping landslide

The Shuping landslide is an old landslide which composed of two blocks. This can be confirmed in the photograph (Fig. 12). After the first impoundment of the Three Gorges reservoir ended on June 15, 2003, obvious deformation phenomenon appeared at the slope, and it became intense from February 8, 2004. Also, the two blocks shows different deformation rate at slope surface. The serious deformation situation made 580 inhabitants and 163 houses in danger directly, and all of the inhabitants were asked to live in the disaster prevention tents which were provided by the central government. Until May 2004, most inhabitants moved their houses out of the landslide area.

Fig. 14 shows a crack at the right boundary of Block-1 outcropped at a local road. The right-hand side is the sliding mass consisting of red muddy debris of old landslide, and the left-hand side is bed-rock of sandy mudstone, muddy siltstone of Badong formation of Triassic period (T3b).

Fig. 15 shows muddy water coming from Block-1. It appears at the river even at continual sunny days showing no relationship with surface water erosion, but the underground water erosion from the inner part of the landslide.

3.2 Slope deformation characters of the Shuping landslide

Because the landslide area is a densely populated area and its active deformation occurred just after the occurrence of the Qianjiangping landslide, the deformation situation was observed by the inhabitants and reported to the local government promptly. According to the urgent investigation report (Gan et al. 2004), the typical deformation behaviors were recorded as follows.

Fig. 14 Crack at the right boundary of Block-I outcropped at a roadside

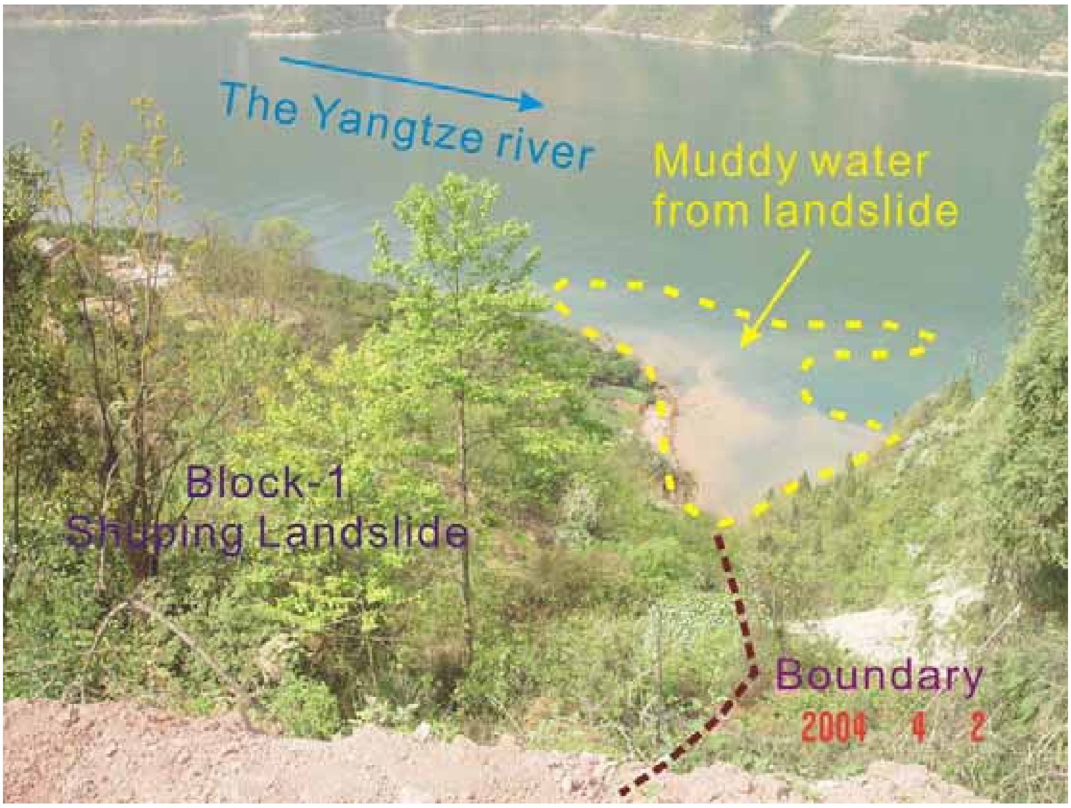

Fig. 15 Muddy water seeped out of the toe part of the Shuping landslide

From the end of October to the beginning of November 2003: Cracks became obvious at the slope surface, especially at the upper part. These cracks were enlarged from January to February 2004.

On January 5 and February 8, 2004: The water at the toe part of the landslide became very muddy. From March, the muddy water appeared almost everyday. Fig. 15 shows the muddy water situation in April 2004. This phenomenon is a very dangerous sign for slope deformation, because it may mean that the newly sheared soil at the sliding surface was eroded by underground water gradually.

On January 25 and February 8, 2004: Sharp noises coming from underground were heard by the inhabitants at night for two times. The noise is possibly caused by shearing at the sliding zone.

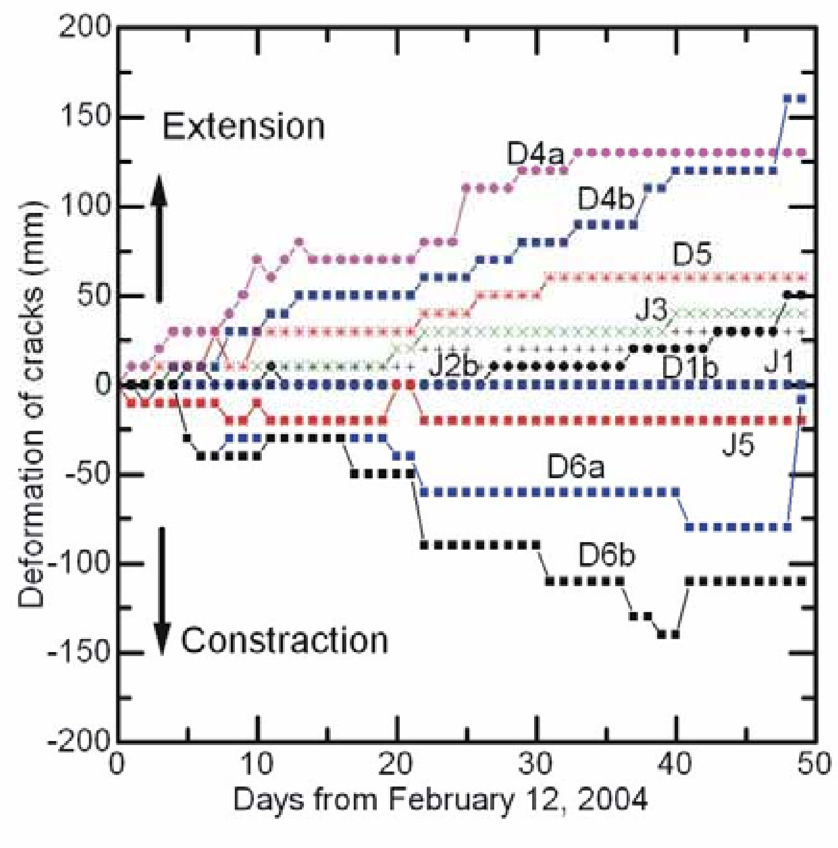

Fig.16 Measured results of crack deformation in Block-I

Because of the serious deformation situation, local government decided to monitor the cracks distributing in the slope from February 12, 2004. The inhabitants were asked to measure the width change of the cracks near their houses (see Fig. 13). For measurement, two small piles were set across a crack, and the distance between the two piles was measured three times one day. Fig. 16 shows a part of the measured results of the cracks. However, because the inhabitants are moving out of this area, the measurement points are decreasing gradually.

Roughly, the measurement results of the crack deformation shows that the extension behavior occurred at the boundary and inside landslide, and contraction deformation occurred at the other parts in the landslide block. For the 50 days period from February 24, 2004, the maximum displacement including extension and contraction respectively reached about 140 mm, showing an active deformation.

3.3 GPS Monitoring results

Two GPS monitoring lines were arranged at the central longitudinal section of the two blocks by

China Geological Survey. Each monitoring line has three GPS monitoring points, i.e., ZG85, ZG86 and ZG87 from toe to upper part in Block-I, and ZG88, ZG89 and ZG90 from toe to upper part in Block-II (See Fig. 13). The monitoring started in July 2003, just one month after the first impoundment. The measurements were conducted one time each month by Rockfall and Landslide Research Institute of Hubei Province.

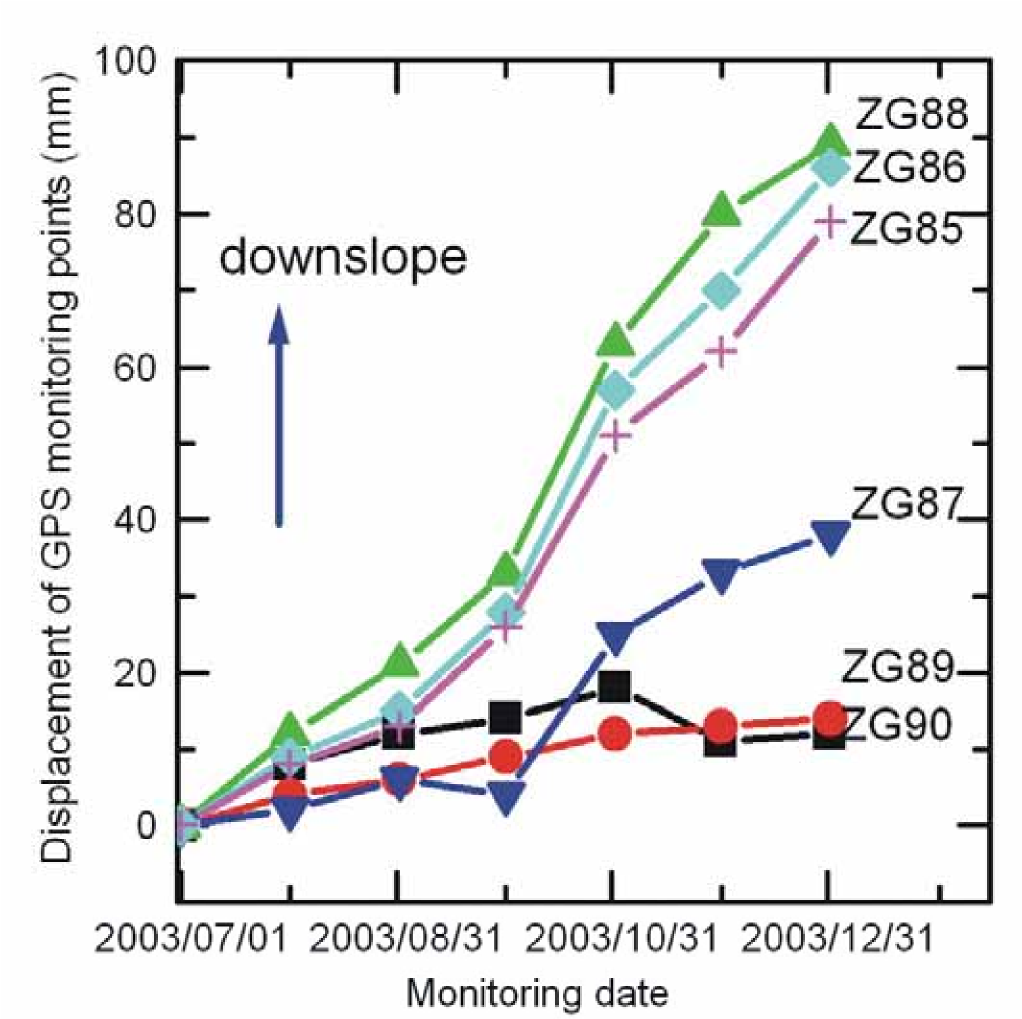

Fig. 17 GPS monitored results along the central section lines of Block-I and Block-II

Fig. 17 shows the monitored results of the GPS monitoring at the first six months after the impoundment. The displacement rate of Block-I increased rapidly after October 2003, and other two tendencies are also very clear. (1) The displacement at the lower part is larger than that at the upper part, this may be caused by water buoyant of the impoundment of the reservoir; (2) The displacement of Block-I is more active than Block-II, showing that the two blocks are independent from each other.

3.4 Installation of extensometer and the monitoring results

Until April 2004, the displacement monitoring of the Shuping landslides included crack measures conducted three times each day, and the GPS monitoring conducted one time each month. However, because of the evacuation of the inhabitants, the crack monitoring was interrupted gradually. Located at the main stream of the Yangtze River, it is not enough for the

Shuping landslide to be monitored only with GPS when considering the safety of shipping along the Yangtze River. Although GPS monitoring has high precision, the time interval of measurement is too large. Facing this situation, two extensometers donated by Kowa Co. LTD., a Japanese company, were installed in the Block-I of the Shuping landslide in April 2004. The extensometer is Sakata Denki style. The monitoring can continue for one week or one month automatically. A warning system is also connected with the extensometer. When the displacement rate exceeds 2mm/hour, a warning will be announced.

The automatic monitoring with the extensometer was confirmed to be working well (Zhang et al. 2004b). However, two extensometers are not enough for such a large landslide. In August 2004, another 11 extensometers were installed along the central line of the longitudinal section of Block-1, with emphasizing on the serious deformation parts. Also because of the limit of funds, the extensometers cannot form a continual longitudinal section line.

Fig. 18 shows the extensometer installed in Shuping landslide. The positions of all of the thirteen extensometers were shown in Fig. 13 as “SP1-x”. Among them, SP1-1 and SP1-2 were set across the main scarp; SP1-3 to SP1-6 were set below the Shahuang road which has a high traffic. SP1-7 and SP1-8 were set almost parallel with SP1-5 and SP1-6. SP1-9 was set at the low part. Then, SP1-10, SP1-11, and SP1-12were set near the Yangtze River at the toe part of the landslide. SP1-13 was set at the right boundary of Block-1 shown in Fig. 14, because the crack extension is obvious.

Fig. 19 is the monitoring results of all the thirteen extensometers from August 2004 to June 2005, companying with the water level in the Three Gorges at dam site showing at the bottom, and the rainfall records of this area showing at the top.

Fig. 18 Extensometer installed in Shuping landslide. The deformation is recorded on the rolled paper and also saved in a memory (visible in the right side)

The monitoring results show some tendencies of the landslide displacement. (1) The SP1-1 and SP1-2 at the main scarp did not record obvious displacement. One possible reason is that the setting positions of the two extensometers did not cross the main scarp. (2) The deformations at SP1-5, SP1-6, SP1-7 and SP1-8 were the most active ones showing extension. Because of local failure, the SP1-13 showed extremely great extension. (3) The toe part of the landslide showed compression behavior. Comparing with the largest displacement at the lower part by GPS monitoring in the first six months after the first impoundment, it may estimate that the toe part moved down faster at the first period and became silent now; the upper part moved slowly at the first stage, and now followed the movement of the lower part and compressed the lower part. An exact examination will be conducted with the comparison of the recent GPS monitoring data along the central longitudinal section, which is not open currently.

Another important tendency was recorded in the monitoring results. In mid-September, the water level of the Three Gorges was raised for about 3 m, corresponding to this water level raising, the displacement velocity of SP1-5, SP1-6 and SP1-7 in-creased obviously, reflecting the influence of the impoundment on the slope deformation. Also, during the rainy season after April 2005, displacement acceleration tendency at some point (SP1-6, 7, 8) was monitored, showing the displacement of the landslide is also influenced by groundwater conditions.

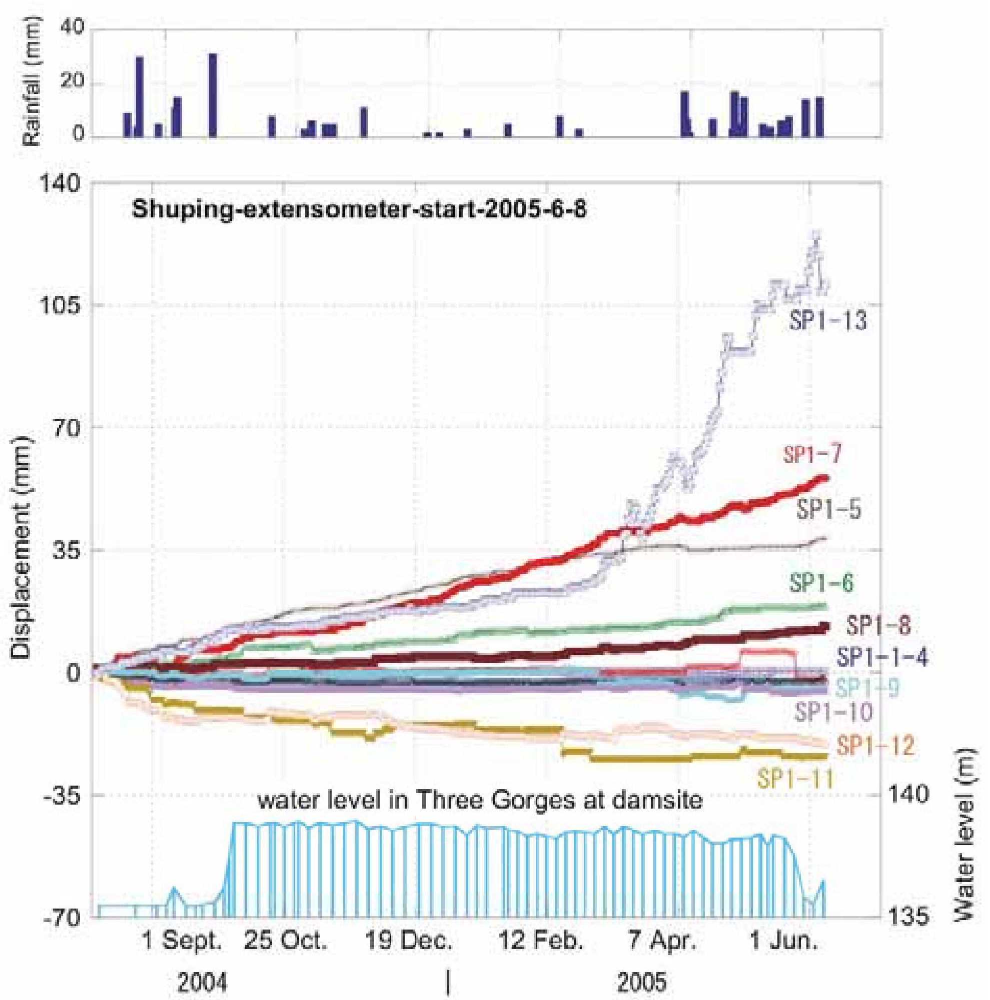

Fig. 19 Monitored results of the extensometers (middle), the precipitation data in Yichang City (top) and water level in the Three Gorges Dam site (bottom)

3.5 1M-Depth ground temperature measurement for groundwater veins

Takeuchi (1972) developed a method for the investigation of groundwater veins through 1m-depth ground temperature measurement. This method is widely applied in the practice of groundwater exploration in landslide area, especially in Japan (Takeuchi 1996).

Fig. 10 shows the principle of the 1m-depth ground temperature measurement for groundwater vein. Comparing with the ground without water, the ground with water always has a temperature similar to that of the groundwater. Generally, groundwater temperature does not change so much around a year. While, the temperature in the ground without water is controlled by the atmosphere temperature, which will be higher than groundwater in summer and autumn, and lower in spring and winter. Through measuring the temperature distribution in an area, the distribution situation of groundwater vein can be estimated.

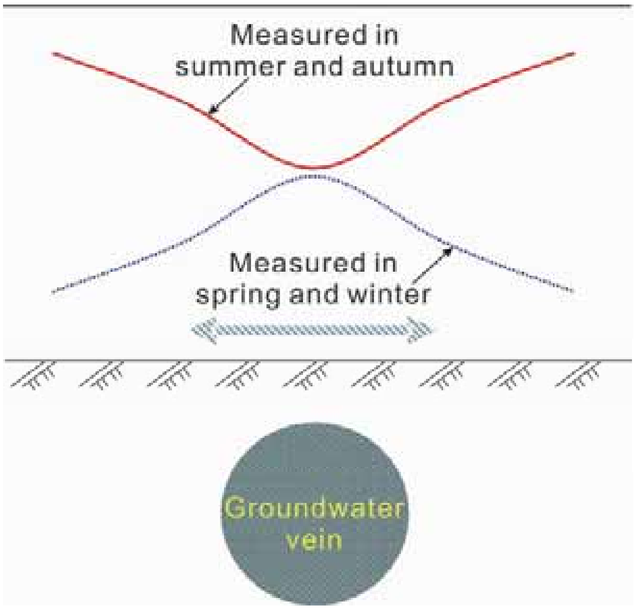

Fig. 20 Principle of the 1m-depth ground temperature measurement

1m-depth ground temperature measurement was conducted to detect the groundwater veins in the lower part of the Shuping landslide. The measured area was shown as a square in Fig. 13. Fig. 21 is the measured results. From the ground temperature distribution, two independent groundwater vein groups were estimated existing in Block-1 and Block-2. The exit of the groundwater vein in Block-1 is lower that that in Block-2. It is estimated that the groundwater veins No.8 and No.9 correspond to the muddy water seeped from Block-1.

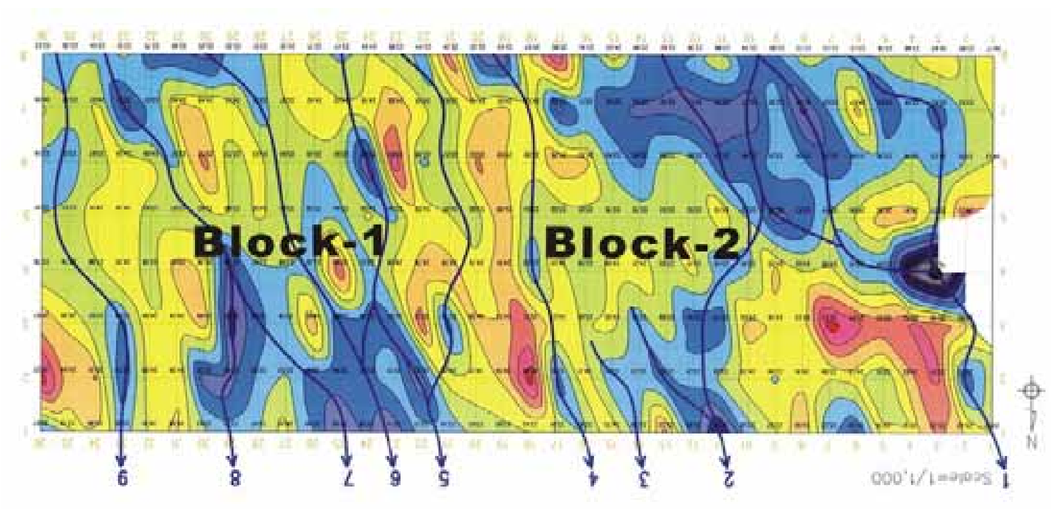

Fig. 21 Groundwater veins distribution estimated from 1m ground temperature measurement

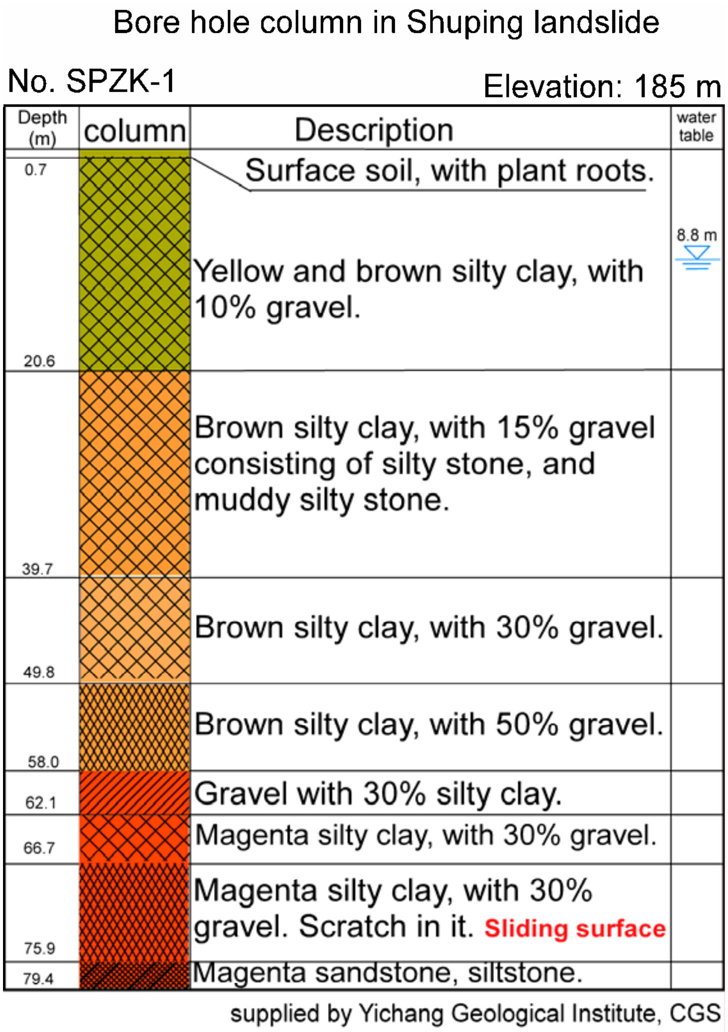

Fig. 22 Column diagram of borehole SPZK-1 in Block-1 of Shuping landslide

To confirm the above estimation, and to explore the sliding surface, a borehole drilling was conducted at SPZK-1, as shown in Fig. 21. Fig. 22 is the column diagram of this borehole. The groundwater table was found at 8.8 m deep, and the sliding zone formed at the depth between 66.7 and 75.9 m. The sliding zone consisted of silty clay with 30% gravel. Scratches caused by sliding are rich in the zone.

3.6 Summaries and conclusive remarks

Through the GPS monitoring, crack displacement measurements, extensometer monitoring along the longitudinal section of Block-1, the deformation style of the Block-1 of Shuping landslide can be sketched as Fig. 23. Sooner after the impoundment of the water reservoir, the toe part displaced downward faster than the upper part. In the current stage, two years after the first impoundment, the slope deformation style changed. The displacement of the lower part almost terminated while the upper part displaced downward gradually, and compressed the toe part.

For the Shuping landslide, reactivating from an old landslide and with rich groundwater in it, the influencing factors on the slope deformation is complicated. From about one year monitoring with the extensometers, it is very clear that the slope displaced soon after the impoundment of the water reservoir. It is very important to keep the monitoring continued especially during the next stage of impoundment which will be conducted in June 2006 (Water level will be raised from 139 m to 156 m.).

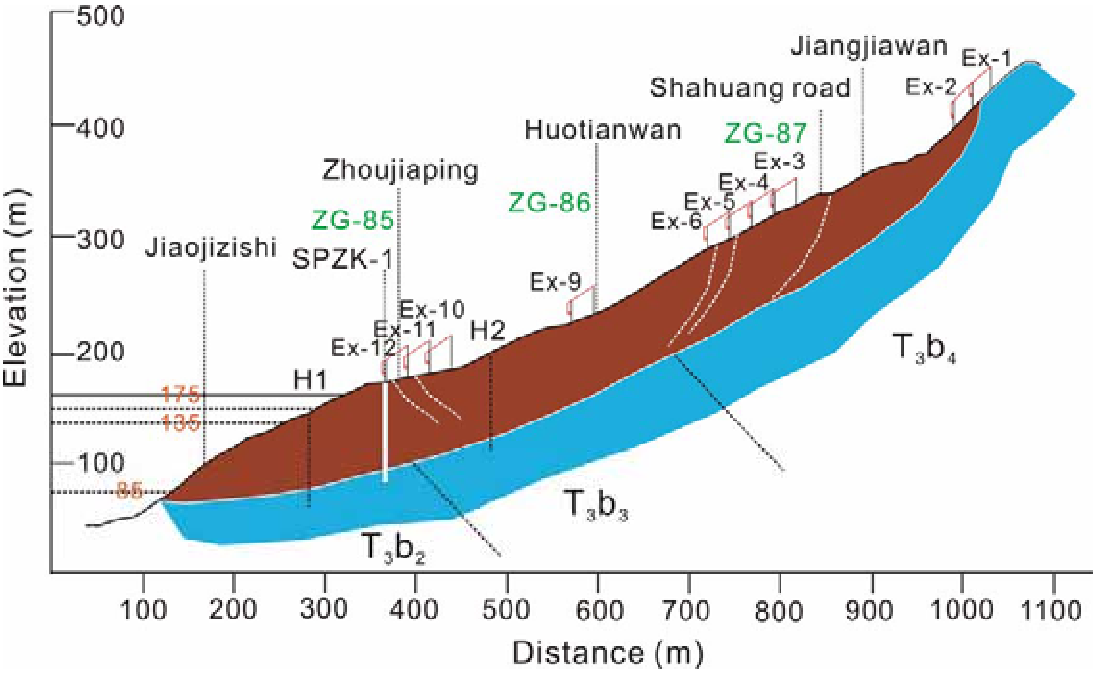

Fig. 23 Longitudinal section of the Shuping landslide

4. Conclusions

Through field investigation and monitoring on the landslides in the Three Gorge Water-Reservoir, the following conclusions were drawn.

(1) The investigation on the Qianjiangping landslide shows that the Qianjiangping landslide occurred along a pre-existing shear surface along the strata layer of sandstone and siltstone with mudstone. Quarrying of mudstone for brick manufacture from the toe of the slope, and intense rainfall before the landslide put the slope in a critical state. It is clear that the high water level in Qinggan-he River through impoundment of the reservoir was the trigger for the landslide occurrence.

(2) The monitored results on the Shuping landslide shows that sooner after the impoundment of the water reservoir, the toe part displaced downward faster than the upper part. In the current stage, two years after the first impoundment, the slope deformation stH16yle changed. The displacement of the lower part almost terminated while the upper part displaced downward gradually, and compressed the toe part. It is very clear that the slope displaced soon after the impoundment of the water reservoir.

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