Landslides and slope deformation caused by water impoundment in the Three Gorges Reservoir, China

FAWU WANG[1], XUANMING PENG[2], YEMING ZHANG[3], ZHITAO HUO[4], ATSUO TAKEUCHI[5] , KIMINORI ARAIBA[6] & GONGHUI WANG[7]

[1] *Disaster Prevention Research Institute, Kyoto Univ., Japan. (e-mail: wangfw@landslide.dpri.kyoto-u.ac.jp)*
[2] *Yichang Institute of Geology & Mineral Resources, CGS, China. (e-mail: ycpxuanming@cgs.gov.cn)*
[3] *Yichang Institute of Geology & Mineral Resources, CGS, China. (e-mail: yczyeming@cgs.gov.cn)*
[4] *Yichang Institute of Geology & Mineral Resources, CGS, China. (e-mail: ychzhitao@cgs.gov.cn)*
[5] *Natural Groundwater Research Institute, Japan. (e-mail: takeu-a@mx.cable-net.ne.jp)*
[6] *National Research Institute of Fire & Disaster, Japan. (e-mail: araiba@mail.fri.go.jp)*
[7] *Disaster Prevention Research Institute, Kyoto University, Japan.*
(e-mail: wanggh@landslide.dpri.kyoto-u.ac.jp)

Abstract: The Three Gorges Dam on the Yangtze River in China is the largest hydro-electricity project in the world. The first impoundment started from 95 m 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 paper, two landslides, the Qianjiangping landslide which occurred on July 14, 2003, and the Shuping landslide which is deforming actively, are discussed. Concerning the Qianjiangping landslide, field investigation revealed that failure occurred when the reservoir reached 135 m, but the stability of the slope was already reduced by pre-existing bedding-plane shears, quarrying of mudstone from the landslide toe, and previous heavy rain. The Shuping landslide is located on a slope in the main stream of the Yangtze River. After the first impoundment, obvious deformation appeared and became intense from February 2004. Through monitoring, bore-hole investigation and physical exploration, the possible deformation mechanism is analyzed.

Résumé: Le barrage des Three Gorges, situé le long du cours du fleuve Yangtze en Chine, est le plus grand projet hydro-éléctrique du monde. Le premier remplissage a eu lieu a partir de 95 m et a atteint 135 m le 15 Juin 2003. Peu de temps après que l'eau avait atteint le niveau maximum, de nombreuses pentes ont commencée à se déformer et des mouvements de versants se sont vérifié. Ce travaille concerne le mouvement de Qianjiangping qui s'est vérifié le 14 Juillet 2003 et celui de Shuping qui est encore en voie de déformation. Dans le premier cas, les investigations ont démontrée que la rupture avait eu lieu quand l'eau avait rejoint le niveau 135 m, mais la stabilité des pentes avait déjà été réduite par la présence de joints de stratification-cisaillement, par les effets de l'activité d'exploitation de roches argileuses au pied de la masse en mouvement, ainsi qu'a cause des fortes pluies précédentes. Le mouvements de Shuping affecte une pente située le long du cours principale du fleuve Yangtze. Après le premier remplissage, les déformations qu'on pouvait s'attaindre sont devenues très intense à partir du mois de Février 2004. A l'aide des renseignements fournis par le monitorage, les sondages et les essais geophysiques et hydrogeologiques, on analyse le possible mécanisme des déformations.

Keywords: landslides, monitoring, reservoirs, site investigation, extensometers, risk assessment

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 town 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 paper, the investigation results on the Qianjiangping landslide and the monitoring results on the Shuping landslide are reported.

FEATURES OF THE QIANJIANGPING LANDSLIDE

In the early morning, at 00:20 July 14, 2003, the Qianjiangping landslide occurred at Shazhenxi Town (Figure 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).

Figure 2 shows photographs of the landslide taken from the opposite bank of the river and upstream side of the landslide. The landslide had was elongate shaped in plan, with a length of 1200 m, and a width of 1000 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. It was thinner in the upper zone and thicker at the lower zone. 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 (Figure 2). Factory buildings on the sliding mass still remained standing after sliding for about 250 m. However, because serious cracks developed in the buildings, they were rendered unsafe for occupation and were subsequently demolished. The building materials were recycled.

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

Figure 2. View of the Qianjiangping landslide from the opposite bank (Left: Taken by Y.M. Zhang, July 15, 2003) and upstream side of Qinggan-he River (Right: Taken by F.W. Wang, March 15, 2004)

Figure 3. View of un-rotated trees on the sliding mass in the middle of the Qianjiangping landslide (left) and the exposed planar sliding surface (right), which is also a sandstone-bedding plane (there is a damaged rice paddy in front of the person)

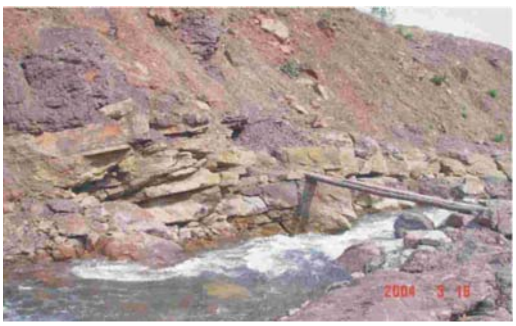

Figure 4. View of the reversed dip direction of the sandstone beside Qinggan-he River (Taken by F.W. Wang, March 16, 2004)

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

Standing trees on the sliding mass in the middle of the landslide (Figure 3) indicate that the angle of the sliding surface remained constant and no rotation occurred. The exposed sliding surface at the upper part was planar, and sub-parallel to the sandstone bedrock strata (Figure 3). 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 (Figure 4). The deposits at the distal landslide margin contain white gravel with clasts up to approximately 100mm in diameter. The dip angle of the sandstone bedding at the distal margin exceeds 30° (Figure 5).

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 consistent. The slope was considered safe because there was no evidence for landslides during the field investigations for the Three Gorges Dam construction project. The slope appeared to be relatively uniform with a dip-slope surface. However, striations (slickensides) were observed after the rapid, long-runout landslide occurred and this enabled the failure surface and mechanisms to be directly investigated.

Striations on the failure surface

Figure 6 shows a sequence of two photographs of striations on the sliding surface at the upper part of the landslide. Figure 6a shows the pre landslide bedding plane whereas in Figure 6b a slice of sandstone has been removed from the bedding plane to reveal more striations. This shows that some striations were present beneath the landslide failure surface before the landslide occurred. The strike direction of the striations was S15°W (red arrow). The sliding direction (S45°E) of the July 2003 event (blue arrow) is shown by the water flow in Figure 6b. The angle between the sliding direction and the striations is about 60°. Comparison of the two photographs shows that the striations were not formed by the event of July 2003. They must have formed earlier, probably in a much older geological processes, because calcite mineralisation 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). The striations may be interpreted as slickensides formed by bedding-plane translational shear during folding of the strata.

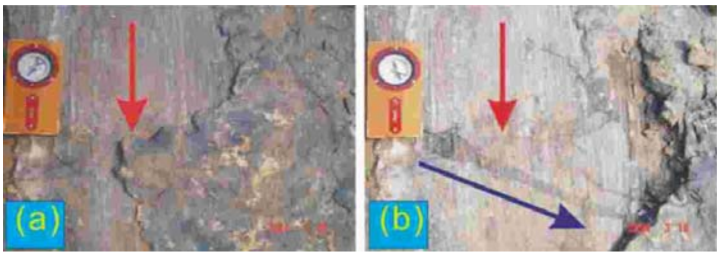

Figure 6. Photographs (a) and (b) showing striations on sliding surface from the July 2003 event (the blue arrow shows the sliding direction, red arrows show the strike direction of the pre-existing striations). The striations are inferred to be slickensides formed by bedding-plane translational shear during folding of the rocks in the Cretaceous period.

Possible triggering factors and sliding mechanism

High water levels at the toe of slopes were caused by the impounding of the Three Gorges Reservoir. This was considered to be the trigger for the landsldies. Impoundment started from June 1st, 2003, and the reservoir water level reached 135 m on June 15th, 2003. The first fissures 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 reports, sandstone and mudstone were exposed in the Qinggan-he River bank before the reservoir was impounded. The dip of the sliding surface, which is also a bedding plane, was measured as 32°. Zhang *et al.* (2004a) observed two sets of large transversal fissures crossing the upper and middle parts of the slope. Although some rice paddies were located on the upper part of the landslide (Figure 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 were clear. Only small parts of the upper slope were influenced by landsliding. The right lateral boundary was exposed, and so had no friction to resist sliding. As shown in Figure. 6, the sliding surface was a pre-existing bedding-plane which acted as the shear surface.

Precipitation is monitored in Yichang City (Figure 1), about 70 km from the landslide site. Intense rainfall from June 21st to 26th, and rainfall from July 4th to July 9th (Figure 7) may have saturated the sliding mass, and increased its unit weight. However, considering the high permeability of the slickensided sandstone, and the transverse fissures crossing the sliding mass, it is not likely that high pore pressure would have resulted.

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 neighbouring rock mass. For such a huge landslide, the mechanical model can be simplified as a two-dimensional longitudinal model as shown in Figure 8(a). The model of the landslide after failure is sketched in Figure 8(b).

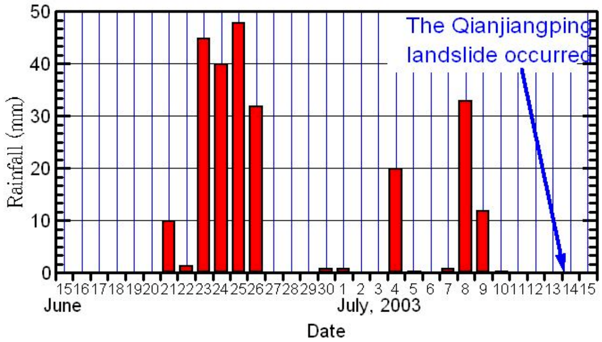

Figure 7. Precipitation data monitored in Yichang City, 70 km from the landslide.

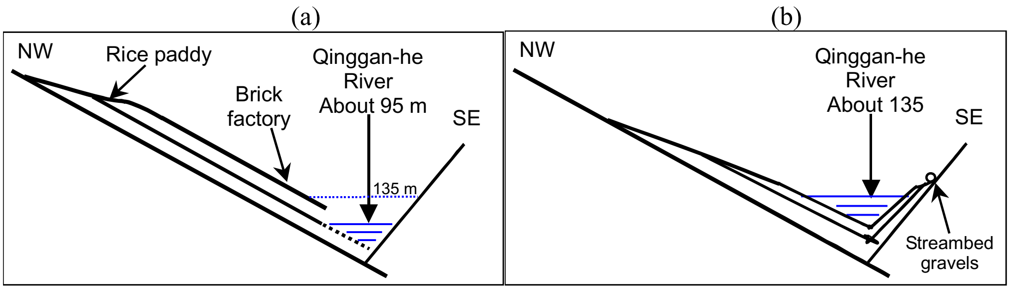

Figure 8. Structural model of the Qianjiangping slope before failure (a) and a sketch of the landslide after failure (b).

With the slope in a critical state (Figure 8a), 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. The extraction of a relatively large mass of rock from the toe of a landslide may have potentially contributed to slope instability (but the possibility for a potential landslide to occur was not appreciated by experts until the fissures appeared in 2002).

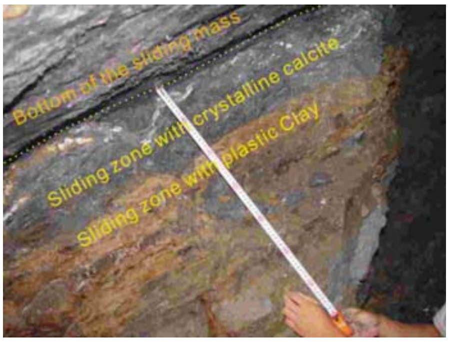

Figure 9. Photograph of the sliding zone taken at a horizontal tunnel. Under the bottom of the sliding mass, the sliding zone can be observed with two layers. The upper layer in grey colour includes crystallized calcite, and the lower layer in yellow colour is plastic clay with high water content

When the existence of the widely distributed striations on the sliding surface are considered, it is possible to assume that the shear strength between the sliding mass and the sliding surface was at residual strength. If this assumption was 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 stated above the striations probably were generated in the Cretaceous period, and the beds on either side of the slickensided 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. In 2005, a horizontal tunnel was excavated crossing the sliding zone of the landslide at the neighbour landslide with the same structure. Figure 9 shows the sliding zone containing two layers. The upper layer contains crystallized calcite and the lower layer is very soft and has high water content. Generally, failure of crystallized calcite is characterized by brittle fracture. After a certain distance of shearing, the cement bonding would have been destroyed. The quick loss of adhesion of the crystallized calcite could be the main reason for the rapid landslide acceleration after the initial failure of the slope.

Discussions

A detailed field investigation was undertaken on 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:

- 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).
- Quarrying of mudstone for brick manufacture from the toe of the slope, and intense rainfall before the landslide influence the stability of the slope generating 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 a good practice, there was no information to indicate that it was potentially detrimental to the stability of the slope, until the landslide was recognized. Prior to the fissures appearing, there appears to have been no reason to expect that the slope was unstable, and hence little reason to exercise caution.
- The high water level in Qinggan-he River through impoundment of the reservoir was the trigger for the landslide occurrence.
- Brittle fracture of crystallized 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.
- There are several other slopes in the area in similar tectonic and geological settings. Detailed evaluations for those slopes are recommended to determine their potential impact on the Three Gorges reservoir when it is raised to its final operating level.

THE SHUPING LANDSLIDE IN THE MAIN CHANNEL OF THE YANGTZE RIVER

The Shuping landslide is located at the main channel of the Yangtze River (Figure 1) in Shazhenxi Town, about 3.5 km to the NW of the Qianjiangping landslide. Deformation became apparent after the first impoundment of the reservoir. Figure 10 is an oblique photograph of the Shuping landslide, and Figure 11 is the plan of the landslide. The landslide ranged in 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 borehole data, and the total volume was estimated as 2.0 x 10^7 m^3. The toe of the landslide extended under the water level of the Yangtze River. The slope is gentle in the upper part, steep in the lower part and has a slope angle of 22^o and 35^o respectively.

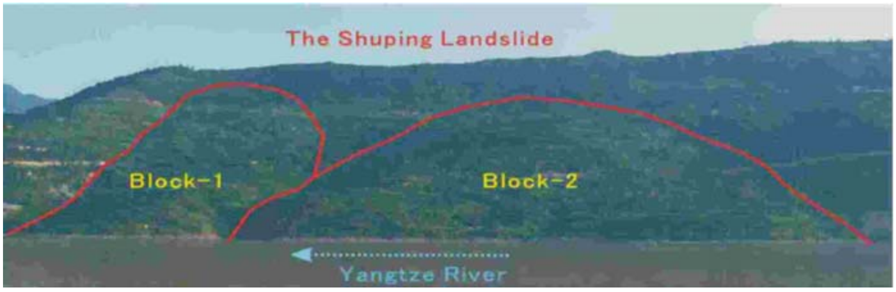

Figure 10. Shuping landslide consisting of two blocks in the main channel of the Three Gorges Water Reservoir

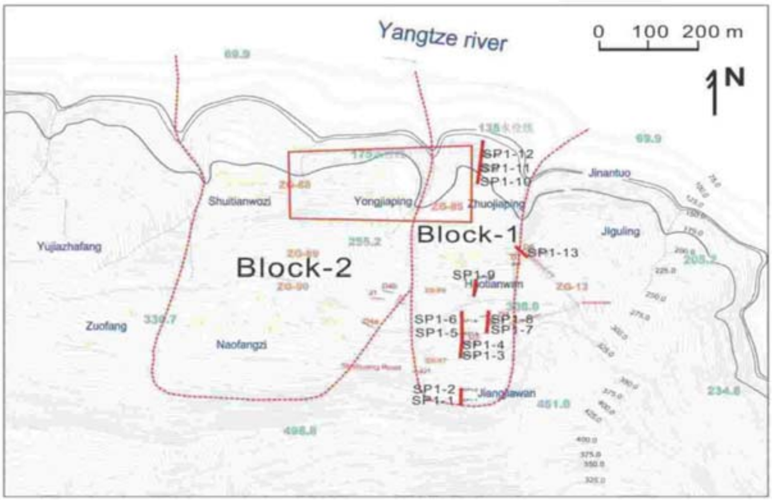

Figure 11. Plan of the Shuping landslide showing the locations of monitoring sites (extensometers and ground temperature measurements).

Morphology of the Shuping landslide

The Shuping landslide is an ancient landslide which composed of two blocks (Figure 10). After the first impoundment of the Three Gorges reservoir ended on June 15, 2003, ground deformation was observed on the slope, and these become more common from February 8, 2004 onwards. Also, the two blocks shows different deformation rates on the slope surfaces. These ground movements posed a risk to 580 inhabitants and 163 houses situated directly in the vicinity of the landslide. As a precaution all of the inhabitants were evacuated, by central government, and placed in temporary tented accommodation to reduce the possibility of a disaster. In May 2004, most of the inhabitants relocated their homes beyond the area of the landslide.

Figure 12 shows a fissure at the right boundary of 'Block 1' which is situated adjacent to a local road. The right-hand side is the sliding mass consisting of a red, muddy-debris which forms part of an old landslide. The left-hand side is exposed bed rock of Triassic age. This consists of sandy mudstone and muddy siltstone of the Badong Formation.

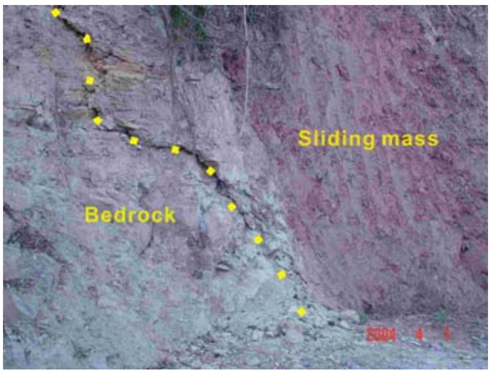

Figure 12. Fissure at the right boundary of Block 1, observed at a roadside exposure.

Figure 13 shows discoloured water which is derived from streams flowing from 'Block 1'. This is a consistent feature, which is also present on dry, warm days when rainfall is less. This sediment plume appears to show no relationship to the water in the Yangtze River. But instead appears to be related to groundwater flows from the landslide on the adjacent slope.

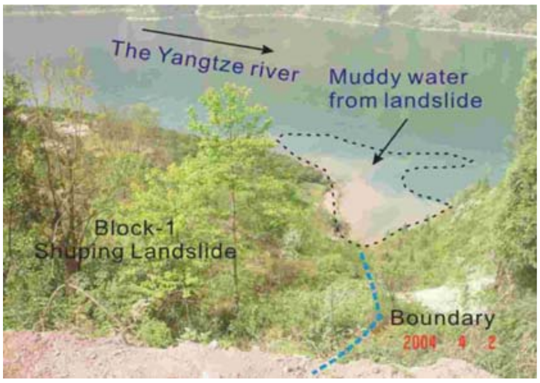

Figure 13. Groundwaters containing sediments in suspicion flowing from the toe of the Shuping landslide into the Yangtze river.

Slope deformation and characteristics of the Shuping landslide

The Shuping landslide area was located near to a densely populated area and deformation occurred just after the occurrence of the Qianjiangping landslide. Therefore the ground movements were observed by the inhabitants, who were fully aware of the impact of landsldies, and reported to the local government promptly. Gan *et al.* 2004 reported the initial ground deformation the as follows.

From the end of October to the beginning of November 2003 fissures became observed on the slope surface, and in particular in the upper part of the slope. These fissures became enlarged from January to February 2004.

On January 5 and February 8, 2004 groundwater discharges at the toe of the landslide became discoloured. From March 2004 this discoloured water was present on a daily basis. Figure 13 shows the discoloured groundwater water in April 2004. This observation was considered to indicate active slope deformation processes, because the newly sheared and displaced soil on the sliding surface was subsequently eroded by groundwater.

On January 25 and February 8 2004 'sharp' noises were heard and reported, on two consecutive nights, by the local inhabitants. These noise were considered by the authors to have been generated by shearing along the landslide failure surface.

Because of the potentially hazardous circumstances the local government, in February 12, 2004, decided to monitor the fissures which had developed on the slope. The inhabitants were asked to measure the change in the width of the fissures near their houses. Two small piles were established across the fissures and the distance between the two piles was measured three times one day. Figure 14 shows some of the results indicating the contraction and extension of the ground fissures. However, because many of the inhabitants gradually evacuated the area the frequency of the measurements gradually reduced.

The data shows that the fissures underwent extension within the main body of the landslide and along its periphery, whereas contraction of the fissures occurred within other parts in the displaced block. The monitoring period lasted for 50 days from February 24, 2004. The maximum displacements were approximately 140 mm, including both extension and contraction, this being indicative of active ground deformation.

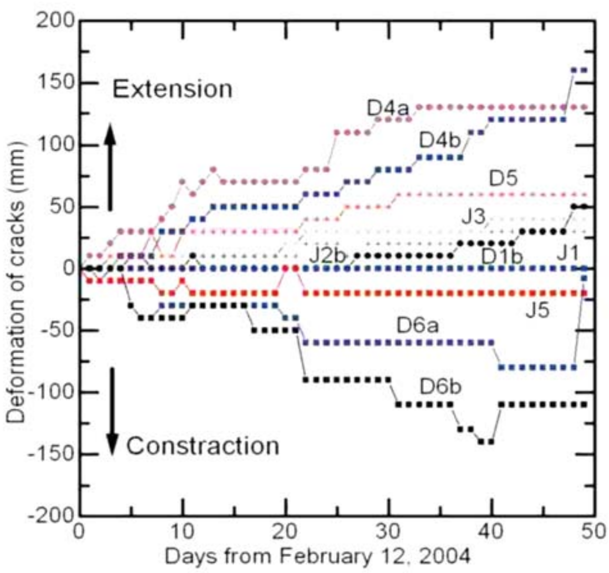

Figure 14. Results showing the measurement of fissures on the slope in Block 1.

GPS monitoring results

Two GPS monitoring lines were established, by the China Geological Survey, at the central longitudinal section of the two displaced blocks Each monitoring line had three GPS monitoring points, i.e., ZG85, ZG86 and ZG87 from toe to upper part in Block 1, and ZG88, ZG89 and ZG90 from toe to upper part in Block 2 (Figure 11). The monitoring started in July 2003, just one month after the first impoundment. The measurements were taken monthly by the Rockfall and Landslide Research Institute of Three Gorges University, based in China.

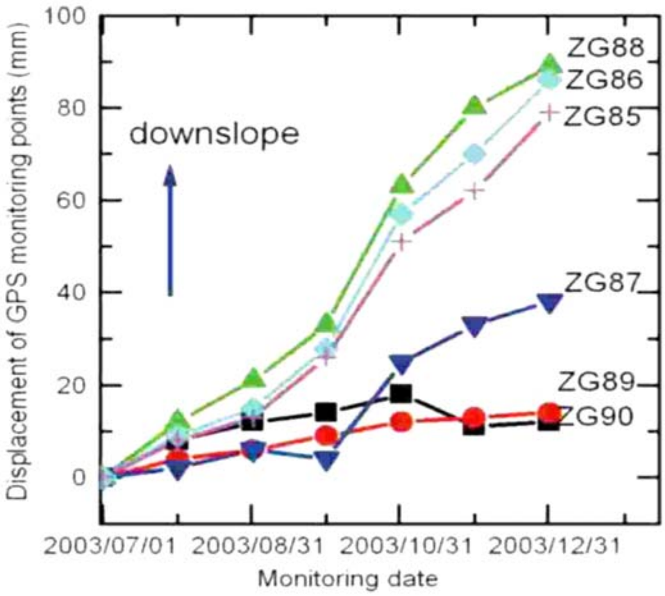

Figure 15. GPS monitored results along the central section lines of Block 1 and Block 2 (obtained by the Rockfall and Landslide Research Institute of Three Gorges University).

Figure 15 shows the results of the GPS monitoring for the first six months period after the impoundment. The displacement rate for Block 1 increased rapidly after October 2003. Other observations include (a) the displacements on the lower part of the slope are larger than that the upper slope, this may be caused by water buoyancy induced by the impoundment of the reservoir, and (b) the displacement of Block 1 is more active than Block 2, showing that the two blocks behave independently from each other.

Installation of extensometer and the monitoring results

Until April 2004, the displacement monitoring of the Shuping landslides included fissure measurements conducted three times each day, and GPS monitoring conducted once monthly. However, because of the evacuation of the inhabitants, the fissure monitoring became gradually inconsistent. Located at the main channel of the Yangtze River, it was considered insufficient for the Shuping landslide to be monitored with only GPS when considering the safety of shipping along the Yangtze River. Although GPS monitoring has high precision, the time interval between measurements was too large. Therefore, two extensometers (donated by Kowa Co. Ltd., a Japanese company), were installed in the Block 1 of the Shuping landslide in April 2004. The extensometer was the Sakata Denki type and automatic, continuous monitoring was possible, for one week or one month. A warning system was also connected to the extensometer. When the displacement rate exceeded 2mm/hour, a warning was announced.

The automatic monitoring system with the extensometer was confirmed to be operating satisfactory (Zhang *et al.* 2004b). However, two extensometers are considered to be not sufficient for such a large landslide. In August 2004, a further 11 extensometers were installed along the central line of the longitudinal section of Block 1, with emphases on the more severely deformed parts of the slope. However because of the limit of funds, the extensometers did not form a continual longitudinal section line.

Figure 16 shows the extensometer installed in Shuping landslide. The positions of all of the thirteen extensometers were shown in Figure 11 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 SP1-12 were 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 Figure 12, because the fissure extension was apparent.

Figure 16. An extensometer installed in the Shuping landslide. The deformation was recorded on the rolled paper and also saved electronically to the instruments memory (visible in the right side)

Figure 17 shows the monitoring results for the thirteen extensometers, from August 2004 to June 2005. This is accompanied with the water levels in the Three Gorges dam (bottom) and the rainfall records for the area (top).

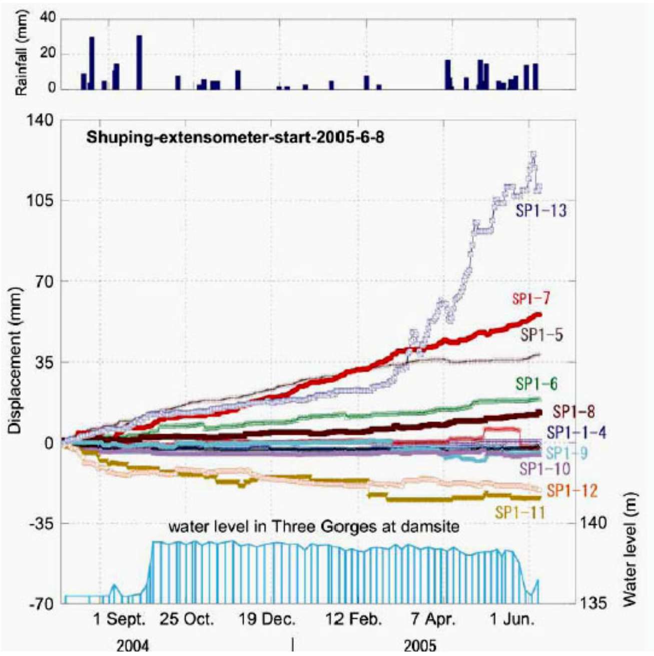

Figure 17. Extensometer monitored results (middle), precipitation data in Yichang City (top) and water level in the Three Gorges Dam site (bottom).

The monitoring results show the following: (a) The SP1-1 and SP1-2 at the main scarp did not record any obvious displacement. (b) The deformations at SP1-5, SP1-6, SP1-7 and SP1-8 were the most active showing extension. Because of localised failure, the SP1-13 showed the most extension. (c) The toe of the landslide showed compression behaviour.

The largest displacement, measured by GPS monitoring, occurred at the lower part of the slope, within six months after the first impoundment. It was estimated that the toe moved greatest at this initial period but then became relatively stable. The upper part moved slowly at the first stage, and then followed the types of movements which occurred on the lower, compressed part so the slope.

In mid-September, the water level at the Three Gorges reservoir was raised about 3 m. Corresponding to this water level rise the displacement velocity of monitoring stations SP1-5, SP1-6 and SP1-7 increased, reflecting the influence of the impoundment on slope deformation. Furthermore, during the rainy season, after April 2005, displacement acceleration (at SP1-6, 7, 8) was also monitored and this showed that the displacement of the landslide was also influenced by fluctuating groundwater conditions.

Ground temperature measurement for groundwater channels

Takeuchi (1972) developed a method for the investigation of groundwater channels and ground temperature measurement. This method is widely applied to groundwater investigations in landslide areas, especially in Japan (Takeuchi 1994).

Figure 18 shows the principle for ground temperature measurements, above groundwater channels, 1 m below ground level. Compared with the ground which does not contain any water, saturated ground has a temperature similar to that of the groundwater. Generally, groundwater temperature does not change throughout a year. Temperature in dry ground is controlled by the atmospheric temperature. This will generally be higher than groundwater in summer and autumn and lower in spring and winter. By measuring the temperature distribution in the landslide area the distribution of groundwater channels may be estimated.

Ground temperature measurement were conducted, 1 m below ground level, to detect the groundwater channels in the lower part of the Shuping landslide. The area where the measurements were taken is shown as a square in Figure 11.

Figure 19 shows the results and the ground temperature distribution. Two independent groundwater channels were inferred in Block 1 and Block 2. The discharge of the groundwater channel in Block 1 is at a lower elevation than in Block 2. It is estimated that the groundwater channels No. 5, 6, 7, 8 and 9 correspond to the discoloured water seeps from Block 1.

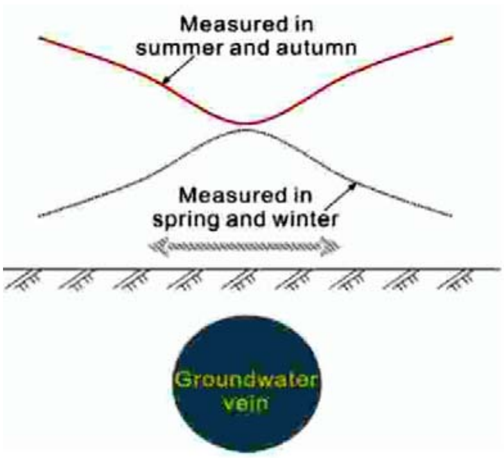

Figure 18. Principle of the ground temperature measurement, undertaken 1 m below ground level.

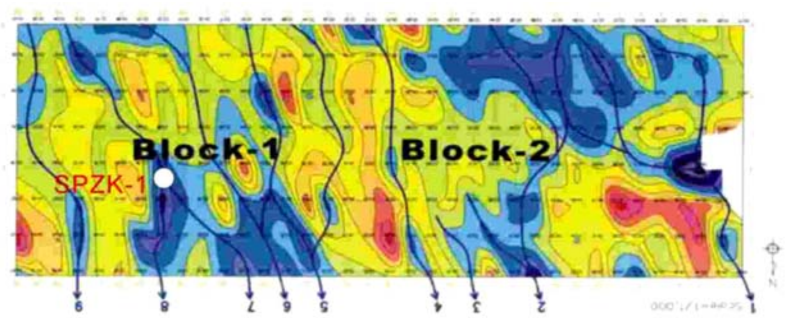

Figure 19. Groundwater channels distribution, estimated from the measurements of ground temperature, taken 1 m below ground level.

To confirm the above and to investigate the sliding surface, a borehole was drilled at SPZK-1, as shown in Figure 19. The borehole log is shown in Figure. 20. The groundwater table was observed at 8.8 m below ground level, and the sliding zone was observed between 66.7 and 75.9 m below ground level. The sliding zone consisted of silty clay, with 30% gravel. Striations caused by sliding were abundant in this zone.

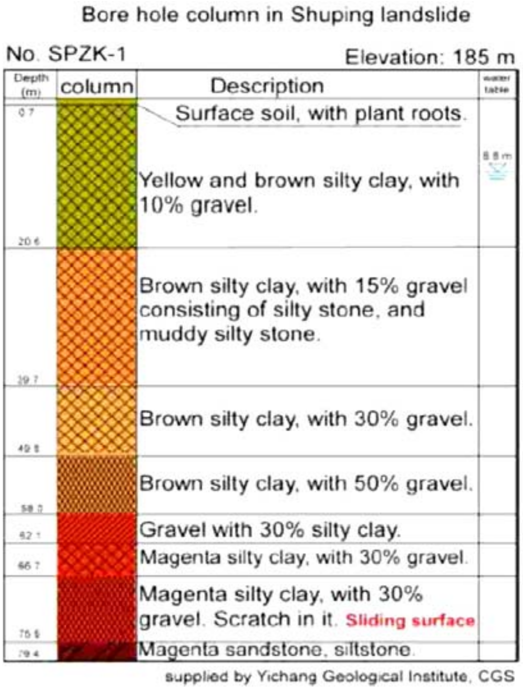

Figure 20. Summary of borehole log drilled at position SPZK-1 in Block 1 of Shuping landslide

Borehole logging with temperature measurement for flowing layers

Temperature measurement were taken in boreholes to investigate the flowing layers in borehole SPZK-1. This method was developed by Takeuchi (1994). The measurement is started by pumping hot water into the borehole. After mixing the hot water in the borehole and making the water temperature even, the water temperature in the borehole was measured with elapsed time. Because water flowing will make the water temperature return to its natural temperature, the temperature returning ratio, which is defined as the ratio of returned temperature to the difference between hot water and natural water, is used to locate flowing layers.

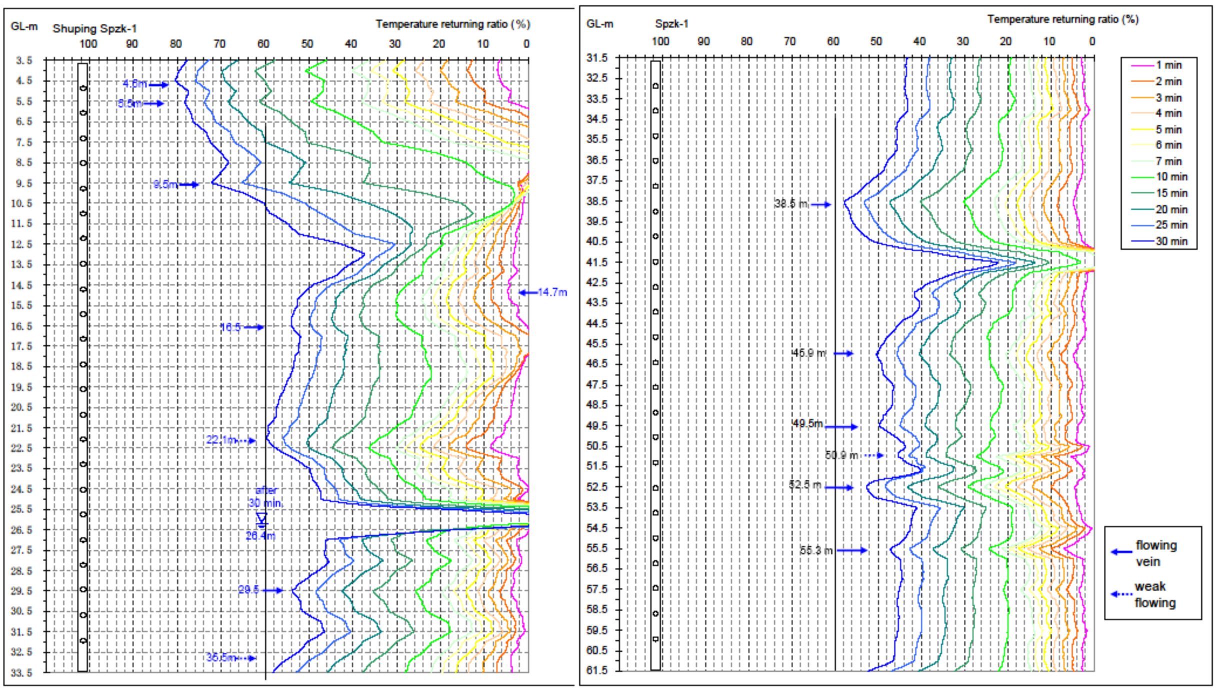

Figure 21. Borehole logging result showing groundwater flowing layers in the Shuping landslide

Figure 21 shows the measured results. Near the slope surface, at a depth of 4.5 m and 5.5 m, the flowing layers may be caused by rainfall infiltration. Below that, at a depth of 9.5 m, 16.5 m, 22.1 m, flowing layer of groundwater may exist. The 9.5 m deep flowing layer was confirmed by an excavation when the groundwater level was initially observed. The flowing layer at 16.5 m deep was also influenced by the flowing at 14.7 m deep. Below the stable groundwater level, there are several weakly flowing observed. These are at the depth of 29.5 m, 38.5 m, 45.9m, 50.9

m, 52.5 m, and 55.3 m, respectively. To determine which flowing layer has affected the landslide, pipe strain gauges are planned to be installed in the borehole. The information on groundwater flow horizons will be important for analyzing the factors which have influenced the Shuping landslide. These include including reservoir impoundment and groundwater flowing caused by rainfall.

Summary of field investigations and deformation mechanisms

GPS monitoring, fissure displacement measurements and extensometer monitoring have enabled a conceptual model through Block 1 of the Shuping landslide, this is presented in Figure 22. Soon after the impoundment of the reservoir, the toe of the slope became displaced in a downslope direction faster than the upper part of the slope. 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.

The Shuping landslide represents the reactivation of an existing landslide and the factors which influence instability and sliding are complex. About one after year monitoring with the extensometers, it became clear that the slope displaced took place soon after impoundment. It is important to continue with the monitoring specially since the next stage of impoundment is estimated to commence in June 2006 (the water level will be raised from 139 m to 156 m). Any remedial works may require more detailed investigations on the effect of groundwater, slope deformation and drainage of the slope.

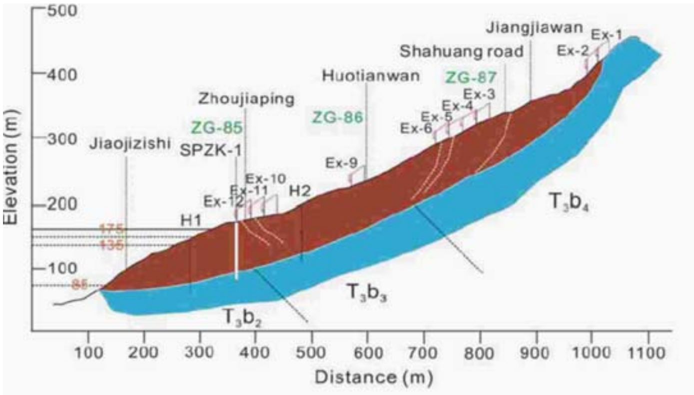

Figure 22. Longitudinal section of the Shuping landslide showing the deformation mechanism.

CONCLUSIONS

Through field investigations and monitoring of the two landslides in the Three Gorge Reservoir, the following conclusions were drawn.

- Investigations on the Qianjiangping landslide shows that this landslide occurred along a pre-existing shear surface, which formed a bedding plane within alternating layers of sandstone, siltstone and 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.
- The monitored results on the Shuping landslide shows that sooner after the impoundment of the reservoir, the toe part displaced downslope at a greater rate than the upper part of the slope. 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.
- For further understanding on the mechanism of landslide deformation caused by reservoir impoundment, continued monitoring and detailed investigation are necessary.

Acknowledgements: Deep thanks are given to Mr. Masahiro NAGUMO in Kowa Co. LTD., Japan for donation of the first two extensometers. The local government of Shazhenxi supplied measurement results of the fissure displacements and information about the slope deformation and economic losses. The research funds from Sabo Technical Center, Japan, and Hubei Environmental Geotechnical Engineering Open laboratory, in the Institute of Rock and Soil Mechanics, the Chinese Academy of Sciences, China are highly appreciated.

Corresponding author: Dr Fawu Wang, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan. Tel: +81 774 38 4836. Email: wangfw@landslide.dpri.kyoto-u.ac.jp.

REFERENCES

GAN, Y.B., SUN, R.X., ZHONG, Y.Q., LIAO, S.Y. 2004. Urgent investigation report on the Shuping landslide in Shazhenxi town, Zigui County, Hubei Province (in Chinese).

TAKEUCHI, A. 1972. Ground temperature measurement in landslide area. Journal of Japan Landslide Society, **8**(4): 29-37, (in Japanese).

TAKEUCHI, A. 1994. Flowing groundwater investigation by temperature measurement. Kokon Syoin Press (in Japanese).

WANG, F.W., ZHANG, Y.M., HUO, Z.T., MATSUMOTO, T., HUANG, B.L. 2004. The July 14, 2003 Qianjiangping Landslide, Three Gorges Reservoir, China, Landslide, **1**(2): 157-162.

WANG, X.F., CHEN, X.H., ZHANG R.J. 2002. Protection of geological remains in the Yangtze Gorges area, China with the study of the Archean-Mesozoic multiple stratigraphic subdivision and sea-level change. Geological Publishing House, Beijing, 341 pp (in Chinese)

ZHANG, Y.M., LIU, G.R., CHANG, H., HUANG, B.L., PAN, W. 2004a. Tectonic analysis on the Qianjiangping landslide in Three Gorges Reservoir area and a revelation. Yangtze River, **35**(9): 24-26 (in Chinese).

ZHANG, Y.M., PENG, X.M., WANG, F.W., HUO, Z.T., HUANG B.L. 2004b. Current status and challenge of landslide monitoring in Three-gorge reservoir area, China. Proc. of Symp. On Application of real-time information in disaster management, JSCE, pp.165-170.