A study of monitoring, early warning and control engineering for the Danba landslide, China

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Abstract: The Danba landslide is located at the rear of Danba town in Sichuan. It is approximately 270 m long and 200 m wide. The average thickness of the slide body is about 30 m. Its capacity is about 2 million m^3. The slide originated from an ancient giant one, which was reactivated by excavation for the construction of the town at the foot of the slide. From October 2004, apparent deforming phenomena of the slide occurred. The monitoring results indicated that the deformation had speeded up since the middle of February 2005; the average displacement was about 2-3cm per day and the maximum was near to 5 cm. At the same time the sharp deformation made a long pulled fissure, about 1 m wide, which appeared at the rear of the slide, while the bilateral sheared fissures and the swelled ones in front were becoming apparent. Fissures on the surface almost connected with each other and had the trend to glide entirely. If the landslide moved forward as a whole, more than half of the Danba town would become a dangerous area. About 4600 civilians had been forced to retreat from the unsafe area.

The Chinese government swiftly organized professional teams to prewarn of slide movement by round-the-clock monitoring, on the one hand, and to take emergency counter-measures to control the deformation of the slide, on the other hand. By stacking 7000 m^3 sandbags and construcing 6 rows including 282 bundles of pre-stressed anchor rope, the speed of the slide was reduced and is now less than 1 mm per day. At present, integrated control engineering is executed to keep the slide stable in the long term. This paper will give a systematic and comprehensive introduction on monitoring prewarning and control engineering for the Danba landslide.

Résumé: Le glissement de terrain de Danba se trouve au derrière de district Danba de la Province Sichuan. La longueur longitudinale est de 290m. La largeur est de 200-250m. L ‘épaisseur moyenne du glissement de terrain est de 30m. La dénivellation est de presque 200m. La volume globale est de 200 x 104m³. La zone du glissement de terrain était la zone du glissement de terraine ancienne. A cause de la construction de la ville, il est éxcavaté du pied de la pente. C’est pourquoi le rejeu du glissement de terrain ancien. A partir d’août 2004, la pente surgit la déformation évidente. Le résultat de la surveillance montre que la déformation accélère au début de février 2005. La déformation moyenne est de 2-3cm/d. La déformation maximum est presque 5cm/d. Au derrière du glissement de terrain, il surgit une fissure de traction d’une forme d’arc à la largeur de 1m. La fissure de cisaillement de deux côtés et la fissure de bombement du devant sont évidentes. Toutes les fissures montrent être en circulaires. Il surgit une tendance du glissement de terrain. A cause de l’ensemble du glissement de terrain qui se déplace en avant faisant des milles maisons devant le glissement de terrain sont tombés ou surgissant des fissures. Car une grande moitié de la ville du District Danba était dangeureux. Il y a à peu près de 4 600 habitants étant obligés de quittés.

Pour assurer la sécurité des biens et de la vie de population et la stabilité sociale du District Danba, le gouvernement de la Chine a organisé rapidement l’équipe spéciale qui en observait et prévoyait 24 heures sur 24 heures d’une part, d’autre part, a pris la mesure urgente des travaux pour renforcer le traitement du glissement de terrain. On entassait des sacs de sable de 7000M³ devant le glissement de terrain et a mis 244 pendeurs en 6 rangs devant le glissement de terrain. Après la mise de traitement, la vitesse de la déformation du glisseùent de terrain diminue évidemment. Maintenant il est moins de 1mm/d. Le glissement de terrain est fondamentalement stable. Pour assurer la stabilité longue du glissement de terrain, maintenant, on est en train de faire des travaux de traitement synthétique du glissement de terrain. Le texte raconte détaillement la prévision et la surveillance et des trauvaux urgents de traitement du glissement de terrain.

Keywords: Geological hazards, landslides, monitoring, slope stability, Danba.

INTRODUCTION

Danba is situated in the western part of Sichuan province in China. The Danba town is located in the junction of four rivers where the river valley is narrow. The town faces the Dadu River and backs on the Baiga Mountain. The giant ancient slumping accumulative formation of the Baiga Mountain is at the back of the Danba town. Because of the restrictions of the land form and building site conditions, in recent years, the construction of Danba town had to be done next to the foot of the ancient Baiga landslide. For building houses, the foot of the landslide was excavated, which made the ancient slide revive gradually. The deformation began to speed up since early February 2005 and had a tendency to glide entirely. According to the preliminary estimation, if the landslide glided integrally, more than half of the Danba town would be destroyed, and the lives and assets of over 4600 civilians would be endangered. More than ten enterprises with the town government, the police station and the health centre for women and children etc would be destroyed thoroughly. The total number of the damaged houses is up to 1071. Meanwhile, if the landslide glided entirely, the Dadu River would be blocked and a natural rock-fill dam would form as well as the barrier lake, which would submerge towns that lie in the upstream areas. In addition, the dam-break would make ruinous damage to lives and assets of the people in the down stream areas.

In order to protect the Danba people's lives and assets and to ensure the social stability at the same time, the Chinese government organized professional teams to pre-warn the deformation of the landslide by round-the-clock monitoring as soon as possible. They also took emergency counter-measures to control the deformation of the slide. Danba people had won the war of defending Danba city and made Danba people's lives and assets out of danger. During the urgently wrecking engineering, we have accumulated much experience of the monitoring pre-warning and the preventing and curing measures of the geologic hazards. This paper will give a brief introduction to those.

THE BASIC SITUATION OF DANBA LANDSLIDE

The landslide lies in the mountain canyon area of Dadu River at the eastern edge of Qiangzang plateau. The slope angle of the river valley varies from 30° to 50 °. The bedrock in the bilateral areas of the landslide have been exposed and formed cliffs. The landslide is mainly composed of the unconsolidated debris of the ancient one. The exploration results indicated that the major constituents of the debris were block and reduced stones with sandy clay filled in stone gaps. The major components of the block and reduced stones are greyish-white and greyish-black biotite. The contents of the block and reduced stones are about 50% -60% and 20%-30 %, respectively. The average particle size of block stone is 0.2-0.5m and the larger ones can reach to 1-6m. The particle size of many reduced stones is 3-10cm. The silty sandy clay and the brecciated clay filled the gaps between the block and reduced stones. The structure of the debris is unconsolidated.

The plan view of the landslide is collar chair-like. Its altitude varies from 1881m to 2110m and the difference in elevation between the front and the rear is 223m. The rear of landslide lies in the front of the second terrace of Baiga Mountain. The toe of the landslide is next to the Jianshe Street. The border of the landslide is extremely obvious. After the foot of the landslide was excavated, a 6m-28m high dry rubble retaining wall was built in the front of the slide. The slope angle of the wall is 56 °- 65 °. The slope of the rear landslide is gentle, in the order of about 10°. The average slope angle of the middle is 31°. The landslide is a catastrophic accumulation formation slide. It is 200-250m wide, 290m long and about 30m thick. The area and the volume are approximately 0.08 km^2 and 2.2 million m^3, respectively. (Figure 1)

According to the developing process of the landslide deformation, the mechanism of formation and the character of the displacement, the landslide can be divided into three regions: the main body (Region I), the drag region in the left rear (Region II) and the one in the right rear (Region III), which are shown in Figure 1 and Figure2.

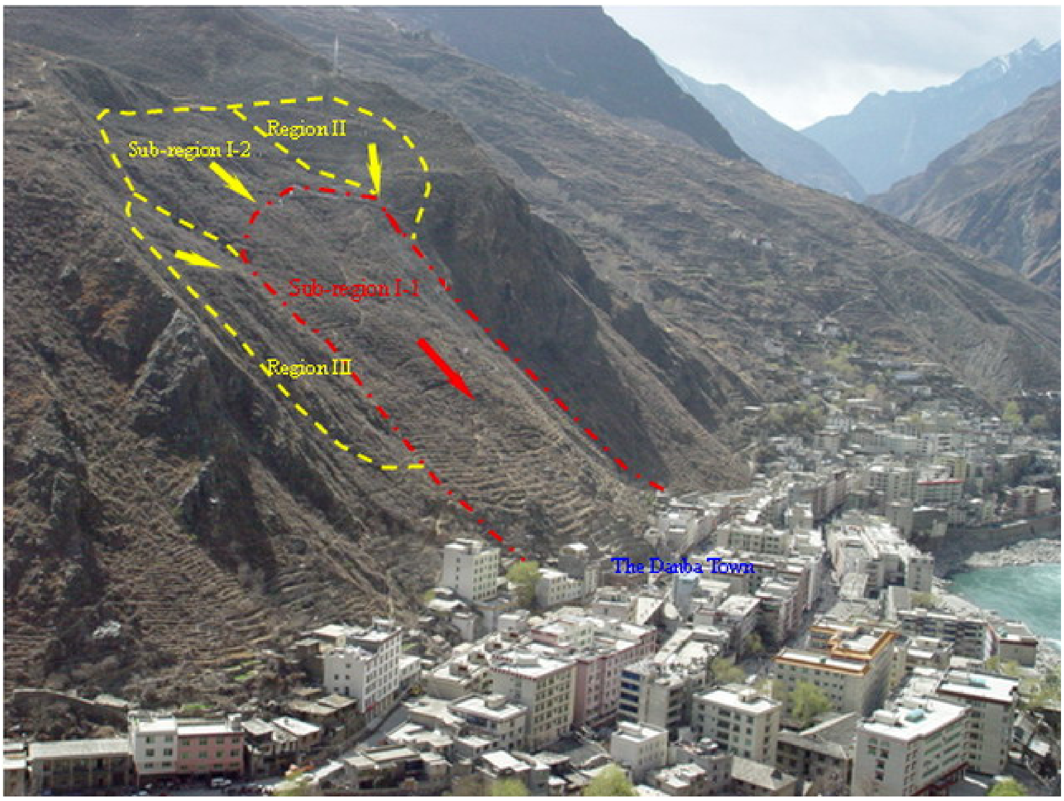

Figure 1. The Danba town and the Danba landslide

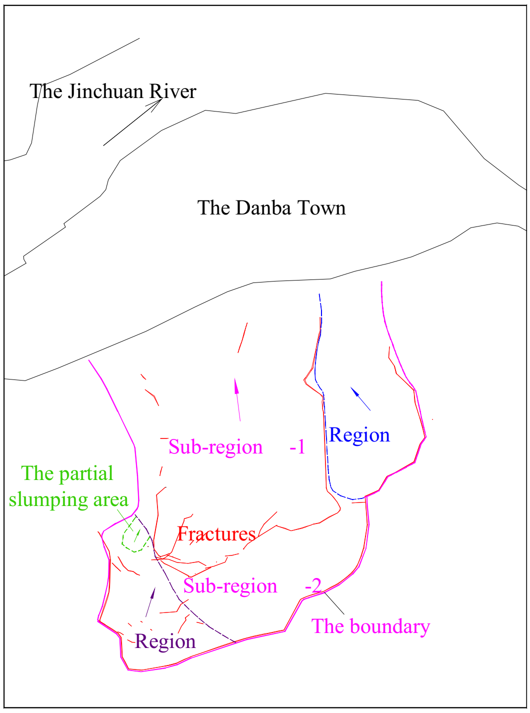

Figure 2. The Region-divided plane graph and fracture pattern

Region I

Region I can be subdivided into two sub-parts. They are called sub-region I-1 and sub-region I-2. In fact, sub-region I-1 glided as a whole firstly, which is the real main body of the landslide. The width of the front of sub-region I-1 is about 200m, the crown of it is approximately 150m, the length is 270m and the thickness is 30m. The shape of region I-1 is like an irregular rectangle in plan view. The volume of I-1 is about 1.5 million m^3 and the main sliding direction is 353^o (in the orientation of the river valley). The deforming phenomena of sub-region I-1 began to appear in 2003 and became more and more serious till December 2004. After 15 February 2005 obvious accelerating deformation characters had come out. Until about 20 February, the tensile fractures in the rear of sub-region I-1 and the lateral shear fractures had almost connected with each other and closed. The toe of the Danba landslide rupture surface cropped out just on the Jianshe Street. The whole of the landslide moved forward. More than 10 houses next to the foot of the landslide were destroyed by the landslide's pushing (Figure 3). Since early March, the sub-region I-1 moved forward entirely and the maximum width of the rear tensile fractures had come to 0.6-0.8m. The downward displacement of sub-region I-1 is also 0.6-0.8m. In the posterior part of sub-region I-1 a large tensile fracture began to form in the rear of it, so the deformation continued expanding to the rear slope and made the tensile fractures in the trailing edge of sub-region I-2 develop and break through gradually.

Because both sides of the slope in the rear of sub-region I-1 are relative steep, since early March the left rear (region II) and the right rear (region III) began to move integrally by the draw of region I-1, while many fractures came out and connected. By the influence of landform, the glide orientations of the region II and III were drawn towards region I (Figure 1).

Figure 3. The destroyed houses in the leading edge of the landslide

Region II

According to the geological survey and the exploration results, the shape of region II is an irregular hemicycle in plan. Its area is about 6000 m^2, thickness is approximately 15-20m and the volume is about 150,000 m^3. The posterior edge of region II had a large number of tensile fractures and faulted terraces. In addition, influenced by the steep landform (the slope angle is 50^o-80^o), small scale slumps often happened in the left front of region II. For example, the total volume of slumps happened on 9 and 14 March totalled 100m^3. At 2:00 pm 14 March, about 600m^3 soil and stones fell and rolled down rapidly (Figure 4). A boulder greater than 1m^3 fell down from over 200m height. The pre-stressed anchor rope machines and houses at the foot of the slope were destroyed seriously by the rockfall (Figure 5). Fortunately, the constant monitoring forecast the accident in time, so it caused no casualties. But after the accident, a huge boulder, approximately 5m height,m was found in the slumping area, which seems like a sword of Damocles hung over the Danba city. The lives and assets of the Danba civilians were in a great danger. It was moved by blasting, and any danger was alleviated.

Figure 4. The partial slump in Region II on 14 March 2005

Figure 5. The houses destroyed by the partial slumps in Region II at the foot of the landslide

Region III

Region III is in the right rear of the landslide. The slope angle varies from 30^o-45^o. The width at the front of the region is about 50m and at the rear is approximately 85m. The length and the thickness are about 180m and 25m, respectively. The area is 0.014 km^2 and the volume is about 0.35 million m^3. The monitoring results indicated that the deformation of region III was smaller than region II and the deformation speed of region III was reducing gradually by the construction of the pre-stressed anchor ropes in sub-region I-1. After the urgently remdial engineering, the deformation tended to stop and did not do serious harm to Danba people.

THE REMEDIAL ENGINEERING OF DANBA LANDSLIDE

When we discovered that the landslide had stepped into the accelerative deforming stage and had been detected to show signs of movement by monitoring from the middle of February, the correlative departments attached great attentions to the Danba landslide and created the aim, which is “Ensure no casualties and make the movement of the landslide stop”. In order to achieve the aim, departments organized professional teams in geological hazards as soon as possible. Under the guidance of experts, the projects for remedial engineering were established. The details are shown below:

- In order to grasp the dynamic development of deformation and protect lives and assets of people in Danba, the government organized professional teams to pre-warn the deformation of the landslide by round-the-clock monitoring.
- In order to ensure no casualties, the residents in the dangerous areas must be evacuated rapidly. The dangerous and influenced areas were marked off from the safe areas. 1188 families with 4923 people were evacuated from the dangerous areas. At the same time, the anti-hazard preparatory projects were established. The anti-hazard cards were distributed to the residents in the influenced areas, once the alarm was sent out, they should retreat immediately.
- The aim of the remedial engineering is to stop the movement of the landslide. According to experts' advice, the engineering work could be divided into two parts: firstly, in order to reduce the sliding velocity, sand bags were pilec up in the leading edge of the landslide. With this mission, we can save time for the construction of active reinforcement project (the construction of the pre-stressed anchor rope); secondly, the pre-stressed anchor ropes were constructed to reinforce the landslide actively in the centre and anterior part of the landslide. 300 army soldiers and 1000 militiamen and citizens began to pile sand bags in turns by round-the-clock work from 20th February to the end of February. Finally the capacity of the sand bags had reached to 7170m^3(Figure 6). 6 rows with 244 bundles of pre-stressed anchor ropes were arranged in the centre and anterior part of the main body (sub-region I-1). The average depth of the rope holes is 40- 50m and the level interval is 4m. These pre-stressed anchor ropes were connected by cross beams. One pre-stressed anchor rope was made of 9 non-cohesive steel strands whose diameter is 15.24mm. The designed pre-stressing force applied to the anchor ropes is 1300KN. The first anchor rope in region I was stressed on 15 March. At the end of April, the construction of pre-stressed anchor ropes in region I was accomplished.

Figure 6. The sand bags piling engineering in the leading edge of the landslide

In the process of the engineering work , the displacement of region II was always large. Slumps in the left front of region II were serious as narrated before. In order to make the region II stable as soon as possible and allow the people in dangerous areas remove back to their houses, 2 rows with 40 bundles of anchor ropes were constructed in the centre and upper part of region II. After soil and stones in the slumping area were cleared, anchor rods and concrete injection engineering were constructed to reinforce region II.

After the completion of the engineering work the deformation velocity of the whole landslide had reduced from 2-3cm per day (the maximum is 4.64cm per day) to less than 1mm per day. The effect of the remedial engineering was very obvious. At the end of April, residents in the dangerous areas had returned to their houses.

THE EFFECT ANALYSIS OF THE MONITORING EARLY WARNING AND THE REMEDIAL ENGINEERING OF DANBA LANDSLIDE

In order to grasp dynamic development of the landslide deformation, at the same time to help to make decisions to guide people to evacuate as well as to guide the urgently wrecking engineering, the pre-warning of the slide was carried out by round-the-clock monitoring. Since 21 January 2005, 46 professional monitoring points and 26 artificial monitoring points were placed in the landslide to monitor the deformation. Meanwhile there were certain patrol people to investigate the fractures on the landslide. In addition, in order to grasp the deep deformations of the slide and to find out the definitive embedded depth of the rupture surface, 3 deep deformation monitoring holes were set following the axle wire of the main body in the middle and later periods of the engineering work (ZK13•ZK10 and ZK13 in Figure 7). A clinograph was adopted to monitor the deep deformation.

Figure 8 and Figure 9 show the deforming velocity curve of the 2# monitoring point in the front of the principal section and the 9# point in the rear of it, respectively. The accumulating displacement curve of 9# point is shown in Figure 10. It can be seen from Figure 8 that from 6 February 2005, the front of the main body appeared to show the tendency of accelerative deformation and on 22 February the maximum deformation per day had reached 27.6mm. Once sand bags were piled form 22 February, the deformation per day tended to reduce (due to the disturbance of piling sand bags, sharp fluctuations happened on 26 February and 27 February). Figure 9 indicates that the rear of the main slide body also had the accelerative deforming tendency, beginning from 6 February. The maximum deformation on 22 February came up to 30.3mm, then the deformation velocity began to reduce gradually. As seen from Figure 8 to Figure 10, the sand bags piling engineering had a very obvious effect on reducing the deforming velocity so it earned enough time to construct the pre-stressed anchor ropes.

During the decision-making stage of the urgently remidial engineering, according to the monitoring data recorded before 20 February, we can predict the time that the landslide might glide integrally by making use of the present landslide prediction and forecast model. The results indicated that if we didn't take urgent measures, the landslide would glide during 2-15 March. It also proved that the sand bags piling engineering really had a great effect.

The pre-stressed anchor ropes in the anterior and centre part of the main body were prepared for construction in the last ten days of February. The rope holes began to be drilled at the end of February. As it was too hard to maintain the hole in the thick unconsolidated debris, and the deformation velocity of the landslide was rapid, many anchor holes were ruptured and discarded before they were completed. The construction of pre-stressed anchor ropes was not well-off at the beginning. The first pre-stressed anchor was stretched on 10 March (in the middle of row A shown in Figure 7). As the number of the stretched, pre-stressed anchor ropes was small, they didn't have obvious effects on reducing the deformation of the landslide. By 15 April, the hole drilling, rope installing, and grout injecting of 244 pre-stressed anchor ropes in region I was completed. At the same time, 166 anchor ropes (about 70% of all) were applied pre-stressing force in different tonnage respectively. It can be seen clearly from Figure 8 and Figure 9 that after 15 April, the daily deformation tended to decrease obviously, the daily displacement reduced to 1-2mm per day, the slope became stable gradually and the threat of landslide to the Danba town was dissolved.

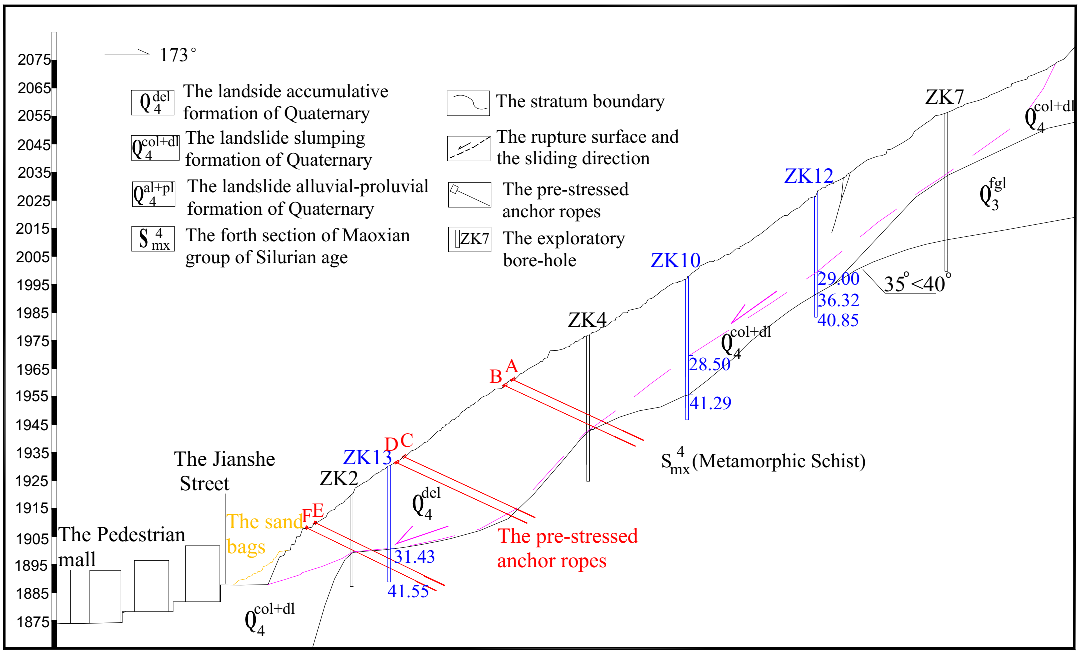

Figure 7. The sectional arrangement plan of the urgently wrecking engineering

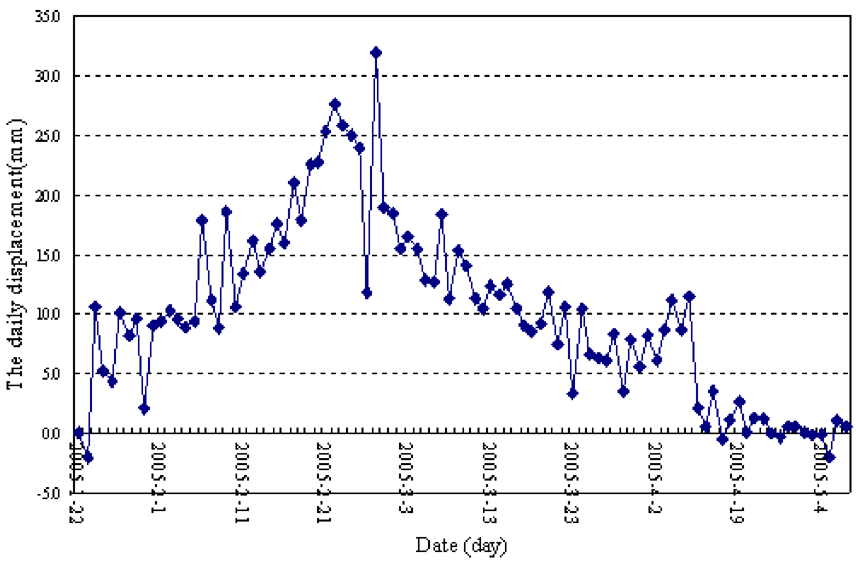

Figure 8. The deforming velocity curve of the 2# monitoring point in the front of the principal section in region I

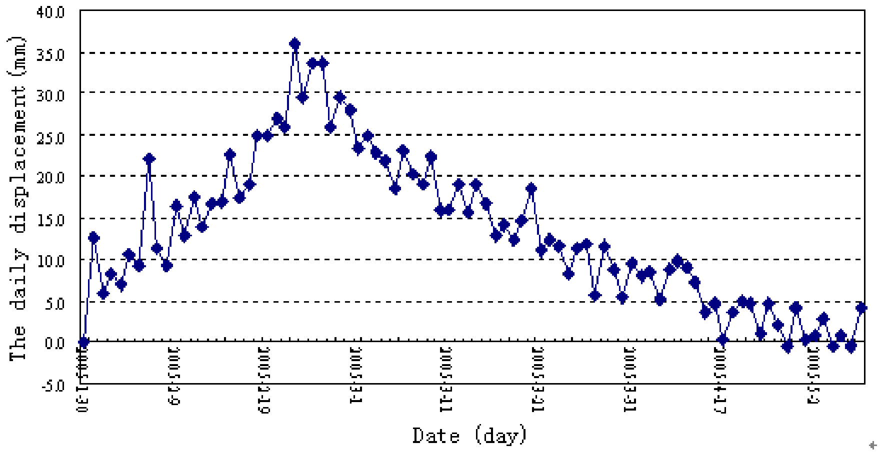

Figure 9. The deforming velocity curve of the 9# monitoring point in the rear of the principal section in region I

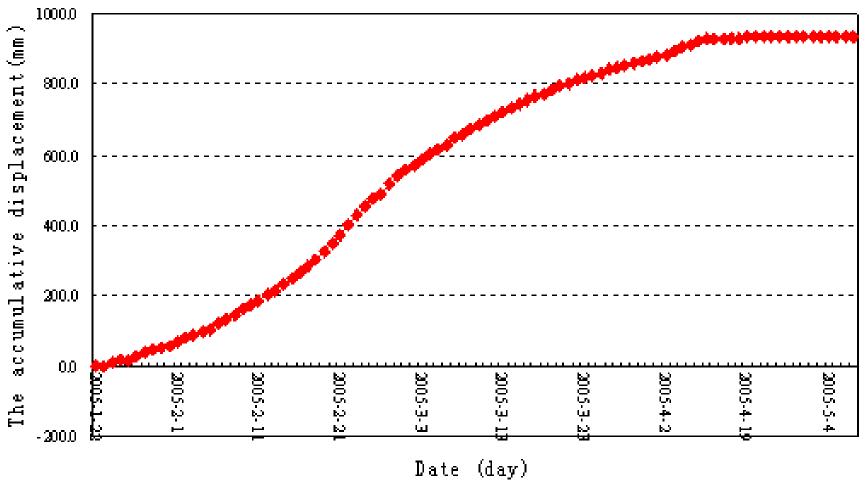

Figure 10. The accumulative displacement curve of the 9# monitoring point in the rear of the principal section in region I

The accumulating displacement curve of the posterior part of region I (the main body) is shown in Figure 10. From this picture we can obviously see the whole process that the deformation of the landslide began to accelerate from the beginning of February, and to decelerate after 22 February, and became stable gradually after the middle of April. The remarkable effects of the engineering work can be seen obviously in Figure 10. In addition, it still shows that the biggest accumulating displacement monitored by 9# monitoring point had approached 1.2m (The accumulating displacement monitored by 11# monitoring point near to I-1 region approached 1.5m. This monitoring point was damaged by construction). The monitoring results indicate that the total deformation of the landslide had already been big enough.

Figure 11 shows the monitoring results of the deep displacement of ZK12 (Figure 7) in the centre and posterior part of the main body. As clearly shown in Figure 11, the rupture surface was embedded in the 29m below the ground surface. During exploration, it was considered that the rupture surface was the contact surface between the unconsolidated debris of Quaternary sediments and the underlying bedrock. But the results of deep displacement monitoring showed that the previous thought was wrong. The Danba landslide didn’t glide completely along the contact surface, many segments cropped out from the unconsolidated debris. For example, the depths of the contact surface monitored by ZK12 and ZK10 were 36.2m and 41.29, but the depths of the real rupture surface were 29m and 28.5m, respectively. The depth of the rupture surface and the contact surface monitored by ZK13 were almost the same, which is 31.43m (Figure 7). Through deep displacement monitoring, we cannot only make sure the exact position of the rupture surface, but also can grasp the evolution of the space deformation of the landslide. The landslide not only crept down entirely, but also had the character that the deformation declined gradually from the deep to the surface, which can be seen from Figure 11. As time goes by, the deformation of the landslide is on a downtrend (Figure 11). Until August 2005, the daily deformation is less than 1mm per day. Affected by rain and other factors, the deformation of the landslide might increase suddenly (9 May, 10 July), but returns back to normal soon after.

Both the surface displacement monitoring (Figure 8 & Figure 9) and the deep displacement monitoring results (Figure 11), all indicate that the deformation velocity of the landslide has decreased sharply by carrying out the remedial engineering and now the possibility of gliding entirely is very small. But the deformation didn’t completely cease. Nowadays, the slope is gliding at a 1mm per day deforming rate. To stop the deformation completely and keep

Danba landslide in a long-term stable condition, as well as to ensure the Danba people live and work safely and happily, comprehensive measures are carried out now. The measures are using friction piles in place of the sand bags piled during the emergency period, at the same time adding 3 rows of pre-stressed anchor ropes in centre and posterior part of sub-region I-1. Finally, the Danba landslide will be cured drastically.

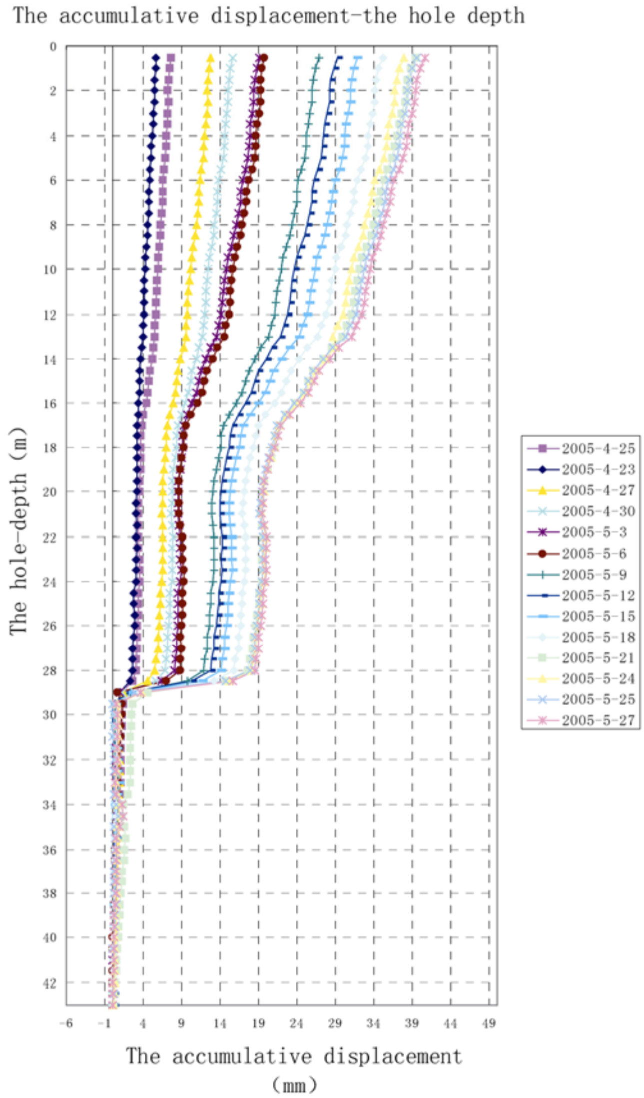

Figure 11. The deep displacement monitoring results of ZK12

CONCLUSIONS

Danba landslide is one of the landslides, which have the fastest deformation velocities, the most serious harms and the largest curing difficulties. Through the successful remedial engineering for Danba landslide, we can reach to some conclusions as following:

The basis of forecasting and early warning

Correct judgment on the evolutive periods of landslides is the basis of forecasting and early warning of landslides. During the engineering work on the Danba landslide, correlative departments organized experts to demonstrate the evolution and development tendency of the landslide and the feasibility of the remedial engineering in the middle of February. Then the experts came to two agreements:

- The landslide had been in accelerative deformation periods. If the anti-sliding measures hadn't been carried out, the gliding down of the whole landslide could be inevitable and the gliding time is not long.
- The landslide was in the initial stage of the accelerative deformation periods. It was possible to make the landslide not to glide integrally by the correct urgent measures.

So we undertook the remedial engineering as fast as we could. Looking back at the whole process, there is no doubt that the decision made at that time was very right and in time, otherwise the result was awful to imagine.

The pledge of preventing and curing of the landslide

Reinforcing the early warning monitoring is the important pledge of preventing and curing the landslide successfully, which is on the point of gliding down. During the urgently wrecking process, we integrated the professional monitoring, the simple artificial monitoring and the artificial patrol together perfectly. By the synthetical analysis, on the one hand we exactly forecast the partial slumps in region II time after time, and achieved the aim of “no casualties”, on the other hand we ensured the security of the construction by the round-the-clock monitoring and early warning.

The capture and identification of the landslide prognostications

Reinforcing the capture and identification of the prognostications that appeared on the point of gliding is very important to direct the engineering work of the landslide that is threatening to slide. In the early period of the remedial engineering, according to the characters of Danba landslide, we put forward some early warning criterions as follows:

- Several small scale partial slumps took place in the leading edge of the landslide at one time.
- The deforming velocity tended to increase sharply.
- According to the latest monitoring data, we forecast the exact time that the landslide might glide down within 24 hours.

If one of the three cases occurred, we suggest that engineering teams and residents in dangerous areas and affected areas should be evacuated immediately.

The function of sand bags piling engineering

The sand bags piling engineering in the front of the landslide and the cutting engineering in the centre and posterior part of it played a very important role in the remedial engineering.

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