Study on the formation mechanism and design of control engineering for the super-huge Tiantai landslide, Xuanhan County, Sichuan Province, China

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Abstract: On 5 September 2004 a catastrophic super huge landslide was induced following prolonged heavy rain, at Tiantai village, Xuanhan Country, Sichuan Province, in China. The landslide was 950m to 1200m long, 1400m to 1600m wide and its average thickness was 23m. It had an estimated volume 25 million m^3, which is uncommon for rock landslide in China. Approximately 2983 houses and 59600m^2 of land were destroyed which caused 1255 people, and nearly 317 families to lose their houses. Furthermore, an estimated 2.1 million m^3 of debris from the landslide became deposited into the Qianhe River. This formed a rock dam some 1500m wide and 20m high impounding a lake about 60 million m^3. Because the Qianhe River was blocked and water level rose, 5770 houses and 4930 acres of cropland in Wubao town located further upstream, became submerged. In total 19,360 people were temporarily evacuated as a result of the landslide and its secondary affects. The direct economic losses were estimated to be in the order of 100 million Yuan. The objective of this paper is to draw attention to this landslide, analysis the landslide mechanism and document the mitigation and preventative measures used to stabilise the landslide.

Résumé: Le cinq septembre 2004, au canton Tiantai du District Xuanhan de la ville Dazhou de la Province Sichuan, il a surgi le glissement de terrain en rocher. La longueur du glissement de terrain est de 950-1 200m. Largeur est de 1 400-1 600m. L'épaisseur moyenne est de 23m. La volume globale est de 2 500 x 104 M^3. Le glissement de terrain en rocher a détruit non seulement les maisons de 2 983 en une surfaces de 59 660M^2, 317 foyers en 1 255 habitants sans maison, dans un domaine de 1.2K M^2. Mais aussi, il y a eu de 210 x 104 M^3 des biens, des matières et des matériaux qui sont enlevés dans la rivière devant le glissement de terrain, bouchant la rivière. Des entassements qui a une largeur de 1 500m, une hauteur de 20m, se forme un lac en amont. Sa volume de l'eau est de 6 000 x 104 M^3qui submergeait 5 770 foyers, les champs de 4 930 mous. 19 360 habitants se déplacent rapidement. La perte économique est de plus de 100 millions yuan RMB. Le texte a recherché systématiquement et profondément d'abord le mécanisme du glissement de terrain qui se formait. Il a proposé le modèle évolué de plusieurs poussées horizontale de grand glissement de terrain en faille horizontale. Sur cette base, selon la stabilité du profil principal du glissement de terrain et ses résultats de calculation de la poussée de glissement, synthétiquement l'état géologique après le glissement de terrain, on a proposé la mesure de traitement des travaux d'après la surface de la pente qui est le nivellement et le gradin et le support pour l'anti-glissement. Maintenant l'exécution des travaux de traitement est achevé. Il a fait l'épreuve de l'averse de l'an 2005. les résultsts de surveillance actuelle montre que le glissement de terrain est fondammentalement stable.

Keywords: geological hazards, landslides, slope stability, mechanical properties, design, piles

INTRODUCTION

On 5 September 2004, a catastrophic super huge landslide was induced following prolonged heavy rain. It occurred at Tiantai village, Xuanhan Country, Sichuan Province, in China. The landslide was 950m to 1200m long, 1400m to 1600m wide and its average thickness was 23m. It has an estimated volume 25 million m^3, which is uncommon for rock landslide in China. Approximately 2983 houses and 59600 m^2 of land were destroyed which caused 1255 people, and nearly 317 families to lose their houses. About 2.1 million m^3 of debris from the landslide became deposited into the Qianhe River. This formed a rock dam some 1500m wide and 20m high impounding a lake about 60 million m^3. This caused the river level to rise by 20 to 23 m, and the resulting barrier lake reached 20km long. It caused 4500 houses to be flooded, more than 10 thousand people were affected in the towns of Tiantai and Wubao. The direct economic losses were estimated to be 100 million Yuan.

After the landslide occurred the Chinese government rapidly organized the massive manpower and physical resources for emergency disaster relief. At the same time a channel dredging programme was implemented to help protect people living upstream. This was aimed at reduced the water levels in the lake. These works have now been completed and the landslide has once again been subjected to further heavy rain in 2005. However, the engineering mitigation controls appear to have been successful and the apparent stability of the landslides has been verified by monitoring.

THE GENERATION OF THE LANDSLIDE

The landslide occurred in mudstones interbedded with sandstones, belonging to the Suining Group of Jurassic age. The strata are deformed and the landslide occurred at the southeast limb of the Wubao Anticline. The upper parts of the slope consist of mainly weak rocks such as thinly bedded mudstones, whereas and the sliding plane occurred in stronger thick bedded sandstones.

The rocks dips towards 110°SE to 120°SE and the strike of rocks are parallel to the slope. According to the conventional theory of limiting equilibrium, it is not possible for such a large landslide to develop on flat-lying bedrock. To find out the generative cause of the landslide the geological conditions and topography were investigated before and after the landslide (Zhang & Lansbeng, 1994):

Geological conditions

The slope angle was low and was covered with superficial deposit of mainly slope wash debris. This underlying mudstone was about 20 to 30m thick. Northeast and northwest trending fissures developed and divided the rock mass into two separate 'blocks'. This therefore explained the 'zig-zag' morphology along the edge of the landslide which appeared to be related to these two intersecting discontinuity sets (Figure 1).

Topography

The advancing edge of the landslide slipped into the valley generating a large, bulging, a convex slope (Figure 1). A 45 to 65m high scarp formed where the main back scarp intersected the river bed. The angle of the slope before sliding was about 6 to 20º, but this varied and in places. There were some ponds of standing water in the lower lying area and four gullies had formed running down, and draining the slope. After the landslide occurred, the overall angle of the slope changed and in particular the topographic features altered dramatically and were more complex as illustrated in Figure 2.

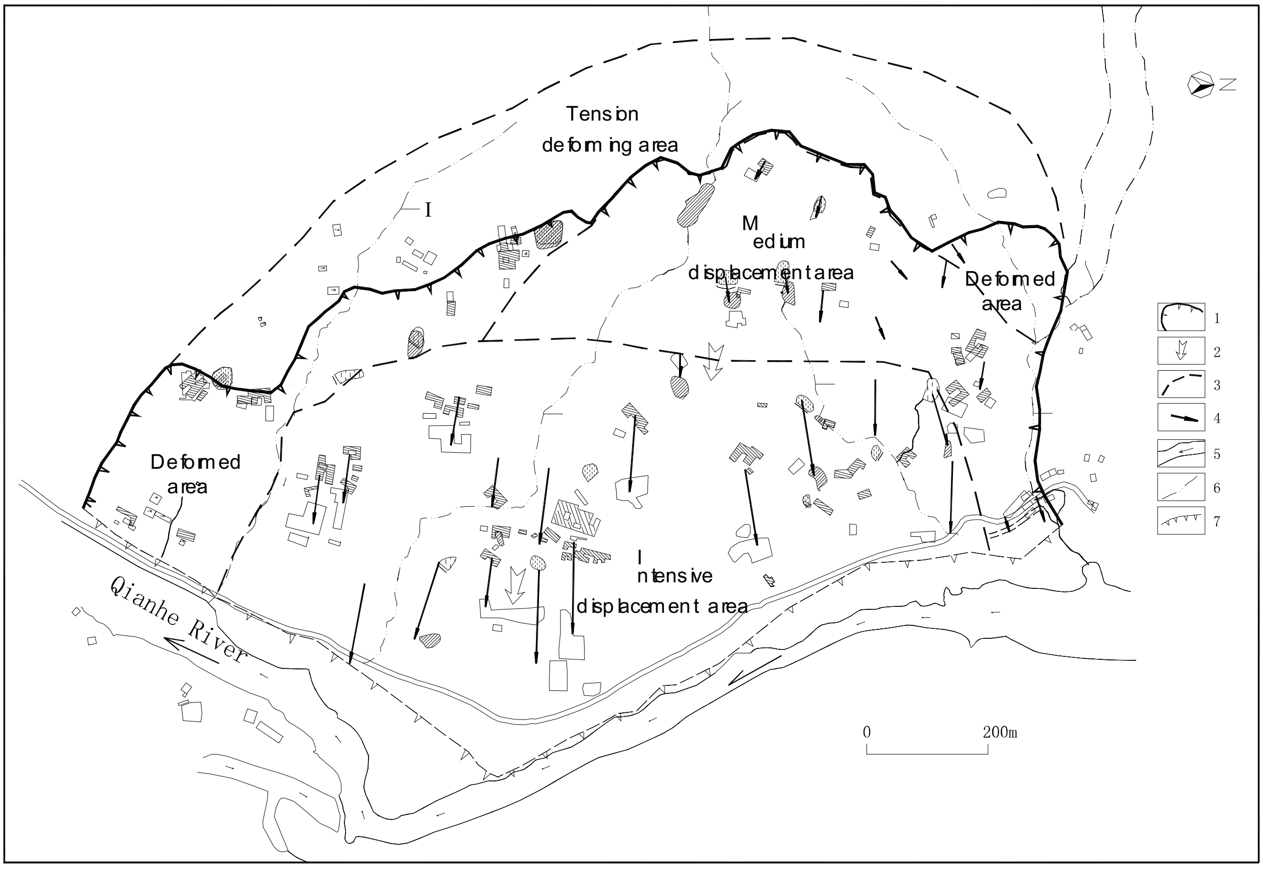

Figure 1. Engineering geological map of the Tiantai landslide: (1) edge of landslide; (2) direction of sliding; (3) boundary of deformation area; (4) displacement vector; (5) main channel of river; (6), four longitudinal gullies; (7) basal thrust outlet; (I) Yujiahe Gully (Huang et al. 2005).

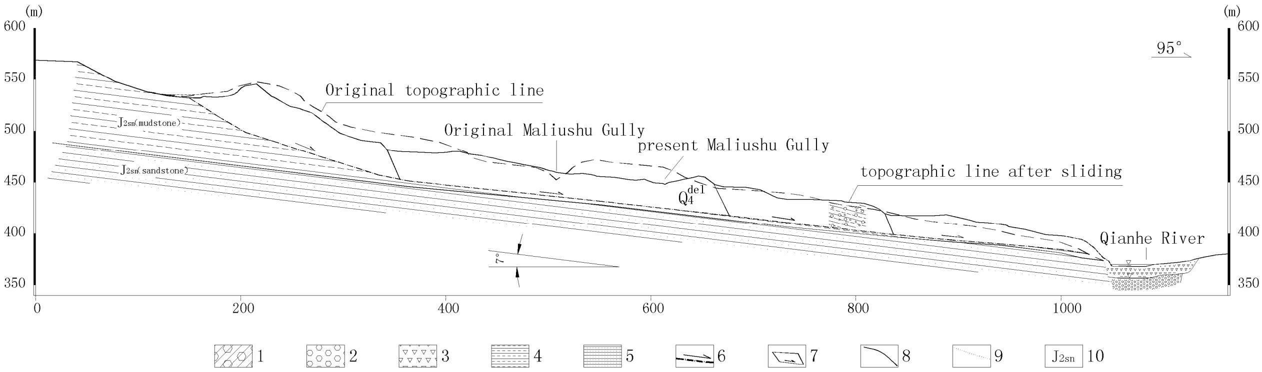

Figure 2. Geological section of Tiantai landslide after failure: (1) silty clay with macadam; (2) macadam and rock (3) macadam and rock from the landslide accumulated in stream channel; (4) mudstone; (5) sandstone; (6) main sliding surface and sliding direction; (7) secondary sliding surface and sliding direction; (8) slope profile after sliding; (9) original slope profile; (1)0, Suining Group of Jurassic age (Huang, 2005).

The landslide appeared to fail not as a single ‘block’ but consisted of about 50 complex, secondary ‘blocks’. The duration of the landslide has been estimated to be in the order of 8.5 hours, from 15:00 to 23:30, on 5 September 2004. The middle and front part of the landslide slipped first via translational type of movement and slumping into the Qianhe River. The landslide changed dramatically the surface morphology to the extent that houses, ponds and gullies were no longer recognisable. In some instances however, certain morphological features remained intact in-spite of having been transported at least 140m (Figure.3).

Figure 3. Large blocks of rock and debris which were displaced by the landslide.

Spreading was observed in the central part of the landslide and this resulted in the generation of a series of terraces and scarps (Figure 4). This has been interpreted to represent secondary ‘gliding’ of large ‘blocks’ (possibly defined by joint sets in the bedrock). Beyond the edge of the landslide graben and multiple reverse fissures were observed.

Figure 4. Spreading in the middle part of the landslide generating a series of terraces and scarp.

Hydrogeology

According to the meteorological data, the rainfall in Xuanhan area reached 403.3mm from 3 September 2004 to 6 September 2004. Furthermore, from 4 September 2004 at 20:00hrs to 5 September 2004 at 20:00, rainfall reached 257mm. This rainfall and associated flooding achieved the 100-year frequency intensity. Although there were four large gullies within the landslide, these channels could not drain the water because they were blocked and so the water accumulation on, and within the slope. According to the local villagers’ surface water breached the channels and flowed along the entire slope. Areas of standing water and ponds were also breached resulting in rapid sheet-wash across the slopes. Based on the above observations a model for the landslide was developed and is presented in Figure 5.

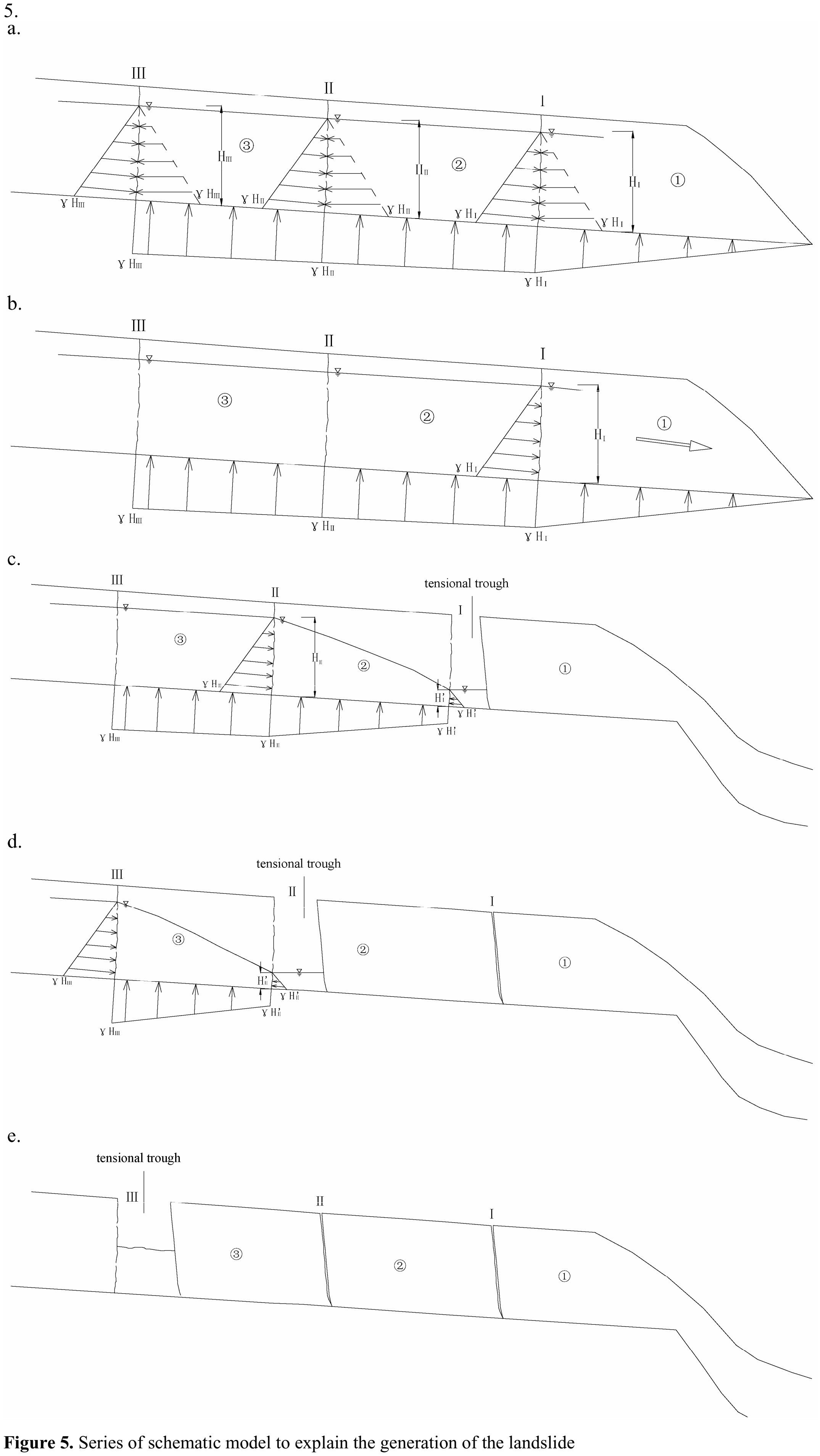

Figure 5. Series of schematic model to explain the generation of the landslide

In Figure 5a the landslide is represented by sliding blocks 1, 2 and 3 separated by fissures I, II and III. Heavy rain was envisaged to wash through the soil cover into the mudstones via these fissures. Due to the relatively low permeability of the weak mudstones the water generated hydrostatic pressures in the fissures and uplift pressure at their bases. This causes elevated hydrostatic pressures in both blocks (1 and 2) which are situated adjacent to fissure I. The thickness of each sliding block is about the same and therefore the depth to the sliding surfaces was consistent. Since gliding block 1 has almost level hydrostatic pressure, then Figure 5a may be simplified as presented in Figure 5b.

The middle and front of the landsdlie (block 1) detached along fissure I and flowed into the Qianhe River. This process was repeated on fissure II, then fissure II. In general, the landslide appeared to have failed in a series of rigid blocks which became detached from the main body of the landslide along principal fissures in the underlying bedrock. Each block failed by translational shear failure along a slip surface (Figure 5d and Figure 5e).

CALCULATION LANDSLIDE STABILITY

Mechanisms

The following parameters were determined for the landslide:

- Weight of the landslide: γ=19.35kN/m^3
- Weight of water-saturated of landslide γ_{sat}=20.81kN/m^3
- Weight of displaced sandstone and mudstones γ'=26.0kN/m^3

The physical parameters for the ‘soil’ on the slip surface of the landslide were determined from laboratory tests undertaken as part the ground investigation (Table 1).

Table 1. Physico-mechanical parameter of soil and rock mass

Group	Cohesion force C (kPa)	Friction angle Φ(°)
Soil in sliding zone	9.4	12.8
Main body of landslide	23.6	21.8
Bedrock/slip surface	14.87	41.70

Stability calculations

Following the initial failure the mudstones became severely degraded and disintegrated. Tension fissures developed which subsequently increased groundwater seepage and this reduced stability. Since groundwater was envisaged to be the main factor in triggering and controlling the landslide, stability calculations were based on the following three possible conditions.

- Condition 1: Considers the pre-failure landslide stage with groundwater levels as identified by drilling.
- Condition 2: Considers the water table in the slipped mass to be half the depth for a 20-year return period heavy rainstorm.
- Condition 3: Considers a partial draining landslide with the water table in the slipped mass to be two-thirds the depth for a 100-year return period heavy rainstorm.

To calculate the stability and thrust of the landslide in the 3 possible conditions identified in Table 1, the factors of safety (Fs) were found to be 1.20, 1.15 and 1.10 respectively. The calculations are shown in Table 2 and Table 3.

Table 2. Results of stability calculations for the landslide

Sections	Methods	Before cutting slope (KN /m)			After cutting slope (KN /m)	
		State 1	State 2	State 3	State 1	State 2
5 -5	Ordinary	1.202	1.088	1.017	1.209	1.094
	Bishop	1.195	1.081	1.013	1.201	1.087
	Transfer coefficient method	1.229	1.118	1.043	1.238	1.124
1-1	Ordinary	1.336	1.106	1.000	1.340	1.106
	Bishop	1.274	1.048	0.954	1.278	1.049
	Transfer coefficient method	1.392	1.165	1.057	1.397	1.166
3-3	Ordinary	1.417	1.180	1.062	1.462	1.183
	Bishop	1.408	1.123	1.057	1.452	1.175
	Transfer coefficient method	1.436	1.199	1.081	1.482	1.203

Table 3. Results of stability calculations for the thrust (slip)

Sections	Before cutting slope (KN /m)			After cutting slope (KN /m)	
	State 1	State 2	State 3	State 1	State 2
5-5	0	2505	4353	0	2022.9
1-1	0	0	1613.6	0	0
3-3	0	0	1638.6	0	0

The results of the calculations show that the landslide had good stability under the natural conditions. But the stability was reduced following heavy rain. The landslide was long, with a linear failure surface and so the cumulative effect of thrusting along the failure surface became enhanced.

The factor of safety and thrust force were particularly sensitive to the parameter of the sliding zone, especially the friction angle. The results of the sensitivity analysis indicated that the friction angle of sliding zone increased by 0.1^{o}, the factor of safety increased and the thrust force was reduced by about 650KN/m, whilst the cohesion force of sliding zone soil increased by 1kPa and the thrust force reduced by about 700kN/m.

Groundwater levels in the landslide body contributed greatly to the factor of safety and trust force. Groundwater levels increases 0.1H (where 'H' represent the thickness of landslide body), the factor of safety reduced 0.07 to 0.08, and thrust force increased about 5600kN/m.

ENGINEERING CONTROL MEASURES

It was considered necessary to design and engineer measures to control surface run-off and groundwater and to prevent further reactivation of the landslide. The landslide covered a relatively very large surface area and the failure planes were buried deep below the ground surface. The dip of the slope was low almost flat and therefore the most appropriate engineering solutions to control further reactivation of the landslide were considered to be a combination of the following:

- Profiling of slope
- Installation of a drainage network, including discharge ditches for surface water and underground drains
- Earthworks, including anti-slide piles and sheet-pile walls

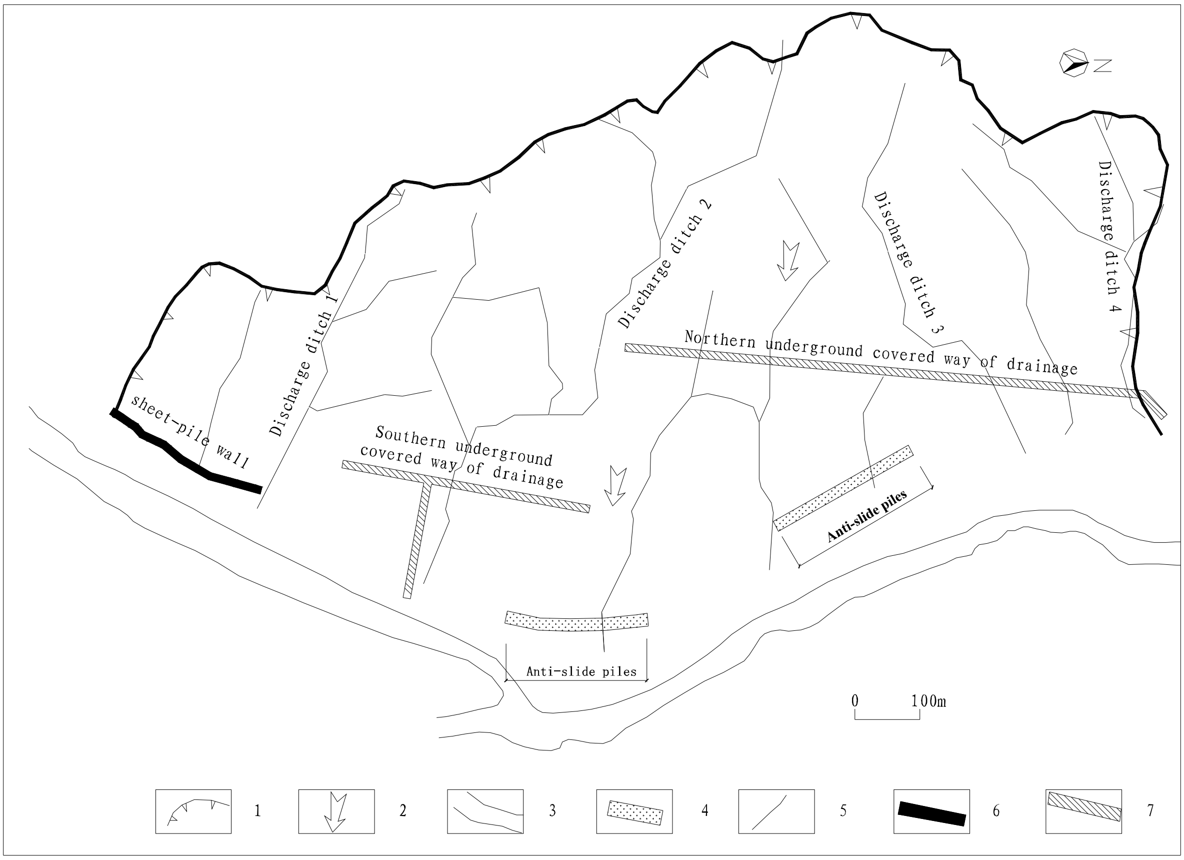

Figure 6. Schematic map showing the landslide control measures: (1) boundary of landslide (2) direction of main sliding (3) main river channel (4) anti-slide pile; (5) discharge ditch; (6) sheet-pile wall; (7) underground covered drainage.

Engineering of cut slopes

As a result of the landslide huge volumes of rock and debris blocked many of the drainage channels, creating ponds of standing water on the ground surface. Furthermore, extensive graben and fissures provided permeable channels, which facilitated groundwater flows in the middle part of the slipped mass, therefore further reducing stability. Parts of the slopes were therefore 'cut and filled' and drains were installed. The cutting of the slopes became focussed on the prominent blocks of rock and debris, which had been transported by the landslide. These were excavated and subsequently and used to backfill zones of tension, ground fissures and ponds. Clay from the superficial deposits was also used as a source for backfill in conjunction with rolling and compaction. The cutting and filling of slopes was designed so the drainage system could be implemented effectively and that surface water could be discharge out of the landslide. The volume of excavation of landslide soil was approximately 180,000 m^3.

Surface drainage

Before the landslide occurred four principal drainage channels existed running longitudinal down the slope. From south to north these were known as Xujiahe Gully, Maliushu Gully, Liangshuijin Gully and Dahe Gully. After the landslide occurred these channels were partially destroyed. These were reclaimed and used as main drainages ditches to help drain the slopes. A further 16 drainage ditches were also constructed to form an interlocking drainage system on the surface of landslide (Figure 6). The design parameters for the main discharge ditches can be seen in Table 4.

Table 4. The design parameters for the main discharge ditches

No	Altitude (m)	Length of ditch (m)	Design flow (m^3/s)	Width of ditch base (m)	Depth of ditch (m)	Cross-section area of ditch (m^2)	Current velocity (m/s)	Actual flow (m^3/s)
1	478.8-401.3	560.44	17.23	1.5	1.2	1.75	18.15	32.67
2	528.5-403.0	1134.22	26.85	1.5	1.5	2.795	19.47	56.73
3	522.0-443.0	681.83	21.54	1.5	1.2	1.75	16.62	29.9
4	505.0-438.0	500.96	57.51	2	2	4.41	23.99	107.98

Due to the long length of the drainage ditches, these were envisaged to deform relatively easy during any movements on the landslide. These were therefore reinforced with a foundation trench and 250mm thick armoured concrete slab at the base of the discharge ditches. These auxiliary ditches were installed in two sizes, they had rectangular sections and their cross-sectional areas were 0.384m^2 and 0.64m^2 respectively. To facilitate water flow through the drainage ditches filters were installed in the walls and in the catchment areas.

Under ground drainage

After the landslide occurred the underlying weaker mudstones became severely disintegrated and compacted, compared to the stronger sandstones. Groundwater was also abundant and in boreholes the head height was about observed to be about one-third of the thickness of the landslide. At the toe of the landslide the groundwater emerged at the ground surface. This generated swamp and marshy ground conditions with standing pools of water. Large volumes of water were observed to drain freely from the toe of the landslide and the underlying sandstone bedrock. Networks of underground drainage channels were therefore designed to control this groundwater.

Drilling enabled groundwater levels to be determined across the landslide. As a result two principal underground drainage channels were installed, one in the north and the other in the south. These were sited within the underlying sandstone below the sliding zone. The total length of the underground drainage was approximately 1500m. These were rectangular in cross section, about 1.8m high and 1.5m wide. The landslide did not displace the underlying sandstone and the groundwater drained freely through the permeable sandstone into the drainage system. It was important however, that the drains were located deep enough to be beyond the influence of any further creep or slippage of the landslide.

Anti-slide piles

Rows of anti-slide piles were positioned in the centre of the toe of the landslide (Figure 6). The positions of these were based on numerical simulation of the main landslide event and monitoring. Four different types of piles were designed according to the anticipated depth of the failure surface; these were known as type I, II, III and IV. In cross section the anti-slide piles were 3m high and 2m wide. The length of type I was 30m and the length of the load bearing was 21m, 24 were installed at 6m intervals. The length of type II was 30m and the length of the load bearing was 20m, 6 were installed at 8m intervals. The length of type III was 34m and the length of the load bearing was 24m, 4 were installed at 8m intervals. The length of type IV was 25m and the length of the load bearing was 17m, 32 were installed at 8m intervals. The total number of piles installed was 66.

Sheet-pile walls

The landslide was not very thick, on average about 5m, but the moisture content was high and this presented favourable conditions for failure. Monitoring indicated continual creep of the toe and therefore an engineered sheet pile wall was designed on the south boundary of the landslide to stabilise the toe and to prevent further damage to a road (Figure 6). As was the case with the anti-slide piles, four different types of sheet piles were designed according to the thickness of the landslide; the lengths were 6m, 8m, 10m and 12m. In cross section the anti-slide piles were 1.8m high and 1.2 m wide. The breast boards established between anti slide piles were made of armoured concrete. The height was from 4m to 8m and it was 300mm thick. To facilitate drainage inverted filters were installed in the breast boards. The total number of sheet piles installed was 6627.

CONCLUSIONS

The Tiantai landslide is a super-huge landslide, which occurred on 5 September 2004 in Xuanhan Country, Sichuan Province, China. It caused widespread damage to large areas of farmland, numerous houses were lost and there were enormous financial losses. The landslide was induced following prolonged heavy rain. The failure surface consisted of a relatively flat lying stratum. The mechanism for the landslide and its initiation were only partly understood.

Engineering geological investigations involving drilling and testing enabled the landslide mechanisms to be determined. This provided important parameters, which were required for the design of remediation and stabilisation measures. This also enabled different failure mechanisms to be modelled. One of the main mechanisms responsible for the failure of the landslide appeared to involve multiple translational type movements of discrete block. Each blocks being bound by principal fissures and prominent joint sets.

Remediation of the landslide involved the profiling, cutting and backfilling of the displaced and disturbed slopes, the installation of surface and subsurface drains and the design and installation of anti-slide piles and sheet pile walls. Ongoing monitoring to date has suggested that the landslide is now relatively stable and the remediation and mitigation measures appear to have been successful. On 8 July 2005, Xuanhan County appeared once more to experience the 100-year frequency heavy rain fall, which had induced the original landslide. But on this occasion, because of the engineering control measures the landslide was not reactivated and no new landslides were initiated.

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