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ORIGINAL ARTICLE

Remediation and analysis of kinematic behaviour of a roadway landslide in the upper Minjiang River, Southwest China

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Abstract Because of terrain, geological structure, river down-incising and human activities, the upriver Minjiang Valley in Sichuan Province, Southwest China, constitutes a disaster area prone to frequent landslides. During the roadway rebuilding periods, the Xiaozongqu landslide reactivated on the G213 Roadway in Maoxian District of Sichuan Province. From the September to November in 2002, the landslide sped up, reaching a maximum movement rate of 32 mm/d. The rapid slide seriously threatened the road. To stabilize the landslide and eliminate the damage of landslide to the road, remedying its damage and monitoring further developments are crucial. Based on its kinematic behaviour, remediation was implemented in two phases from November 2002 to October 2003. Systematic monitoring has been carried out since 18 June 2003 to determine kinematic variations of the landslide during the post-remediation period and to assess the effects of remediation and the potential of the landslide for further destructive influences on the roadway.

Keywords Roadway landslide · Upper Minjiang River · Landslide remediation · Systematic monitoring · Kinematic behaviour · Potential failure

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Introduction

Because of the local terrain, geological structure, river down-incising and human activities, the upriver Minjiang Valley of Sichuan Province, Southwest China, is a disaster area prone to frequent landslides (Chai et al. 1997; Wang et al. 2000; Jiang et al. 2002; Chang et al. 2007). These cause the river to dam up, and they demolish the roadway along the upper Minjiang River basin (Qiao 1994; Chai and Liu 2002).

During the roadway rebuilding periods, a landslide referred to as the Xiaozongqu landslide reactivated on the G213 Roadway in Maoxian District of Sichuan Province, Southwest China (Figs. 1, 2). This was due to a combination of factors: the action of the landslide terrain, river erosion, road cutting, slope geometry and masses properties. Rapid sliding took place on 20 September 2002, and it sped up to 32 mm/d in November 2002. The rapid sliding seriously threatened the G213 Roadway and threatened to cause the Minjiang River to dam up if it slid further downhill.

For a dangerous roadway landslide with rapid movement, the remedial measures are crucial to stabilize it and ensure road safety. Moreover, the landslide monitoring is needed to determine its movement variations during the post-remediation period. The case study presented in this paper attempts first of all to describe the landslide and its causative factors and to suggest the remedial measures for such a sliding landslide. It then presents the systematic monitoring to determine kinematic behaviour from the time of the landslide outbreak to post-remediation, to investigate the slide's temporal and spatial features and to assess the remediation and the potential influence of the landslide on the roadway.

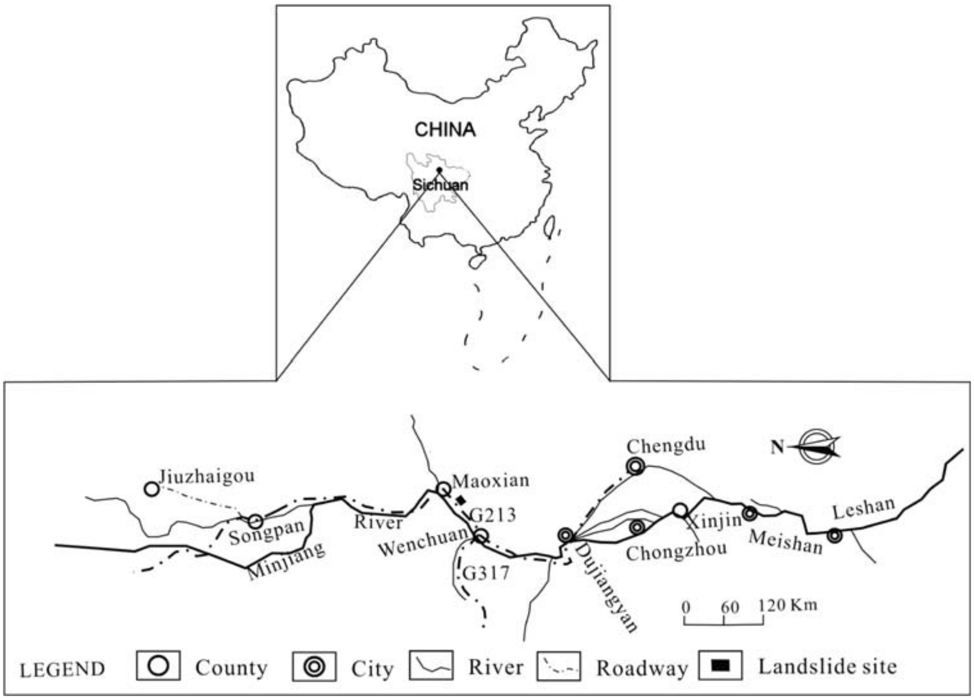


Fig. 1 Location of the study site

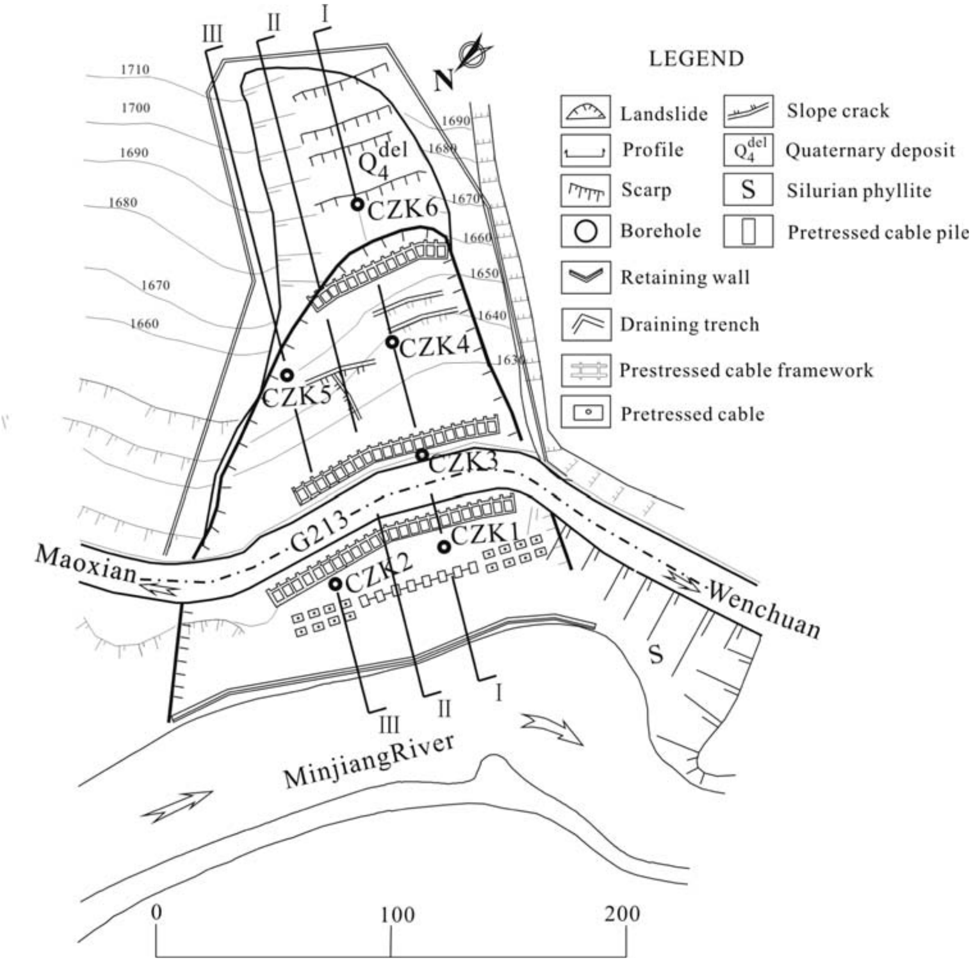


Fig. 2 Plan view of the Xiaozongqu landslide showing the geology, the geomorphology, the remedial engineering and monitoring

Xiaozongqu landslide

General description

The study area is located in the upriver gorge zone of the Minjiang River in the Northwest Sichuan Plateau. The major topography is characterized by extensive undulating lowlands in the southeast contrasting sharply with highlands in the northwest, which commonly reaches an altitude of 800 m above the lowlands (Fig. 3). The Minjiang River cuts deeply across the valley. In the Maoxian-Wenchuan area, the down-cutting of the river is about 50–350 m, and the steep toe provides an advantageous condition for mass slides (Yan et al. 1998). The mountains are covered with seasonal grass and dotted forest. The value of the slope angle is 30°–42°, which makes the terrain highly prone to masses sliding, especially under the conditions of slope cutting and fluvial erosion.

The latest creeping of the Xiaozongqu landslide have initiated since 1998 due to the roadway reconstruction in the area. The archaic landslide from which the Xiaozongqu slide originated has a length of 480 m, an average width of 110 m and an approximate depth of 40 m. Field investigation shows that the most recent landslide is about 190 m long, 110 m wide and 10–40 m deep. It is an active landslide large in scale and above one million cubic meters in bulk. The sliding surface has developed from different lithofacies zones, structurally controlled by the lithofacies contact interface. The average slope of this interface is about 37°, as revealed by the geological borings. Figure 4 shows the cross-section of the landslide as depicted from boreholes information. According to the Varnes landslide classification (Varnes 1978), the Xiaozongqu slide is a rotational landslide. The sliding mass consists mainly of rubble soil and stony soil.

Causative factors

Landslide occurrences are closely related to the interaction of geo-environmental factors, including terrain, slope geometry, mass properties, water and flow, and human activity. In addition to aforementioned factors, Uribe-Etxebarria et al. (2005) point out that unforeseen occurrences and derivate damage also depend on the slope morphology and linear infrastructures features. In the case of Xiaozongqu landslide, adverse tectonic structures, steep interface and easily slippery rocks constitute the basic conditions giving rites to the sliding. In addition, road cutting and fluvial erosion served to break the equilibrium of the slope and ultimately induce the large landslide.

It is concluded that the mechanisms underlying the Xiaozongqu landslide are as follows:

(1) The landslide is controlled by the Minjiang River erosion. How about the previous landslides are not exact, but it can be speculated that the slope failed due to the river erosion. The presence of sedimentary gravel in the river bed provides evidence of this regarding the formation of the archaic Xiaozongqu landslide. Due to the endless down-cutting of the river and the back erosion at the slope toe, the river gravel came to be deposited there. The progressive failure of the slope toe developed upwards, causing large slide retrogressions on the current rupture surface or on new deeper rupture surface. Landslides thus readily occurred under triggering conditions, and their debris came to cover the river gravel layer. This phenomenon is a periodic occurrence in natural conditions, leading

Fig. 3 Photograph of the Xiaozongqu landslide showing the geomorphology, the road, the landslide and the repaired slope

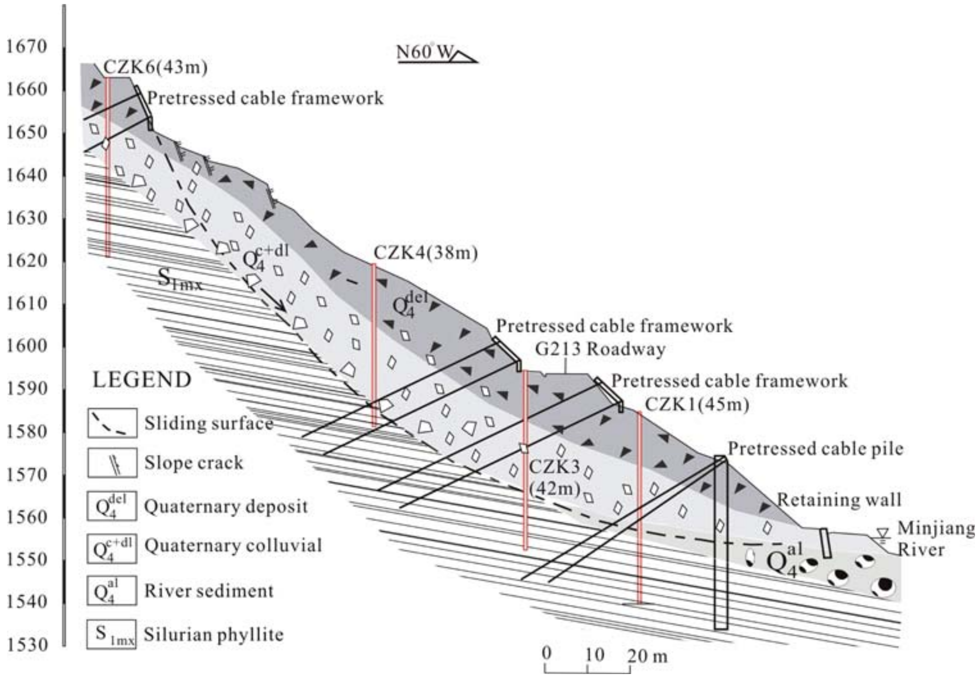


Fig. 4 Cross-section of the landslide profile I–I

to further down-cutting and bank erosion in subsequent landslides. Figure 3 shows the remarkable sedimentary terrain of the landslide materials. Near the landslide, river erosion deflected the riverway sharply to form an obvious slope bulge shaped like a "nose".

(2) Regional geological structure,slope geometry and slope mass characteristics: Slope instability depends mainly on the local lithologic and structural conditions (Bogaard et al. 2000). Northwest Sichuan lies on the eastern margin of the Qinghai-Tibet Plateau, and geological activities in this transitional zone are frequent and intense. The landslide area lies in the Longmen Shan Thrust–Nappe Belt (Chen and Wilson 1996), which is the large-scale geological structure on the eastern margin of the Qinghai–Tibet Plateau. The Longmen Shan structural belt is also an active earthquake zone, and geological activities in this area are intense and frequent (Yu and He 2000). On 12 May 2008, Wenchuan Ms 8.0 Earthquake, the latest catastrophic earthquake, occurred in this area. The complicated geological structures of the region are typically associated with these activities. The Maowen-Wenchuan fault is a large structure, and its sub-structure is one of the controlling factors of slope instability in the area studied (Yan et al. 1998). The strata of the landslide area are thus cracked, and the outcrops became heavily prone to weathering after previous landslides.

In this study, six geological borings were drilled to realize the landslide body (Fig. 2). Geological logs of boreholes in the region reveal its lithostragraphic units (Fig. 5), which consists of Silurian phyllite, Quaternary colluvium and upper Quaternary-Holocene deposits. The exposed top layer consist of Holocene deposits, which are described as grey to dark grey, consist of slightly moist and loose rubble soil and extend from 8.0 to 13.5 m. Quaternary colluvium beneath the deposits layer is grey to yellow, humid and dense stony soil. The thickness of the colluvium ranges from 9.5 to 18.0 m. The underlying stratum is silicon phyllite belonging to the Silurian-Maoxian Group. Geological boring reveals the lithologic sequences of the silicon phyllite: a lightly weathered layer underneath, then a medium-weathered layer and the overlying heavily weathered layer (Fig. 5). The lightly weathered layer consists mainly of micro-crack, thick-block hard phyllite with a little mud filling in the microcracks. However, the medium-weathered layer is dense and fractured, and the overlying heavily weathered layer is highly fractured and soft. The Quaternary layer and the heavily weathered phyllite make contact so as to form a lithofacies interface that constitutes a slippery interface easily prone to sliding. The geological drilling reveals obviously orientated scrapes at the contacts in the boreholes, except for CZK6.

In addition, CZK1 indicates that there is olivary gravel interbeded between the stony soil and the phyllite. This gravel consists of the river sediment material, with some cobbles (Fig. 5).

(3) Slope cutting is unavoidable in road reconstruction, but it simultaneously causes landsliding. The only road, G213 Roadway, which wanders along the Minjiang River bank in the highland-gorge zone, is an important transportation line in Northwest Sichuan and also the golden travel route from Chengdu, the capital of Sichuan Province, to the scenic area of Jiuzhaigou. It was rebuilt from 1994 to

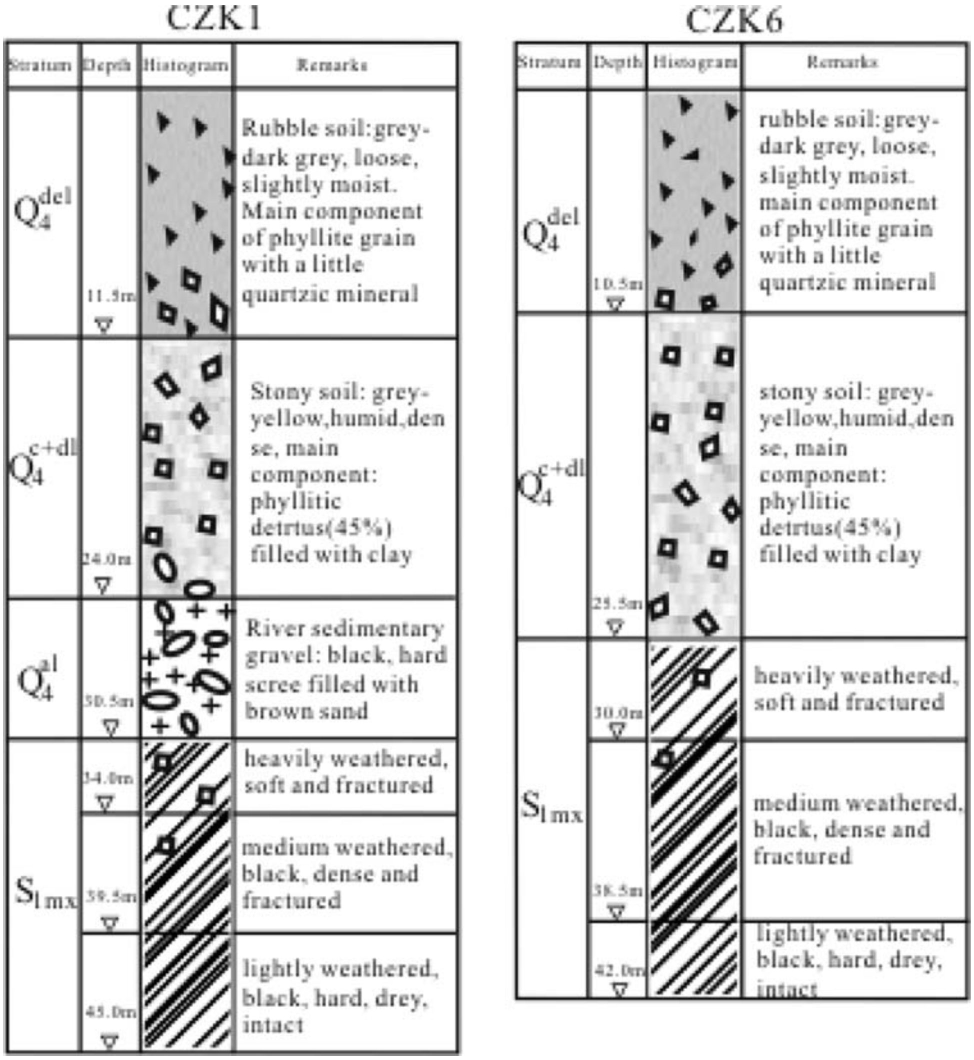


Fig. 5 Borehole column of the landslide area: CZK1 at the slope toe and CZK6 outside the landslide (see Fig. 4). The similar others boreholes are unlisted

2001, during which the natural slope was cut to meet engineering requirements; and this resulted in extensive damage to the slope. The archaic landslide had already been creeping downward, and the Xiaozongqu landslide began obviously to slide ever since the rebuilding of the roadway.

Kinematic behaviour before remediation

In autumn 2000, the archaic landslide reactivated. Since then, it experienced slow acceleration with various movement rates. From September to November 2002, the landslide speeded up and impelled the inboard retaining wall, causing it to fracture seriously so that the road surface rapidly sank. Geodetic monitoring indicates that the vertical sinkage reached 1.2 m and the horizontal slippage was 0.9 m from September 2002 to May 2003. From temporary monitoring results, the average movement rate of the landslide was 28 mm/day and the maximum up to 32 mm/day. Due to the extensive deformation and the rapid sliding, the landslide was on the verge of declining wholly so as to damage the roadway and demolish the traffic at any moment. Granted that the subsequent months are the golden tour season along the route, government officials, experts and geologists attached great importance to the potential danger. Wang et al. were invited to investigate the landslide many times and suggested immediate remediation.

In landslide repair, it is vital to forecast the slide trend in order to determine the limits of the remediation period. This is especially the case for a rapid sliding landslide. How can the safety thresholds of such a rapidly sliding landslide be judged according to field data? Wang (2005) has proposed the parameters of three safety thresholds for the present talus landslide based on analysis of similar landslides. He stressed that these parameters are vital for identifying the characteristics of the landslide and grasping the proper opportunity for remediation. These safety thresholds are as follows:

1. Maximum accumulative horizontal displacement ($D_{\max}$): Once the cumulative horizontal displacement exceeds $D_{\max}$, which is about 1.4 m, a landslide hazard will occur. Up to May 2003, the horizontal slippage of the landslide was approximately 1.0 m less than $D_{\max}$.
2. Maximum daily average velocity ($v_{\max}$): Wang suggests that the threshold value of $v_{\max}$ is approximately 40 mm/d. Up to May 2003, the daily average velocity of the Xiaozongqu landslide reached 32 mm/d, less than $v_{\max}$.
3. Maximum average acceleration ($a_{\max}$): The value of $a_{\max}$ is 0.15–0.20 mm/h^2. Once the acceleration of a rapid sliding landslide exceeds $a_{\max}$, a calamity will occur. The average acceleration of the Xiaozongqu landslide was 0.11 mm/h^2, less than $a_{\max}$.

All three of these kinematic parameters are lower than the threshold values, so there was sufficient time for landslide remediation.

Landslide remediation

Remediation measures are aimed at halting or mitigating the destabilizing process through engineering intervention (Leynes et al. 2005). The basic methods include: (1) reducing the driving forces at the head of the slide, (2) increasing the resisting forces, and (3) reducing hydrostatic pressures (Martens 2007). In the case of the Xiaozongqu landslide, several points needed to be considered in the remediation process. Firstly, the rapid slide had to be controlled in short order. Secondly, the roadsides and the rear margin of the slide were the main focus of the remediation. Finally, the erosion of the Minjiang River at the slope toe and the water influx had to be eliminated and environmentally friendly repairs made to match the travel route.

Immediate repairs were carried out in two phases from November 2002 to October 2003 to stabilize the landslide and to protect the G213 Roadway. The first phase repairs were undertaken to stabilize the landslide and ensure the roadway safety by means of prestressed concrete frames along both sides of the road and at the top of the landslide that could increase forces of resistance. The second phase repairs provided additional protection against the possible failure of remaining parts of the landslide by means of a retaining wall, anchored piles, prestressed anchors and revegetation.

First phase repairs

In order to control the rapid sliding and ensure road safety as soon as possible, two rows of the prestressed concrete frames were set along both sides of the roadway (Figs. 2, 4). A weak-anchoring technique was adopted. By that, we mean a process of setting the cables without fixing the loads to avoid local grout breakage and allow for temporary slope deformation. By means of weak-anchored cables,the active slope was lenitively anchored on the underlying stable bedrock. The loads were then fixed in succession onto the anchor. The prestressed cables provided positive resistance to the slope body while increasing the strength of the slope mass. The concrete framework was constructed seven days after the cables were weak-anchored. It was constructed so as to prevent the failure of the shallow slope. The prestressed cables integrated with the concrete framework to form a composite anti-sliding and anchoring system. Figure 2 shows the prestressed anchor engineering in the landslide.

At the rear margin, the crown scrap of the Xiaozongqu landslide was so high as to be disadvantageous to landslide stabilization. So a raw framework of prestressed cables was set near the main scrap of the landslide (Figs. 2, 4). The purpose was to resist further failure of the rear and stabilize the overall slope.

Second phase repairs

The aim of the second phase repairs was to complete the engineering project, including the formation of a retaining wall for the toe, anchored piles, draining trench and revegetation.

As one of the triggering factors of the landslide, river erosion could lead to toe failure and produce an oversteepened toe. So, a raw retaining wall was built to protect against river erosion and provided more support for the slope toe (Figs. 2, 4). The masonry retaining wall consisted of 24 blocks of concrete slip-stone, with a surface slope of 1H:5V. Because of river erosion, the retaining wall could not be permanent; and its failure would induce a new movement or a larger slide. So it needed to be reconstructed whenever it failed. The influxing water tended to worsen the landslide, moreover; so it had to be drained away. A trench around the landslide was dug to change or cut off the influx path and thus reduce water infiltration (Fig. 2).

For a deep sliding landslide, the use of anchored pile is reasonable in constraining the landslide deformation and is widely applied to landslide remediation (Gui 2005; Fang et al. 2007). In the present study, anchored piles were applied to stabilize the landslide and protect the roadbed outside the G213 Roadway, especially where the sliding surface was deep and force large. Prestressed cables were affixed to the top of the anti-slide piles to form the anchored piles. As the prestressed loads of the cables draw the pile together, the composite system can restrict the landslide deformation. A raw of anchored piles was constructed outside the roadway, with the space between two piles being 6.0 m (Fig. 2). In addition, some individual cables were anchored along the extension line of the anchored piles.

During the remedial periods, the roadside cuts and fills and head of the landslide were the most visible areas of drastically disturbed portions of the slide. In those areas, revegetation was needed to improve the appearance and protect the soil on the roadsides. The revegetation involved soil rebuilding, autochthonic grasses and woods replanting; and it created an environmentally friendly landscape matching the travel route (Fig. 3).

Landslide monitoring

Monitoring scheme

Monitoring technique is an important aspect in the study of landslide movement (Kwong et al. 2004; Bogaard et al. 2000). Through reliable monitoring instruments and systemic processes, the kinematic behaviour of a slide at different stages can be obtained. Monitoring also provides useful data for the back analysis of remedial engineering. There are numerous indexes for landslide monitoring, such as displacement, underground water, earth physical and meteorological factors, all using different techniques (Zhou 2004). One of the major obstacles of others techniques is obtaining subsurface information within the landslide body except inclinometer monitoring. Undoubtedly, inclinometer monitoring is the most straightforward and effective measure to understand landslide activity, including the position of the rupture surface, the displacement of the ground surface and subsurface and movement trends.

Fig. 6 Photograph of field monitoring

In the present instance, six boreholes were chosen for seeking subsurface information bu means of inclinometer monitoring: CZK1, CZK3, CZK4 and CZK6 are located on the I–I profile (Fig. 4) and CZK2 and CZK5 on the III-III profile (Fig. 2). CZK1 and CZK2 are located at the toe of the slope, and CZK3 is at the inboard of the G213 Roadway. CZK4, CZK5 are on the middle of the slope, where the main transitional zones of deformation are located. CZK6, however, was installed outside the scarp to determine whether there is further instability there.

A SINCO Inclinometer (Inclinometer Probe: 50302510) was applied to detect zones of movement and the evolving spatial and temporal movement (Fig. 6). The monitoring in this study had three aims: (1) to determine the kinematic variations in the progress of engineering construction and post-remediation, (2) to investigate tridimensional features of the slide and determine the amount of sliding surface and its depths, and (3) to analyze the potential influence of the landslide on the roadway and carry out the back analysis of the remedial engineering.

The initial monitoring began on 18 June, 2003. Five of the six boreholes were used for 4.5 years until the end of 2007. The other hole, CZK1, was destroyed in July 2005 (Table 1). The inclinometer was read nine times in 2003, twelve times in 2004, seven times in 2005, six times in 2006 and six times in 2007 (Table 2).

Monitoring analysis

Monitoring results from the slope inclinometer are shown in Table 2. The spatial and temporal movements of the landslide under remedial engineering as well as obvious surface ruptures are recorded in the table.

Table 1 Information of monitoring boreholes

Borehole number	Borehole diameter (mm)	Designed depth (m)	Monitoring depth (m)	Monitoring time
CZK1	146.0	43.0	44.0	2003.6–2005.7 (destroyed)
CZK2	146.0	43.0	41.0	2003.6–2007.12
CZK3	146.0	43.0	41.5	2003.6–2007.12
CZK4	146.0	38.0	30.0	2003.6–2007.12
CZK5	146.0	40.0	44.5	2003.6–2007.12
CZK6	146.0	40.0	41.5	2003.6–2007.12

Table 2 Monitoring results of all boreholes from 18 June 2003 to 13 December 2007 (CZK1 destroyed after 12 July 2005)

Time	CZK1		CZK2		CZK3		CZK4		CZK5		CZK6
	Ground surface (mm)	Rupture surface (2.0 m) (mm)	Ground surface (mm)	Rupture surface (5.0 m) (mm)	Ground surface (mm)	Rupture surface (5.0 m) (mm)	Ground surface (mm)	Rupture surface (5.5 m) (mm)	Ground surface (mm)	Rupture surface (2.5 m) (mm)	Ground surface (mm)
2003.6.18	0	0	0	0	0	0	0	0	0	0	0
2003.7.3	3	3	4	5	3	4	0	0	0	0	3
2003.7.18	115	65	7	8	5	8	19	16	0	0	6
2003.8.1	123	71	38	40	8	11	8	7	3	3	11
2003.8.15	129	73	46	60	14	15	13	12	12	10	7
2003.10.8	141	84	72	89	30	32	21	20	21	15	4
2003.10.25	140	83	75	92	29	31	32	30	21	15	15
2003.11.10	138	85	79	96	27	29	31	29	28	21	14
2003.11.29	139	81	83	94	30	33	31	29	29	20	7
2004.1.13	168	95	93	105	30	33	39	38	36	27	3
2004.2.20	187	108	92	106	34	37	49	48	43	33	2
2004.4.20	197	108	91	102	35	39	51	50	40	29	15
2004.5.26	188	101	96	107	39	42	62	61	47	35	18
2004.7.8	193	106	103	113	42	46	66	65	52	39	12
2004.8.7	196	108	106	116	45	49	67	65	54	40	9
2004.9.3	204	115	109	119	46	51	71	69	57	43	10
2004.9.28	204	116	111	121	49	54	68	66	55	41	10
2004.10.14	211	122	111	121	54	59	69	67	51	37	16
2004.11.7	210	121	111	122	50	55	75	73	61	47	7
2004.11.26	211	121	114	125	51	56	75	74	58	43	14
2004.12.14	212	123	117	129	54	59	76	74	67	53	1
2005.1.13	211	123	112	123	53	59	78	76	74	57	17
2005.3.13	212	123	115	126	56	62	83	82	71	55	15
2005.5.19	212	123	113	125	59	65	103	101	73	58	5
2005.6.16	215	125	111	123	55	60	100	99	75	60	8
2005.7.12	213	123	111	122	57	62	103	102	76	60	20
2005.9.21			116	128	67	72	112	109	75	59	20
2005.12.15			120	131	64	71	114	112	71	55	20
2006.2.19			121	134	67	73	115	111	72	55	20
2006.4.12			115	128	67	72	111	108	68	52	19
2006.6.15			115	129	65	72	114	113	70	53	20
2006.8.13			115	131	67	75	117	118	71	55	16
2006.10.17			120	133	69	76	120	118	73	57	16
2006.12.20			121	133	72	79	122	119	74	60	17
2007.3.20			120	132	74	91	125	118	75	61	15
2007.5.22			122	133	76	83	124	121	76	63	16
2007.7.20			123	135	78	84	126	122	79	64	17
2007.8.25			125	136	76	84	128	124	80	66	20
2007.10.18			122	135	74	82	125	124	77	64	19
2007.12.13			123	135	71	79	125	122	76	63	20

As previously mentioned, before remediation, the displacement of the landslide manifested extraordinarily rapid movement. After remediation, however, as was expected, the movement rates gradually became lower and lower. From the monitoring results, it was found that the landslide experienced three slide stages after remediation: a rapid slide in 2003 and 2004, a slower one in 2005 and relatively stability in 2006 and 2007 (Fig. 7). The average movement rate in 2003 was as high as 11.4 mm/m, but it was only 3.4 mm/m in 2004, 1.1 mm/m in 2005, 0.6 mm/m in 2006 and lower than 0.2 mm/m in 2007. This means that the slide gradually stabilized. The displacement increment of each year, as shown in Fig. 8, reveals the kinematic variation of the landslide after remediation. The movement data indicate that the landslide trended to quiet down.

In general, the deformation of different sites on the slope is inconsistent with a rotational landslide. The displacements and movement rates differ for different boreholes (Fig. 8). The displacement of the fore position was found to be larger than that of the rear margin of the landslide at the initial stage (Wang 2005), but the inverse became true after 2005. The movement rates of CZK3 and CZK4 were larger than those of the CZK2 in 2005 and 2006, and the slide rate of all boreholes became miniscule, thus manifesting a consistent lowering trend. As revealed in of CZK6, which is outside the main scarp, the portion of the slide there is an impregnable zone, where the displacement and slide rate of CZK6 have been lower since 2003. At present, there is no further failure in this area. As for CZK3, which is adjacent to the roadway, the movement rate has been very low since 2005. This shows that remedial measures along the both sides have provided dependable support for the G213 Roadway.

The subsurface displacement of the landslide was obtained by analysis of the serial monitoring data. The inclinometer results reveal that the major movement occurred on shallow rupture surfaces (Fig. 9), whose positions are shown in Table 2.

The subsurface deformation of the landslide is characterized by small displacement in the deep zone and a larger displacement in the shallow zone. As determined from the full depth of boreholes CZK3 and CZK4 (Fig. 9), it is

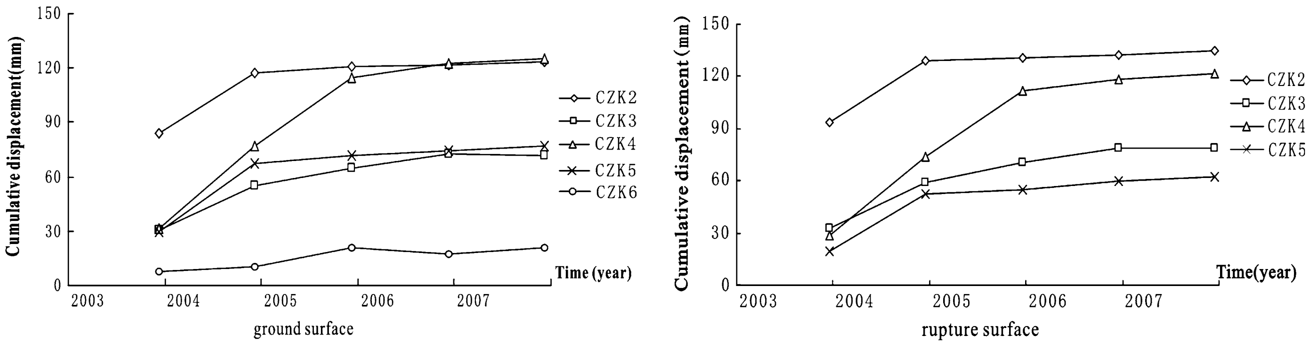


Fig. 7 Cumulative displacement of the ground surface and rupture surface

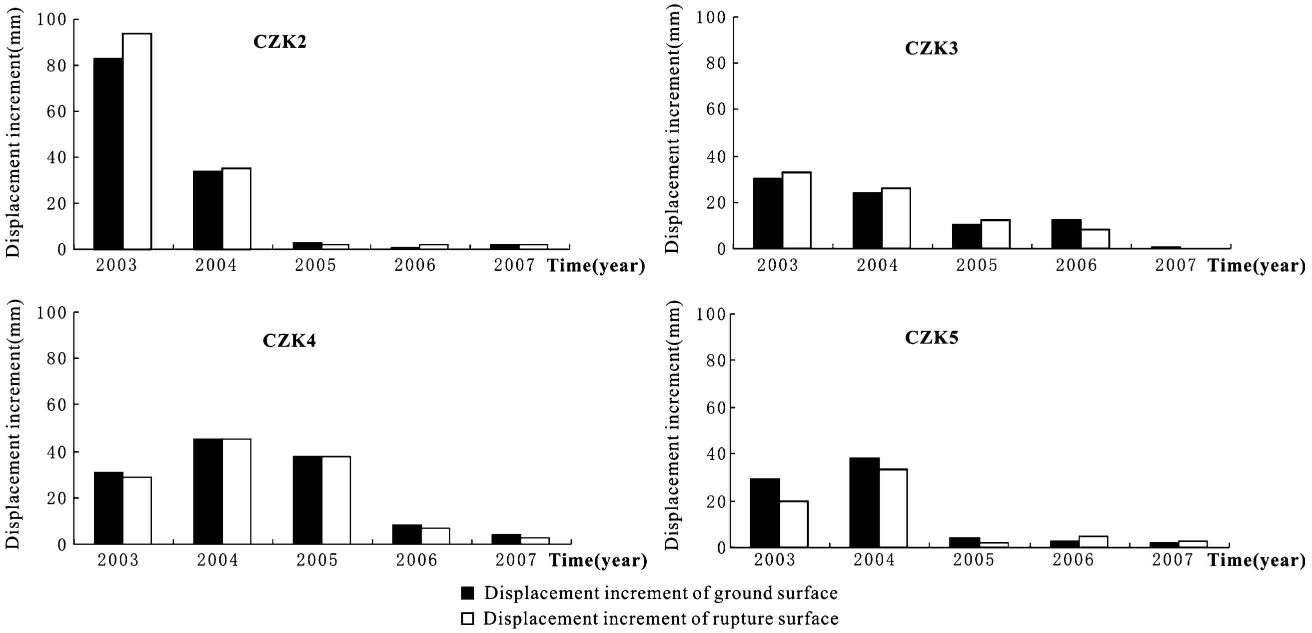


Fig. 8 Displacement increment of the ground surface and rupture surface

evident that the monitoring displacements declined sharply on the rupture surface, where they closely represent the deformation of the ground surface (Table 2). Below the rupture surfaces, the deformation is small. In the case of a landslide under remediation, once the prestressed cables work well, they lock the landslide stably onto the bedrock so that the deep rupture will close up soon. In this study, however, there exists no additional slope surface protection except for the concrete frameworks, so partial failure tended to occur along the shallow ruptures, especially in the transitional zones of the middle section. Shallow failure is very common in mountainous areas and is likely to be a hazard. Xie et al. (2004) point out that rainfall-induced shallow landslide is a major hazard in mountainous terrain.

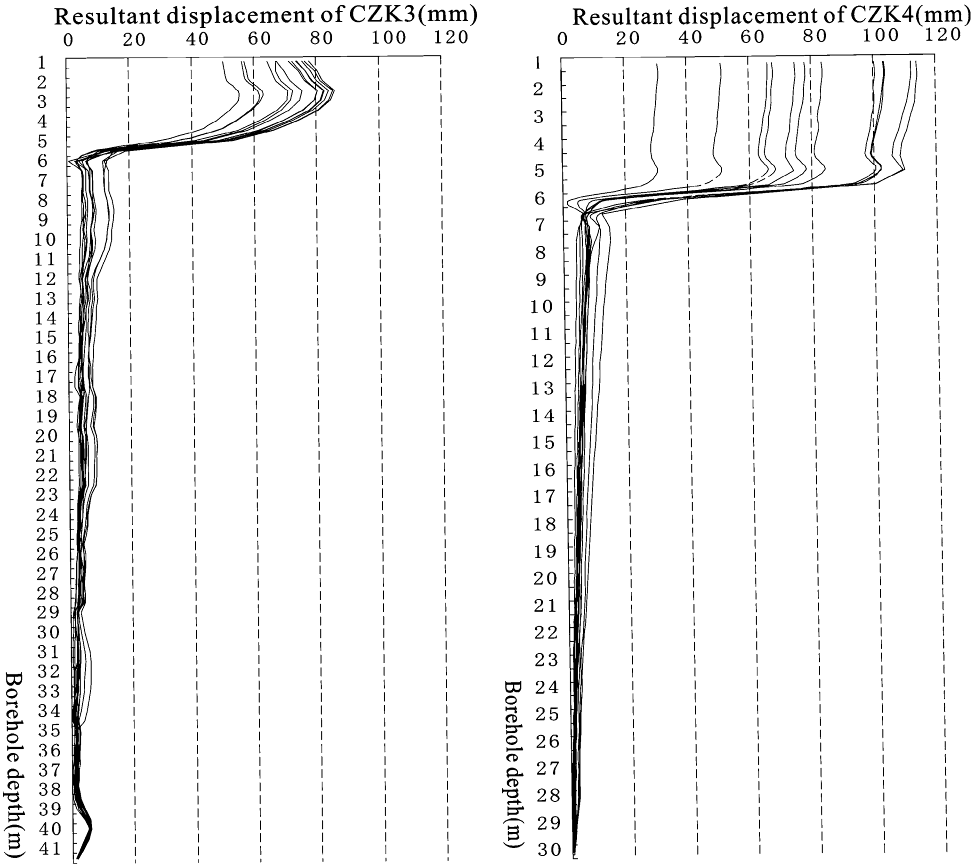
In conclusion, the monitoring results of the Xiaozongqu landslide are consistent with expected variations. The kinematic behaviour of the landslide has tended to become stable in line with the remedial measures. These measures have clearly stabilized the landslide and had a positive effect on restricting its movement. At the same time, the monitoring indicates hysteresis effect on the landslide. That is, the landslide promises to remain stable for 2–3 years after remediation, unless extraordinary geological disturbances occur.

Discussion and conclusions

The study area, the upriver Minjiang River valley in Northwest Sichuan, Southwest China, has been recognized as a frequent landslide area. The road traversing its banks has always suffered from landslides both during construction periods and afterwards. After the rebuilding of the G213 Roadway in this section, the Xiaozongqu landslide reactivated due to the combined action of landslide terrain, river erosion, road cutting, slope geometry and mass properties. At first, in the autumn of 2002, it experienced low, rapid sliding with the maximum movement rate of 32 mm/d. The rapid slide seriously threatened and threatened to the Minjiang River to dam up. To stabilize the landslide and eliminate damage to the roadway and river, remedying and monitoring the landslide became crucial.

Three safety thresholds have been proposed to determine the kinematic features of a slide before remediation. The kinematic parameters of the Xiaozongqu landslide were all lower than the proposed threshold values, which indicated that there was sufficient time for landslide remediation. The roadway was the immediate object threatened by the slide. The roadsides and rear margin of the landslide were the prime focus of remediation.

Fig. 9 Inclinometer graph of subsurface displacement versus depth of CZK3 and CZK4



Considering the rapid movement of the Xiaozongqu landslide, remediation was carried out in two phases. The first phase consisted of the immediate prestressed concrete frames along both sides of G213 Roadway and at the top of the slide. The second involved adding a retaining wall, installing the anchored pile and prestressed anchor and insuring revegetation, all to provide additional protection.

The typical time versus displacement curve of a landslide entails three development stages: initial stage, linear stage and accelerating stage, with the slide always occurring at the accelerating stage (Wei et al. 2006). By autumn 2002, the Xiaozongqu landslide reached such a stage of acceleration so as nearly to become a hazard. This paper discusses whether this landslide has been effectively controlled by the described remedial measures and how its kinematic behaviour has varied under remediation. Subsurface displacement monitoring was used as a straightforward and effective technique for studying the slide movement, for obtaining temporal and spatial information concerning the ground surface and subsurface body, for carrying out back analysis of the remedial engineering, and for assessing the potential influence of the landslide on the roadway.

The inclinometer monitoring data reveal that the rapid slide of the Xiaozongqu landslide was controlled effectively by the remedial measures so that the landslide gradually quieted down. They also reveal hysteresis on the landslide and thus the landslide will become stable gradually 2–3 years after remediation. Accordingly, the movement rate of the slide was high in 2003 (11.4 mm/m) and 2004, but it became slower and slower from 2005 to 2007, reaching a mere 0.2 mm/m in 2007. Remedial engineering thus played an important role in stabilizing the landslide. Up to now, the area of special concern-the roadway, its two sides and the rear margin of the landslide-have remained stable owing to the dependable support provided by the remedial measures.

The characteristic of the subsurface displacement illuminates that the deeper displacement has responded conformably to the effective remedial measures. The main movement occurs only on the shallow rupture surface. The slide has thus performed well under remediation. It even survived the catastrophic Wenchuan Earthquake of 12 May 2008. Although there are partial shallow failures still existing, the previous shallow failures have not yet damaged the roadway. Nonetheless, it is necessary to undertake further measures for slope surface protections, such as hydroseeding, sprayed concrete and reinforced concrete grid (Kwong et al. 2004).

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