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Recent advances in high slope reinforcement in China: Case studies

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ABSTRACT

This paper reviews a number of engineering technologies and workmanships for addressing the challenging issues concerning possible landslides in large-scale slope reinforcement projects in China. It includes: (1) the multi-point anchored piles with a depth of 64 m in the Jietai Temple rehabilitation project, (2) soil nailing strengthened by driven pipe grouting technique covering an area of 530 m × 100 m (length × height) in the Xiluodu hydropower project, (3) the cantilever piles extending vertically from the slope toe to stabilize a 300 m high slope at the Xiaowan hydropower station, (4) a new and simple workmanship for building a pile with cross-sectional area of 20 m × 5 m in the Hongjiadu hydropower station, and (5) comprehensive reinforcement scheme proposed for excavation of a 530 m high slope in Jinping I hydropower station. These new technologies can provide valuable experiences for reinforcement of high slopes of similar projects in China and other regions and countries with similar geological conditions.
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1. Introduction

Reinforcement of slope is a commonly used method to ensure the stability and safety of engineering slopes involved in mining, highway, railway and hydropower projects. The widely used slope reinforcement measures include drainage, cables, slope stabilizing piles, and soil works such as unloading at the slope crest and buttress at the toe (Duncan and Wright, 2005). As high cost in a reinforcement work can normally be reported, drainage is always considered to be the first choice due to its effectiveness in stabilizing slope associated with relatively low cost. Typical examples can be referred to as the giant Downie slide (Imrie et al., 1992). For large-scale slopes in civil and mining projects, some high-performance mechanical stabilizing approaches are basically considered, such as cables, soil nailing, and piles. General review on various technical problems related to ground anchorage can be found in Littlejohn (1992) and Barley and Windsor (2000). Retaining piles have been widely used for slope reinforcement in China, but their applications are limited in developed countries due to heavy manual work by labors in very crucial environments. Basically, construction of this kind of piles is roughly limited to 50 m in depth and a cross-sectional area of 4 m × 4 m approximately.

Some infrastructure projects in China involved in water resources, railway and highway engineering are large- to super large-scale, which are challenging problems in terms of landslides. In this circumstance, a number of new reinforcement technologies and workmanships mostly related to anchors and anti-sliding piles have been developed practically (Chen et al., 2005). These new technical methods have been marked as great advances in reinforcement of large-scale slopes. It is noticed that these new methods have been proposed for the reinforcement of different types of slopes associated with site scope of application. When conducting a slope reinforcement design, the following factors should be considered: (1) selection of reinforcement method corresponding to the failure mechanism of slopes; (2) layout of reinforcement measures in slopes

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Fig. 1. Landslide in Jietai Temple.

and practicability of construction technology used; (3) deformation and stability evaluations of reinforced slopes; and (4) monitoring and evaluation of reinforcement effects.

This paper presents those innovative reinforcement technologies used in five large-scale slope projects at present in China. After implementation of the reinforcement measures, the monitoring results indicate that the reinforced slopes are stable and safe. These new technologies provide valuable experiences for reinforcement of high slopes or landslides of similar projects.

2. Jietai Temple landslide: The deepest multi-point anchored stabilizing piles reinforcement

2.1. Outline

Jietai Temple was built in Kaihuang Administration in Sui Dynasty (A.D. 581) on the north foot of Ma'an Mountain in the west of Beijing, which has a history of over 1400 years. The Jietai Ordination Altar in the Temple, a national cultural relic, is the largest Buddhist Temple in China. It confers the highest commandment of Buddhism in history. The ridge of the mountain is 1200 m long from south to north and averagely 450 m wide from west to east. As a result of southward mining by 2 coal dykes at the depths of 122 m and 175 m in recent years, an opening was observed beneath the fourth level of the terrain. After a heavy rainfall on 20 July 2004, a penetrating fractured zone was formed in the temple yard on the ridge. Cracks were also observed in the yard of the temple, resulting in a rapid development of slope deformation, as shown in Fig. 1. Fig. 2 shows the damage of the buildings in Jietai Temple after landslide.

Investigation (Li and Yang, 2006) showed that there was a 230 m difference in elevation between the front and the tail borders of the landslide. The depth of the sliding surface was up to 47 m, and the total volume of the sliding mass was 9.2×10^6 m^3. Field investigation showed complicated geological conditions of the landslide. The major buildings in Jietai Temple are located on the landslide mass, which is in the tourist area heavily covered by plants. Therefore, massive earthwork construction was not suitable for the landslide reinforcement. In this case, slope stabilizing piles may be the first choice of available treatment measures. However, the depth of the sliding surface reaches over 40 m. To address this problem, a system of multi-point anchored slope stabilizing piles (Wang and Sun, 2007) was developed by Northwest Research Institute Co., Ltd., China Railway Engineering Corporation. In this system, the deepest pile reaches 64 m.

2.2. Reinforcement scheme

2.2.1. Multi-point anchored slope stabilizing piles

Fig. 3 shows the plan view of Jietai Temple landslide reinforcement scheme. For this project, the key in the reinforcement scheme using multi-point anchored slope stabilizing piles is the excavation of slope stabilizing piles with multiple anchors at different depths

(a) Cracked brick wall. (b) Hallowed ground.

(c) Leaned retaining wall. (d) Separated hallway.

Fig. 2. Damage in Jietai Temple after landslide.

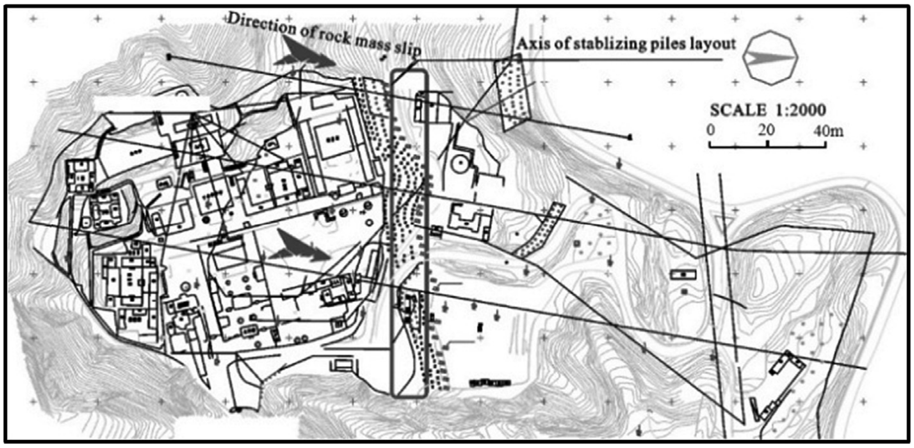


Fig. 3. Plan view of Jietai Temple landslide reinforcement.

Table 1
Anchors in slope stabilizing piles.

Section number	Slope stabilizing pile				Anchor cable			
	Number	Length (m)	Cross-sectional area (m × m)	Wall thickness (m)	Pile row	Slope row	Depth (m)	Length (m)
1	17	55	2 × 3	0.2	2	3	52	62
2	10	64	2.4 × 3.6	0.25	3	5	64	67
3	9	52	2.4 × 3.6	0.25	3	5	54	60

of piles, among which the maximum pile depth is 64 m as mentioned in Section 2.1. Four locations on the side and middle of the landslide were chosen to set the reinforcing piles. One hundred and nine anchors were arranged with a total drilling depth of 5942.4 m. Table 1 shows the layout of anchors in slope stabilizing piles (Wang, 2009).

Fig. 4 shows the multi-point anchored slope stabilizing piles. During the excavation of the vertical holes, drillers were placed inside the well, and pre-stressed anchors were installed along the piles. The dust collectors developed to reduce the raised dust during construction were proved to be very effective (see Fig. 5).

2.2.2. Bottom drainage holes

A tank was used below the bottom of slope stabilizing piles, and water pumps were employed to drain the water from deep soils, as shown in Fig. 6. Then, the pumped water from the tank can supply daily use and greening of the temple. This is an effective use of

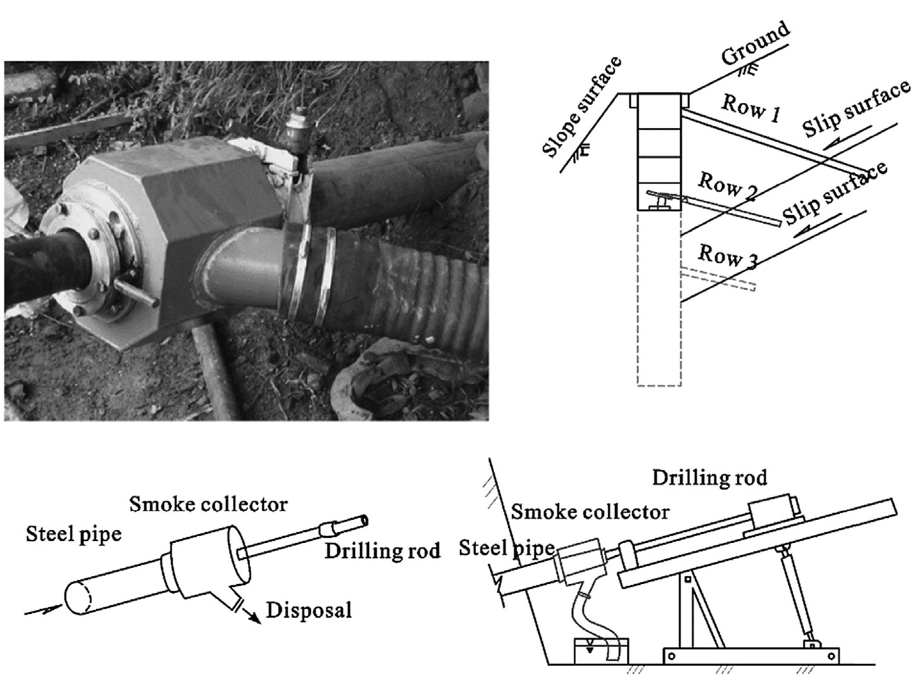


Fig. 4. Multi-point anchored slope stabilizing piles.

Fig. 5. Effect of dust reduction: (a) without dust collectors, and (b) with dust collectors.

Fig. 6. Bottom drainage hole.

water resources as well as the long-term maintenance of this drainage system.

2.3. Effectiveness of landslide reinforcement

Fig. 7 shows the observed surface displacement of Jietai Temple landslide. It can be seen from this figure that the deformation of Jietai Temple landslide tended to convergence after the implementation of reinforcement measures. This indicates that the new reinforcement technology is effective in protection of this Buddhist shrine.

3. Xiluodu hydropower station: The largest-scale soil nailing reinforcement

3.1. Outline

During the construction of Xiluodu hydropower station, a fossil landslide was observed on the left bank above the intake. The deposit from the bottom to the top consists of ancient landslide debris, glacier, accumulation body of ice and water, diluvia soil and slope collapse soil. The landslide is about 530 m along the axis of the Yangtze River, and its height ranges between 740 m and 840 m. This ancient landslide debris, 3.6–49 m in thickness, is mainly distributed in the foot of the rock slope, and its main components are purple sandstone, shale, and limestone of Tongjiezi Group. Its secondary components are sandstone of Feixianguan Group and marl fragments of Jialing River Group. Drilling holes show that the thickness of the main sliding belt ranges from 0.19 m to 3.25 m at the front edge, and from 1.32 m to 1.55 m at the tail edge. The sliding belt is composed of gray aluminous clay rock of Xuanwei Group and chartreuse muddy silt.

3.2. Reinforcement scheme

A technology using grouting and anchor pipe is developed by Sino-Hydro Engineering Bureau No. 4 Co., Ltd., to guarantee the stability of the slope. Soil nailing commonly used in soil slope

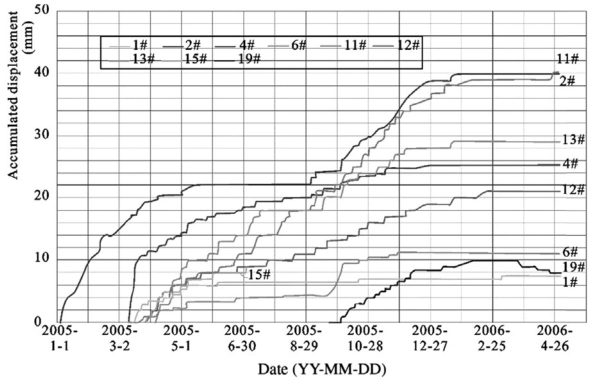


Fig. 7. Surface displacements of Jietai Temple landslide.

reinforcement includes drilling, bonding, and grouting. Xiluodu hydropower project uses striking anchor pipes (Xu et al., 2013). To eliminate the disturbance to soil hammering process, grouting is applied after penetration of the pipe, a new type of hybrid soil nailing technology.

The supported area in this project is divided into five zones (Fig. 8). The scope of reinforcement is 530 m along the river flow direction, and the drop in elevation is 100 m, which is the largest reinforcement area of soil nailing works to date in China. The typical section of the reinforced slope is illustrated in Fig. 9. Pilot production is used to determine the material of the anchor pipes, concentration of grouting mortar, grouting pressure and related parameters of the soil anchor pipes (Fig. 10). The main parameters were determined as follows:

(1) The soil anchor pipes is 6 m in length, 48 mm in diameter, and 3.5 mm in thickness, with conical contour guide heads on one end. Grouting holes with a diameter of 10 mm are installed in the middle of anchor pipes, and are drilled along the circumferential direction of the tube with an interval of 10 cm. Grouting holes are protected with triangle steel barbs.
(2) Soil anchor pipes are rammed vertically into the slope 5.85 m underneath the surface at spacing of 1.5 m $\times$ 1.5 m, which are arranged in the shape of quincunx.
(3) Cement paste with water cement ratio of 0.65:1 is grouted into the anchor pipes at a grouting pressure of 0.4 MPa.
(4) If the grouting comes out of the orifice or slope surface, grouting can be stopped. If the grouting cannot be seen from the orifice, and the pressure of grouting reaches 0.4 MPa and no obvious decline in grout intake is observed, then the grouting can also be stopped (Xi, 2009).

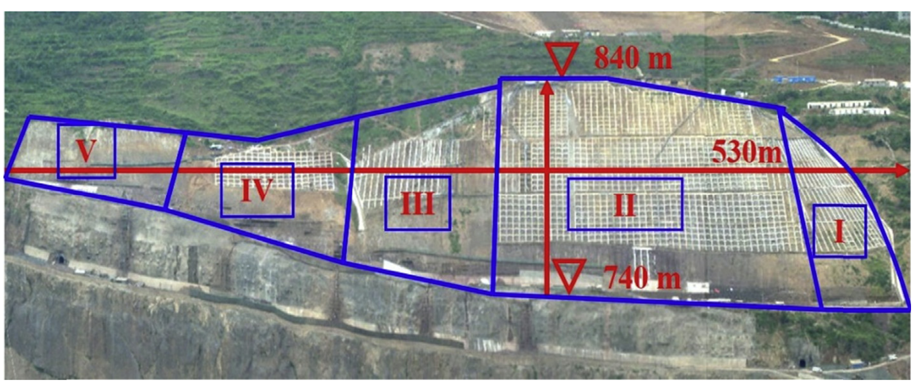


Fig. 8. The alluvium deposit slope at Xiluodu hydropower station.

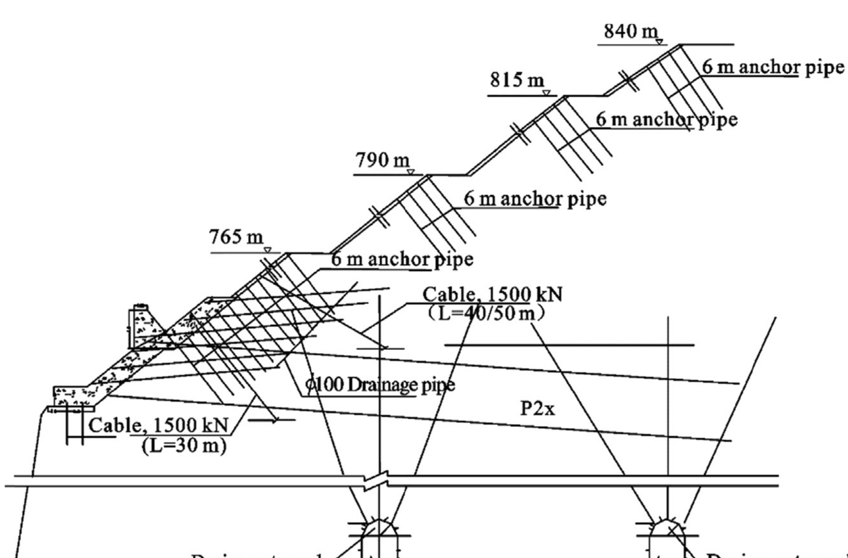


Fig. 9. A typical section of the reinforced slope.

(a) Soil anchor pipes. (b) Construction procedure.

Fig. 10. Construction technology of soil anchor pipes.

3.3. Effectiveness of reinforcement

A total of 18 extensometers were installed in the alluvium mass. Monitoring results show that the maximum cumulative displacement is 125 mm. Significant deformation appeared before September 2006 and in flood seasons, and then the slope was stable (Fig. 11).

4. Xiaowan hydropower station: The highest cantilever slope stabilizing piles

4.1. Outline

Xiaowan hydropower station is located in the middle-lower reach of Lancang River. The project consists of a double-curved arch dam, an underground water diversion, and power generation system. Excavation of the left abutment slope involves a height of about 700 m. The slope ratio is 1:1.3–1:1.5 above the elevation of 1500 m, and 1:1.15–1:1.2 at the elevation of 1500–1380 m. The slope is composed of alluvial deposit body. In December 2003, a remarkable sliding deformation was observed (Liu et al., 2006). The deformation was induced due to slope excavation, blasting, rainfall and low soil material properties. Fig. 12 shows the local failure region during excavation. Fig. 13 shows the monitoring results of an inclinometer at elevation of 1400 m. Combination of all monitoring data indicated that the landslide developed at a rate of 1 mm/d. More information concerning this engineering slope can be found in Zhou (2008).

4.2. Reinforcement scheme

Similar to the case of the Jietai Temple landslide, the depth of the sliding surface of Xiaowan hydropower station is around 60 m. Therefore, it is technically difficult to dig stabilizing piles directly from ground surface. Engineers found that the depth of the sliding surface has been reduced to about 25 m in the low elevation region near the slope toe. Therefore, stabilizing piles were built at the berm at an elevation of 1245 m. These piles were connected to form a wall, and the excavated soil was backfilled behind it. To reduce the cantilever effect, pre-stressed anchorage cables were used in the pipe drilling technology. Eventually, a large cantilever slope stabilizing wall was formed (Zou et al., 2006). Figs. 14 and 15 show the plan view and cross-section of the cantilever slope stabilizing piles.

To prevent borehole collapse in the alluvial, a tube was followed simultaneously with drilling during pre-stressed cable construction. After drilling is completed, the eccentric head allows withdrawing of the rods, as shown in Fig. 16. Subsequent anchoring work can then be preceded. At the end of the anchoring, the steel casing will be pulled out.

The slope stabilizing retaining structure contains ten 3 m × 5 m and five 4 m × 7 m cantilever stabilizing piles, which are installed at the elevation of 1245 m. The depth of the piles in the south is 40 m approximately, and about 40–60 m in the north. Another two-row slope stabilizing piles were arranged at the berm at elevation of 1310 m. Fig. 17 shows the slope stabilizing retaining structure after implementation of stabilizing piles.

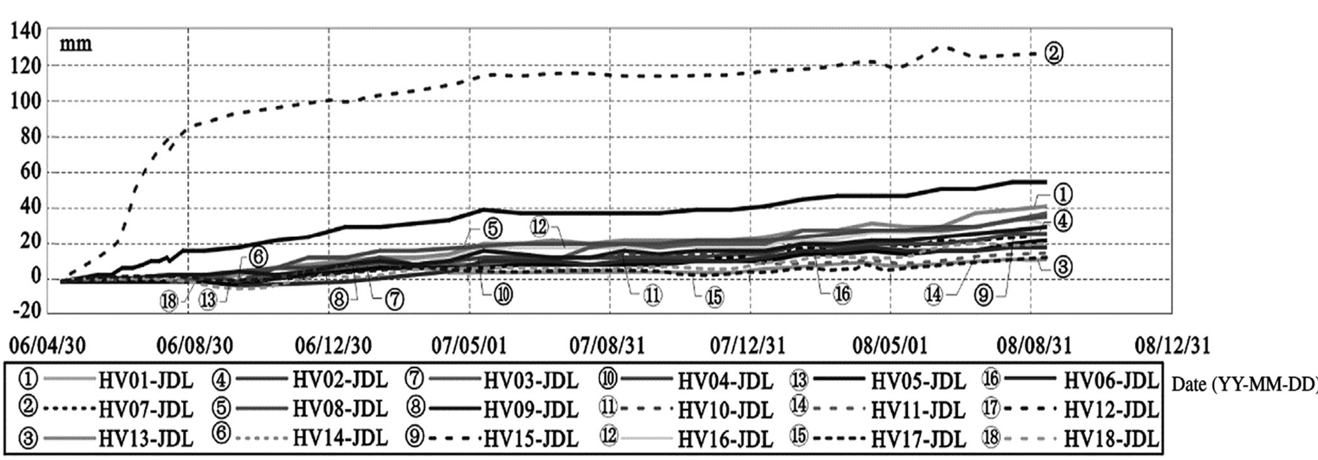


Fig. 11. Displacements of measuring points.

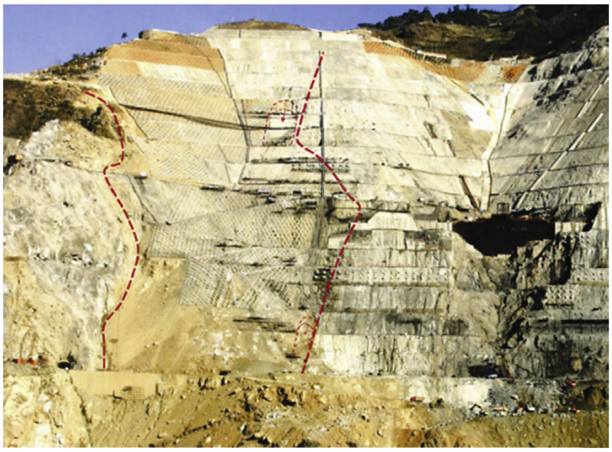


Fig. 12. Crack region of the alluvial deposit slope during excavation.

The deformation of the slope was monitored during the follow-up excavation stages. Monitoring data indicated a stable state achieved after the reinforcement of slope stabilizing piles.

5. Hongjiadu hydropower station: The largest piles used in slope stabilization project

5.1. Outline

Hongjiadu hydropower station is the leading station of the cascade hydropower development on Wujiang River, located in the lower reach of Liuchong River, a tributary of Wujiang River. The project consists of a high rock-fill dam with reinforced concrete face, spillways, flood control drainage, power generation diversion channels, and operation buildings. Due to the layout requirements of the dam and spillway, a 360 m high bedding slope was formed at the left abutment of the dam, as shown in Fig. 18. A key technical issue of construction is the stability of the high rock slope.

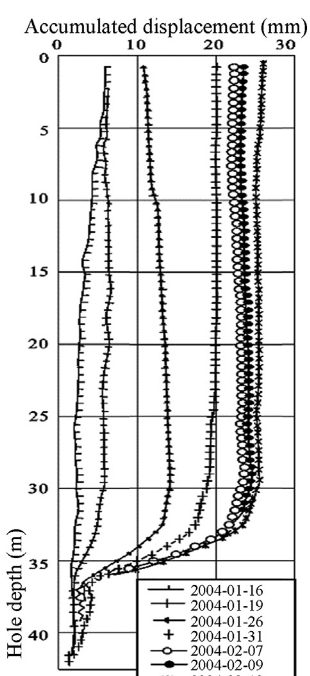


Fig. 13. Monitoring results of an inclinometer at elevation of 1400 m.

5.2. Stability analysis

The left bank intake structures are located at the bottom layer of limestone. Several intercalated layers named J_1–J_8 (Fig. 19) were developed. Landslide would most likely take place during construction. Fig. 20 shows a case of landslide triggered during a road excavation (Deng et al., 2007).

Numerical analysis shows that the factor of safety (FOS) of the intake slope is around 0.8–1 if two-dimensional (2D) limit equilibrium analysis is used. This FOS cannot satisfy safety requirements. In addition, a three-dimensional (3D) limit equilibrium analysis method has been adopted for this slope (Chen et al., 2003).

5.3. Overall stability analysis

As the dip direction of the weak intercalated layer on the left bank is not exactly the same as that of the slope, the layer is bound to cut into the riverbed at a certain altitude (Fig. 19). Obviously, the stability of the slope will be underestimated if 2D limit equilibrium analysis method is adopted to evaluate the stability. Instead, 3D limit equilibrium analysis method is used in which the boundary effects can be considered.

Each intake has been excavated with opening of its own limits (Fig. 21). The stability of the intake slopes at normal situation was evaluated to be a limit state by 2D limit equilibrium analysis. Using 3D limit equilibrium method, the stability of the intake slopes can be significantly increased by 30% (Yang et al., 2008a). It should be noticed that the overall stability of the left bank slope cannot satisfy the requirement of design. Therefore, it is necessary to adopt the reinforcement measures to ensure the overall stability of the slope.

5.4. Reinforcement scheme

As the slope is critically important to the entire project, super large-scale slope stabilizing piles and pre-stressed anchor cables were used to support this slope. Fig. 22 shows the plan view of the high slope at the water inlets. Fig. 23 shows a typical profile of the slope reinforced using ten 20 m × 5 m slope stabilizing piles and 270 pieces of 3000 kN pre-stressed anchors. These piles are so far the largest slope stabilizing piles across the world.

Traditional methods for the excavation of stabilizing piles cannot satisfy the requirements of construction of this slope as there are various technical difficulties remaining unaddressed, such as the difficulties in slag removal, safety of construction, and drainage. To solve these problems, the project team and construction units proposed reversely conducted well blast technology (Yang et al., 2008a,b) with the advantages of quick and safe construction. This is a breakthrough in huge bedding slope reinforcement technology. In this case, the conventional method of lifting muck during excavation using a crane hanging over the workers in the shaft is not adopted. For this innovative technology, the first step is to construct a branch tunnel located at the bottom of the pile for transportation of the slag muck. The second step is to use a geological drilling hole with a small diameter from the top of the surface where the pile is located (see Fig. 24a). A basket is sent from the top to bottom through this hole, so that one person can work in the basket (Fig. 24b). By means of artificial excavation or blasting in the basket, a larger hole with a diameter of 1.5–2 m can be created (Fig. 24b). Next, excavation of the shaft with a cross-sectional areas of 20 m × 4 m is conducted from the bottom to the top (Fig. 24c). The excavated rock fragments are poured down through their own gravity and loaded into a vehicle, which will be transported to the exit through the branch tunnel. The final step includes the conventional concrete works to fill the shaft resulting in a huge pile (Fig. 24d).

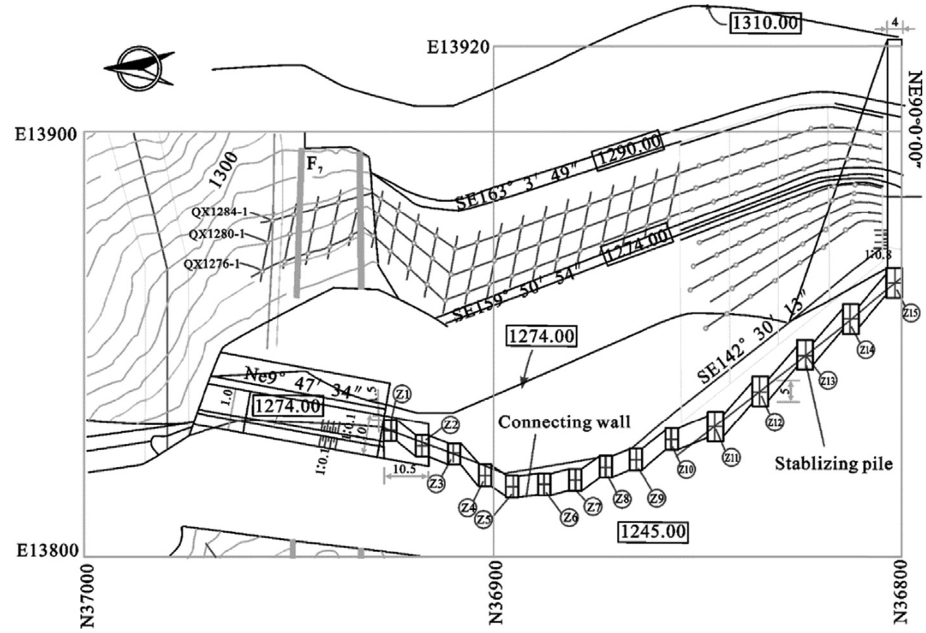


Fig. 14. Plane arrangement of slope stabilizing piles.

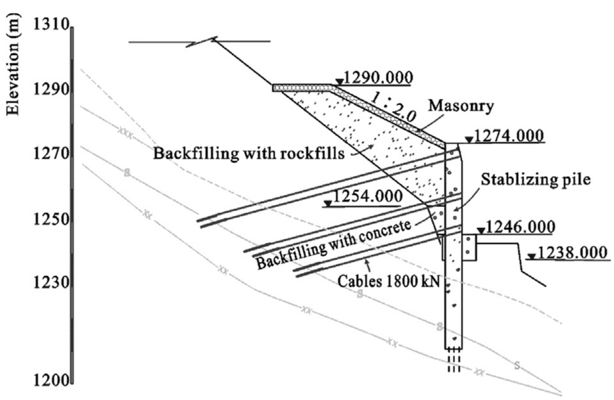


Fig. 15. A typical section of slope stabilizing pile reinforcement.

6. Jinping I hydropower station: The comprehensive reinforcement of a 530 m high rock slope

6.1. Outline

The Jinping I hydropower station is located at the Pusiluogou in the west of Great River Bend of Yalong River, adjacent to Muli and Yanyuan counties in Liangshan Yi Autonomous Region, Sichuan Province, China. The key structure mainly consists of a concrete double-curved arch dam, spillway tunnels, an underground water diversion, and power generation system. The maximum height of

Fig. 16. Tube-drilling technique for installing cables in loose deposit body.

Fig. 17. The slope stabilizing retaining structure.

Fig. 18. Left bank high slope of Hongjiadu hydropower station.

Fig. 20. The bedding landslide occurrence during road excavation.

the arch dam is 305 m, which is the highest dam of its kind at present in the world.

The construction site is characterized by deeply cut valley environments and difficult geological conditions (see Fig. 25). Geological structures, such as bedding planes, fractures, dikes and faults of various scales, are well developed in the left bank slope, which lead to a poor slope stability condition, and even at the natural state (Jiang et al., 2015). For the construction of the arch dam, a volume of rock mass up to 5.5×10^6 m^3 was excavated in the left abutment at elevations of 2110–1580 m, forming an excavated slope up to 530 m high and with a slope varying between 1:0.5 and 1:0.3. Such a large-scale excavation can definitely impose a dramatic disturbance on the slope, which further reduces the stability of the left abutment slope under difficult geological settings. Stabilization of the left abutment slope, therefore, becomes a critical issue for the safe construction of the dam and the success of the hydropower project.

Fig. 21. Excavation of the portals on the left bank.

6.2. Reinforcement scheme

Geological survey and exploration on site showed a large number of small faults and joints developed in the shallow and surface rock masses of the high slope. As slope excavation continued, the spatial intersections of these discontinuities may form a series of potentially instable blocks. To improve the stability of the potentially instable blocks, rock bolts, pre-stressed cables, frame lattice beams and pre-consolidation grouting were used to reinforce the shallow and surface rock masses of the slope. Calculation results of limit equilibrium analysis show that pre-stressed cables of 2000 kN grade should be used and installed with a

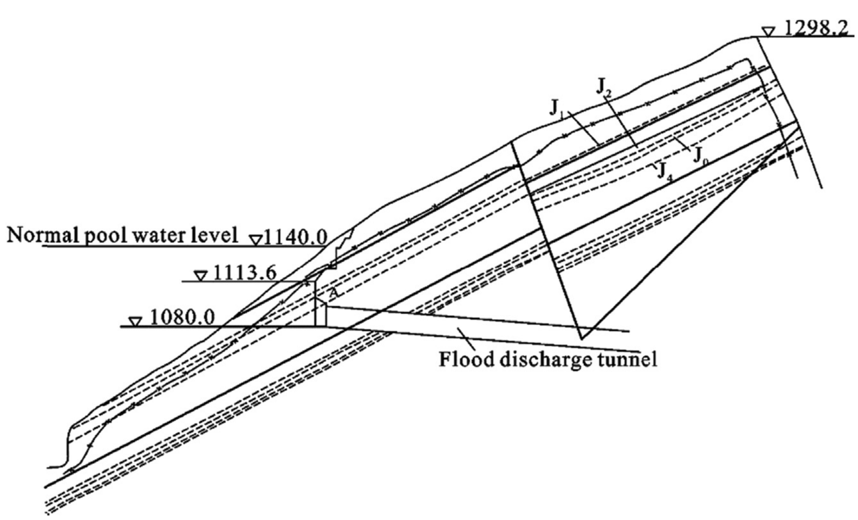


Fig. 19. A typical profile of left bank high slope (unit: m).

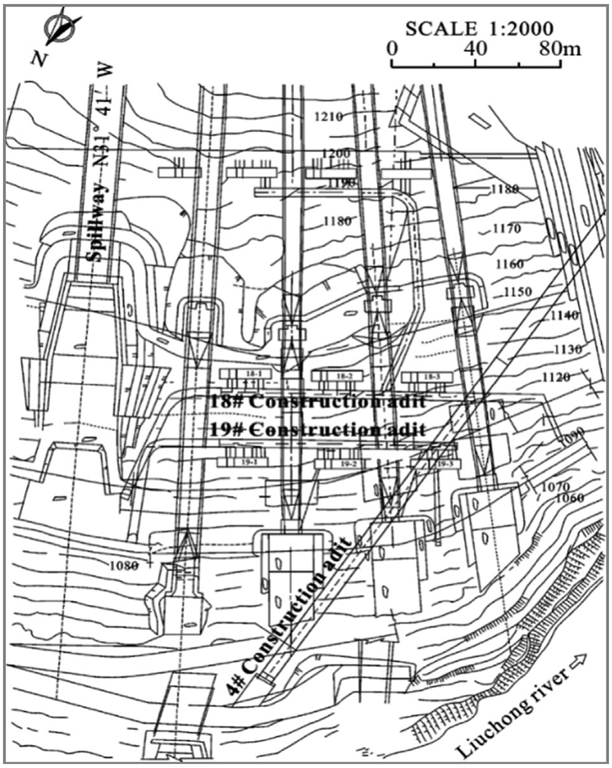


Fig. 22. Plan view of the slope at the water inlet.

spacing of 4 m × 4 m. The optimal trend of anchoring force is in a direction opposite to that of intersection line of the discontinuities. For facilitating drilling and grouting, the cables are installed at 8° below the horizontal (Jiang et al., 2013). The reinforcement layout for stability and deformation control of the shallow and surface rocks of the slope is shown in Fig. 26a. Fig. 26b displays the overview of the left bank slope after reinforcement.

According to the spatial distribution of the discontinuities in the dam's left abutment slope, it can be concluded that the overall stability of the slope is mainly governed by the huge potential failure block, which was formed by fault f42-9, lamprophyre dike X and deep crack SL44-1. To improve the stability of the huge block, three shear resistance tunnels at elevations of 1883 m, 1860 m and 1834 m were arranged along the trend of fault f42-9. The cross-sectional area of the shear resistance tunnels is 9 m × 10 m. To prevent new failure surface being formed throughout the shear resistance tunnels, two concrete key grooves were set perpendicularly to the axial direction of each shear resistance tunnel. The persistence of the key groove extends from the hanging wall to foot wall of fault f42-9, with length over 20 m. The cross-sectional area of the key groove is 4 m × 5 m. The deep-seated shear resistance structure is very effective on the stability control of the high slope (Song et al., 2010; Jiang et al., 2015). Fig. 27 shows the plan view of the shear resistance tunnel and key grooves at elevation of 1860 m. The filling material of the shear resistance tunnels and key grooves is using micro-expansion concrete with some pre-embedded steels.

6.3. Effectiveness of reinforcement

A monitoring system was designed and installed for the safe construction purpose of the high slope (Xu et al., 2011; Zhou et al., 2016). Based on the depth of monitoring instruments, the slope monitoring scheme can be divided into three main components, i.e. surface deformation monitoring, shallow slope deformation monitoring, and deep-seated tensile crack deformation monitoring. In this scheme, the slope deformation was monitored at three levels from the surface to the interior of the slope.

Fig. 28 shows the variation of deformation at some typical surface monitoring points with elapsed time. It is observed that the deformation on the slope surface can be divided into three stages, i.e. initial deformation stage, rapid deformation stage, and slow deformation stage. In August 2009, the excavation and reinforcement of the slope were basically completed, and the deformation rate at the surface monitoring points increased dramatically. There

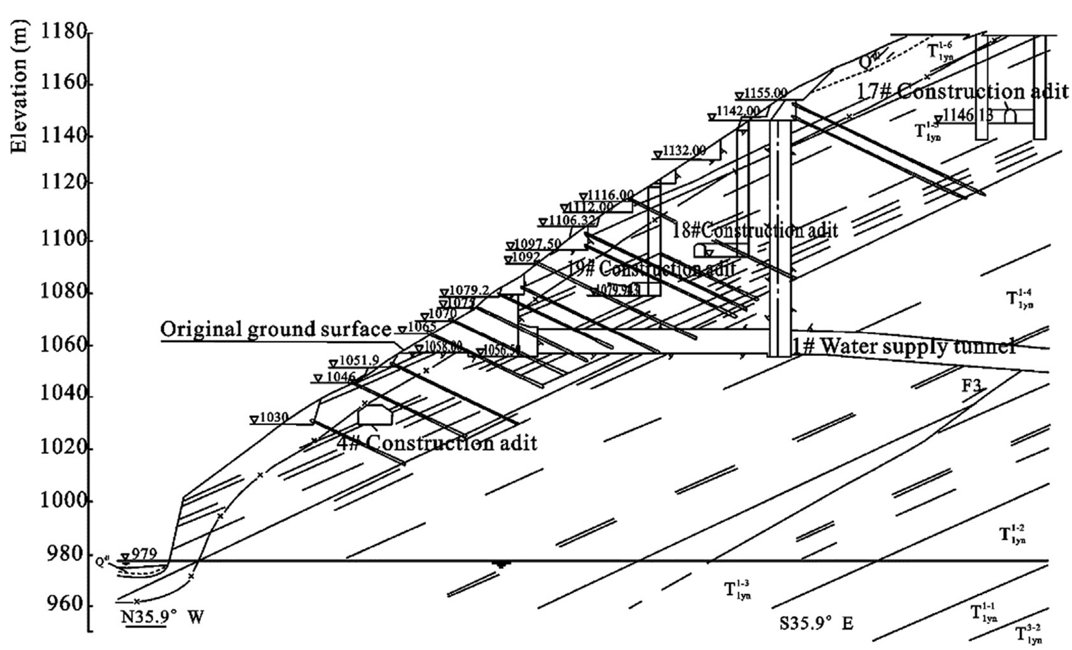


Fig. 23. A typical profile of the reinforcement slope.

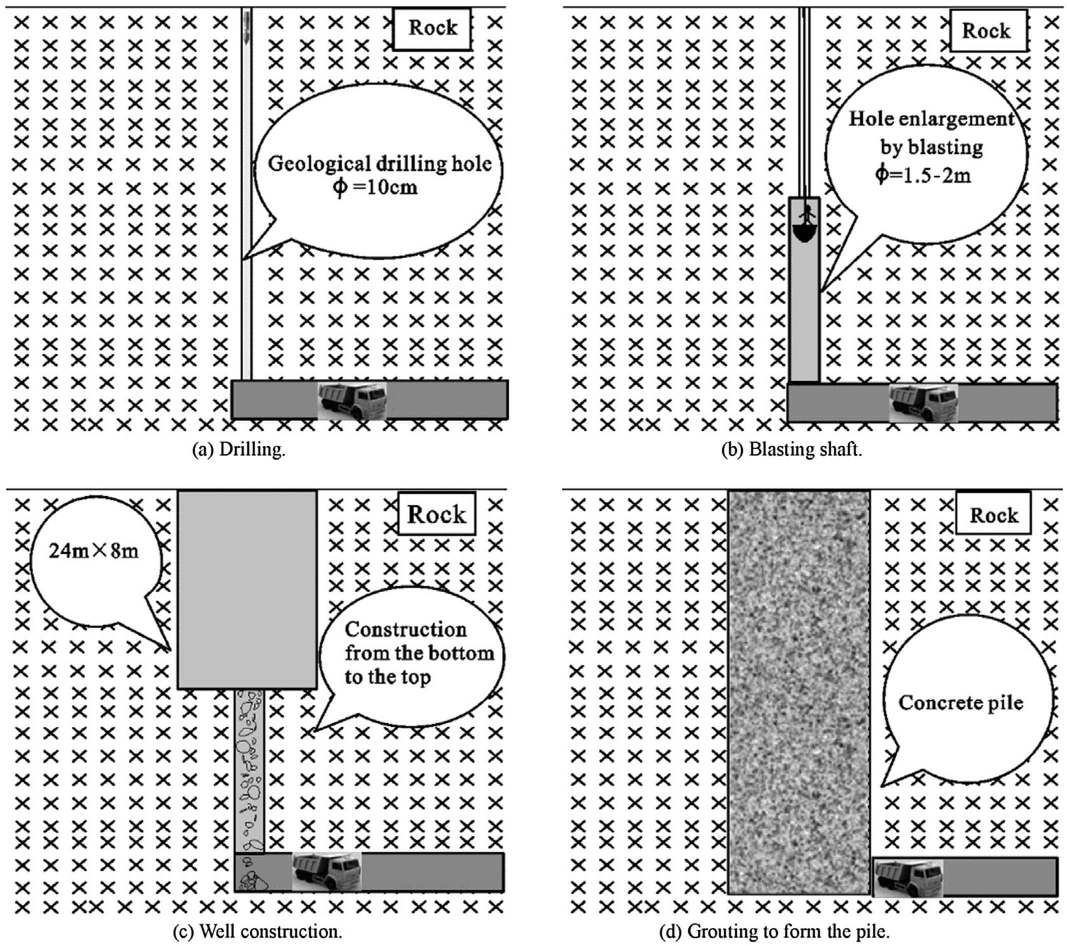


Fig. 24. The reversely conducted well technology of slope stabilizing piles.

are 11 sets of multi-point extensometers installed to measure the deformation of the shallow rocks of the slope. Fig. 29 shows the displacement variations at each measurement point of a typical multi-point extensometer (M_5^4) during the excavation process. Obviously, the displacement variation of M_5^4 tended to be converged after the construction of the slope was basically completed. In order to understand the deformation of deep-seated tensile cracks located in the deeper part of the left bank slope, the graphite rod extensometer (G44) was installed in PD44 at the elevation of 1930 m. Fig. 30 shows the variation of deformation of G44 with elapsed time. The deformation monitoring results indicate that the high rock slope is stable and safe after implementation of slope excavation and reinforcement.

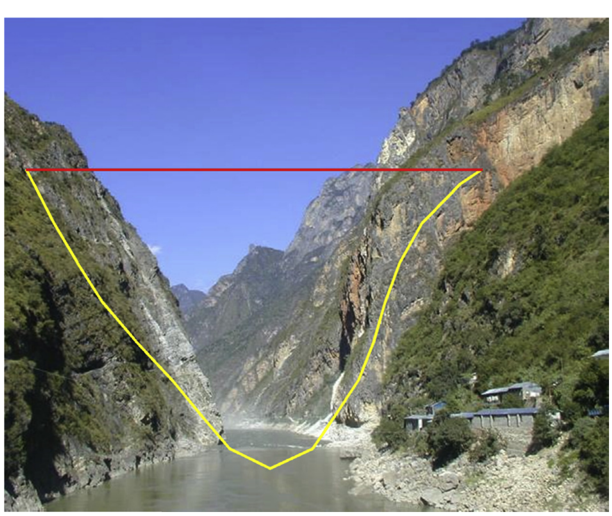
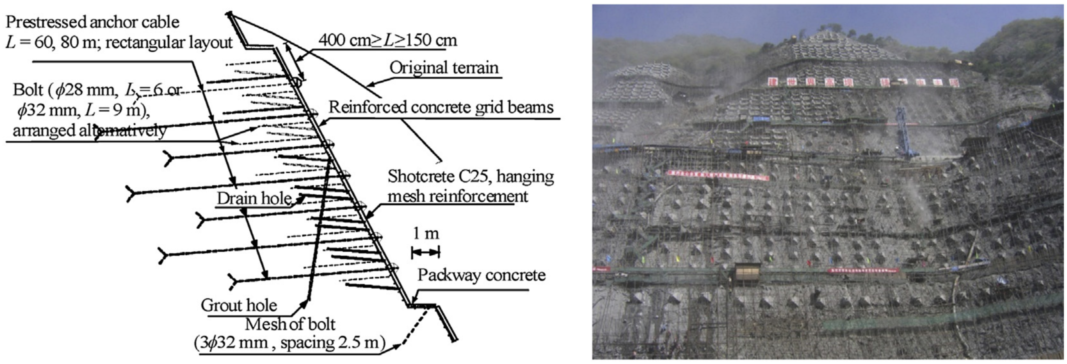


Fig. 25. A deeply cut V-shaped valley at the dam site of Jinping I hydropower station.

7. Concluding remarks

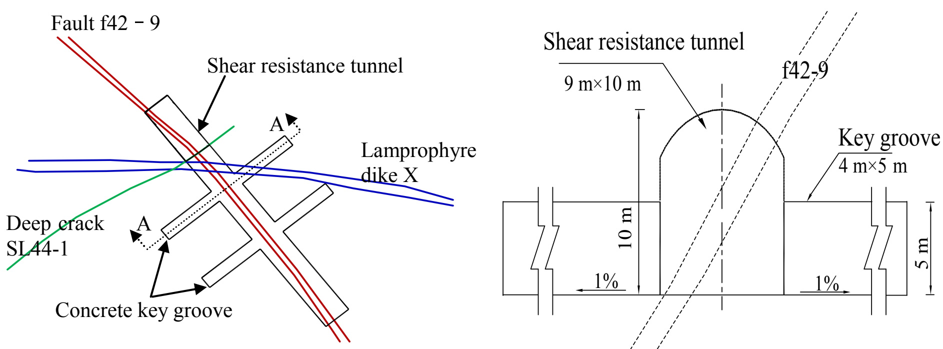
This paper reviews the recent reinforcement technologies that have been developed to stabilize five large-scale engineering slopes in China. Monitoring results of various deformations demonstrate that these reinforced slopes are stable and safe, indicating that the technologies are effective in slope safety control.

(1) The depth of a slope stabilizing pile is basically 20–40 m in China. In view of the large bending moment, deeper piles by traditional method (Poulos, 1995) may not be suitable. This issue can be solved by installation of pre-stressed cables at the middle of the pile. Northwest Research Institute Co., Ltd., China Railway Engineering Corporation has succeeded in developing multi-point anchored slope stabilizing piles. The key technology is the dust release device that makes drilling possible in a narrow well.
(2) Soil nailing (She, 2000) is a mature technology to reinforce earthen slopes, but the driven type soil nailing technology is



(a) Reinforcement layout. (b) overview of the slope after reinforcement.

Fig. 26. Reinforcement for the shallow and surface rock masses of the left bank slope.



(a) Plan view. (b) Cross section A-A.

Fig. 27. Layout of shear resistance tunnel with concrete key grooves.

not widely applied due to the disturbance and damage to soils caused in pipe driving process. Sino-Hydro Engineering Bureau No. 4 Co., Ltd., has proposed a driven pipe grouting technique and completed a large area of slope reinforcement in Xiluodu hydropower station.

(3) A number of landslides are trigged by toe excavation. Rehabilitating the cut slope to its natural state can be a reasonable approach to maintain its stability (Duncan and Wright, 2005). During the excavation of a 300 m high slope of Xiaowan hydropower station, sliding deformation at the crest gives a marked sign that the slope must be treated. The designers used cantilever pile and succeeded in supporting the slope. This technology involved the highest above-ground cantilever wall for stabilizing the slope.

(4) The traditional construction of slope stabilizing piles in China usually adopts manual excavation. As a result, the low efficiency makes it impossible to build a pile with cross-sectional area larger than 5 m $\times$ 5 m. The recent advances made in the Hongjiadu hydropower project succeeded in building the piles with a cross-sectional area of 20 m $\times$ 5 m.

(5) The left abutment of Jinping I hydropower station was cut to form a 530 m high rock slope. To ensure the stability of the

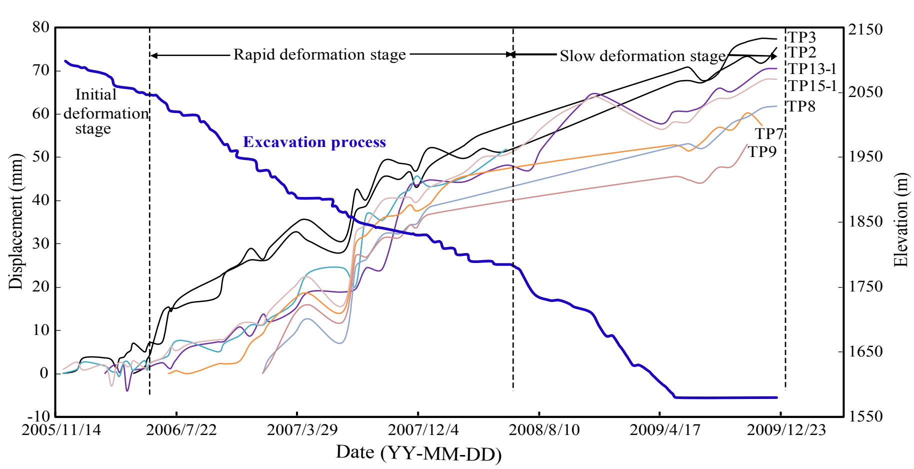


Fig. 28. The deformation evolution of typical surface monitoring points with time.

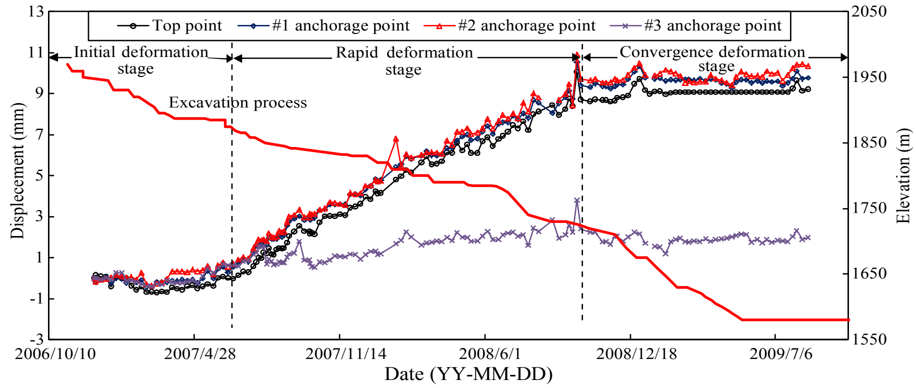


Fig. 29. Variations of displacements of measure points of M_5^4 with excavation process.

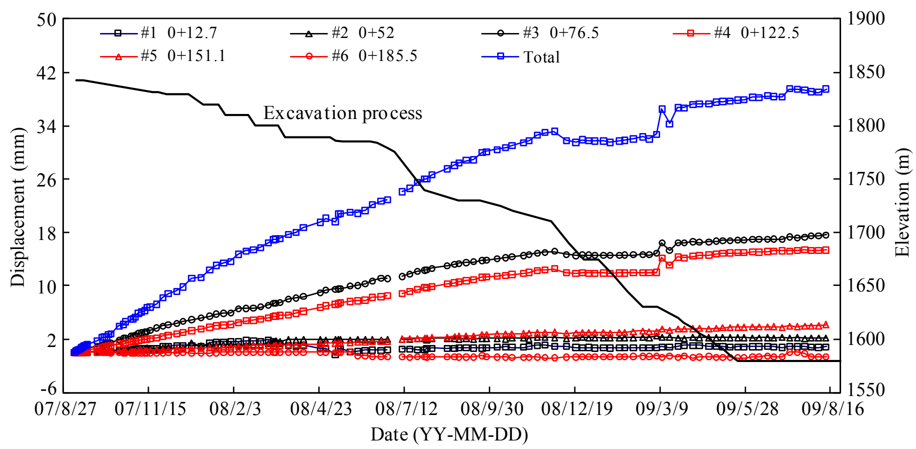


Fig. 30. Variations of displacements of measuring points of G44 with excavation process.

high slope, rock bolts, pre-stressed cables, frame lattice beams and pre-consolidation grouting were used to reinforce the shallow and surface rock masses of the slope. To prevent the sliding of the key slip surface, the deep-seated shear resistance structure was adopted to improve the overall stability of the slope. The comprehensive reinforcement method is proved to be effective.

The cases of reinforcement technology for high slopes presented in this paper are of significance with potential being extended to other large hydropower projects. More in-depth scientific research is desirable so that these new technologies could be improved and used for landslide risk control.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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