Failure of a Rock Slope Ten Years after Excavation

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Abstract: In the present study, a rock cut slope in Chongqing of China, which failed suddenly about ten years after excavation, was reported. The survey results after failure indicated that the rock masses of the rock slope were highly fractured and heavily weathered, the critical slip surface was composed of three connected discontinuities from the toe to top of slope. The factors resulting in the failure of rock slope were mainly initial excavation and weathering process. The initial excavation removed original supporting role of the excavated rock masses at the toe of the slope to the upper unexcavated rock masses, and broken the original ground stress balance. The physical and chemical weathering after the initial excavation cracked progressively the rock masses, deteriorated the mechanic properties of the rock masses, and changed the stresses and strains in the rock slope. The stability of high artificial rock slope during operation should be paid attention to. The characteristics of geological structure, unloading induced by excavation, and weathering have important effects on the evolution for deformation of artificial rock high slope.

Keywords: High artificial rock slope, Time since excavation, Failure, Weathering, Geological structures.

1. INTRODUCTION

With the implementation of Chinese Western Development Strategy and the advance of Chinese Reform and Opening up, many major projects have been completed, including transportation infrastructure, hydropower projects, the development of mining resources, etc. In the implementation of these projects, a large number of high artificial rock slopes have been constructed. Due to the influence of the Qinghai-Tibet Plateau continue to rise, the regional geological environment is complex and the rock stratum is broken, so the deformation and failure mechanism of the high artificial rock slope is complex (Huang 2004,2005). At present, there is no security plan for high artificial rock slope in operation period. And even there is no dynamic stability evaluation method and mechanism for high artificial rock slopes in their operation period. But many of high artificial rock slopes failed during their operation period (Liu et al. 2012; He and Wang 2013).

Rock slope stability or instability is often affected by geological structures (Abbas and Mehdi 2011; Bouissou et al. 2012; Stead and Wolter 2015). But, there are many other factors influencing the stability of rock slope, such as intact rock strength, and groundwater outflow (Pantelidis 2009; Benoît 2016). Recently, excavation (Neiman, 2009; Vyazmensky et al. 2010) and weathering (Admassu et al. 2012; Mišcevic and Vlastelica 2014) were also investigated as the type factors. There are many rock mass classification systems currently (Hack et al. 2003; Liu and Chen 2007), in which the method of excavation was involved as a factor, but the time since excavation not involved (Pantelidis, 2009). Actually, for weathering-related breakdown of excavated rock slopes, the time since excavation should be involved as a factor, and included in the system of rock slope deterioration assessment (RSDA) (Nicholson, 2004, Li 2015).

In this paper, a failure of high artificial rock slope, was reported as a case study. Initial excavation, the time since excavation, weathering were important factors influencing the stability of high artificial rock slope. The systematic stabilization reinforcement measures were in introduced and carried out.

Through this example, it is clear that the stability of high artificial rock slope should be taken seriously. We emphasize the timeliness of the evolution for deformation and failure in high artificial rock slopes, and analyze the factors which influence the stability of the high artificial rock slope during their operation

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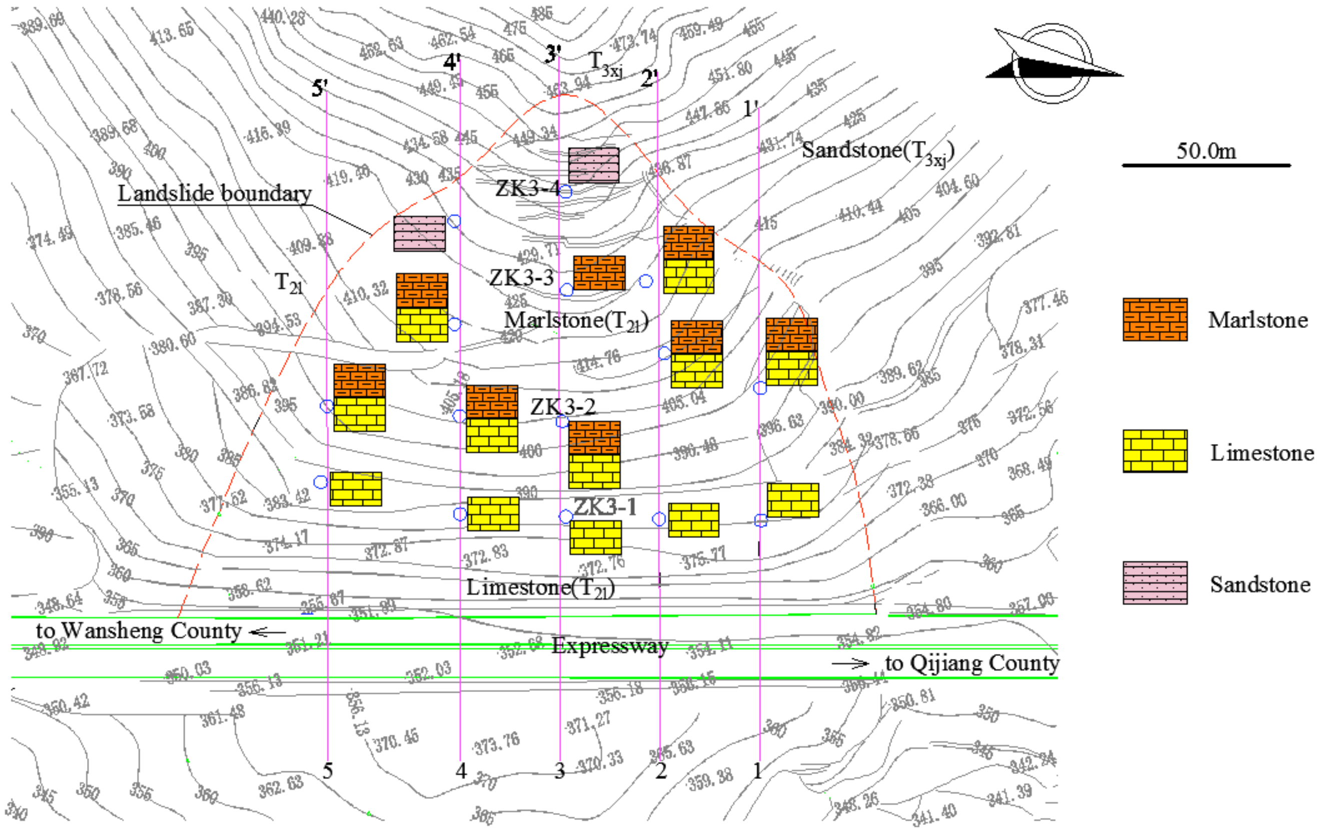

Figure 1: Engineering geological plan of the landslide.

period. The stability of high artificial rock slope during operation period is a problem worthy of attention.

2. GENERAL SITUATION OF ROCK SLOPE AND ITS FAILURE

The investigated rock slope was excavated about in the spring of 2003 during the construction of the expressway from Qijiang County to Wansheng County in Chongqing of China (Figure **1**). The Qijiang-Wansheng expressway was 32km in length and 18m in width, and its construction wasn't finished until in September of 2004. The total investment of the expressway was about 1.2 billion Chinese Yuan. The investigated rock slope, with about 40m in total cut height, was in right side of the expressway. The attitude of natural slope near the expressway ranges from 315m to 500m, and the attitude of the expressway at the rock cut slope is about 352m. The rock slope was divided into five secondary cut slopes with different heights (Figure **2**). The ratio of each secondary cut slope was the same 1.0 (vertical direction) to 0.5 (horizontal direction). The heights of the first and second secondary cut slopes were 5.0m, and other three secondary cut slopes were 10.0m. There was a platform with about 1.0m in width between any two adjacent secondary cut slopes. The average angle of the whole rock cut slope was therefore about 59.0°, which was steeper than the angle of local natural slope, about 30° to 40°. The dip direction of the whole rock cut slope was about NE80°, namely the strike was about NW10°. Based on the then design calculation results, the rock slope was evaluated as stable during and after excavation. Thus, only protective measures to prevent weathering of slope face were designed and carried out in the spring of 2003. These protective measures included drainage ditches, anchors, shotcrete panel and grassing.

At about 12 o'clock on May 4, 2013, the rock cut slope was collapsed suddenly from its first or second secondary slope near the toe of slope, and the traffic of the expressway was stopped (Figure **3**). Several long and open cracks were detected on the mountain slope far away from the top of cut slope. In order to avoid further failure, partly superficial unstable rock masses were excavated to reduce driving forces (Figure **4**), and some excavated rock blocks were filled at the toe of slope to increase resisting forces (Figure **2**). Figure **4** shows the photo of the whole slope after excavating superficial unstable materials. The horizontal width of the unstable slope or landslide, which was the length

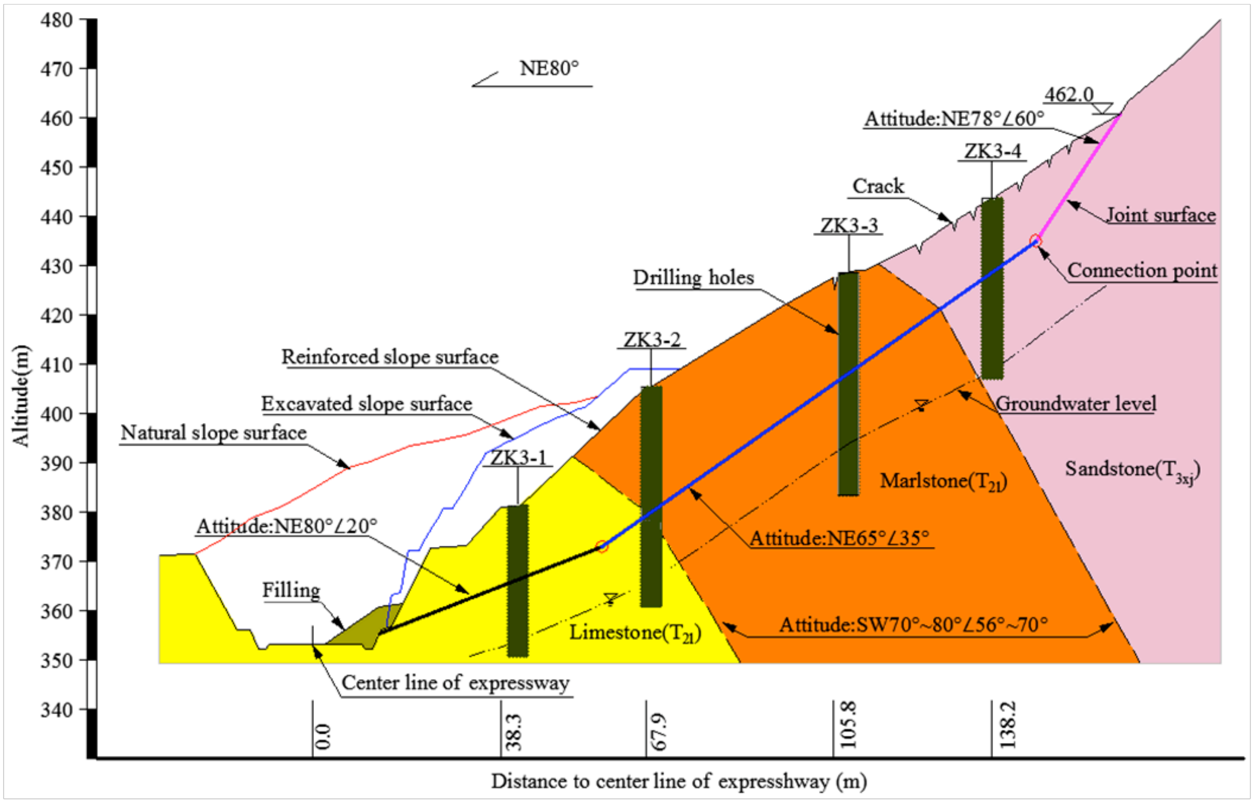

Figure 2: Engineering geological longitudinal section #3-3'.

along the expressway, was about 210m. The horizontal length of the landslide, which was the length along the slip direction, was about 156m. The vertical height of the landslide from its toe to top was about 110m.

3. ENGINEERING GEOLOGICAL STRUCTURES

The geological properties of this high artificial rock slope were surveyed in detail after failure. Figure **1** and **2** show that the strata in the rock slope were thin top-layer loam formed during Quaternary Holocene period (Q_4), sandstone layers formed in Upper Triassic (T_3), limestone and marlstone layers formed in Middle Triassic (T_2).

Figure 3: Photo of rock slope after failure (on May 4, 2013).

In China, the strata formed in Upper Triassic are also called as Xujiahe formation (T_{3xj}) (Wang et al., 2013). The strata formed in Middle Triassic are also called as Leikoupo formation (T_{2l}). The attitudes of the sandstone, limestone and marlstone layers, measured in field, are almost the same. The strike is about NW10° to NW20°, which is almost equal to the strike of the whole rock cut slope of NW10°. The dip direction is about SW70° to SW80°, which is almost opposite to the dip direction of the whole rock cut slope of NE80°. The dip angles is about 56° to 70°. There are three-group joints in the rock masses of the rock slope. The attitude of the first-group joints is dip direction NE20° to NE52° and dip angles 45° to 65°, the second-group joints is dip direction NE65° to NE88° and dip angles 18° to 38°, and the third-group joints is dip direction SE10° to SE80° and dip angles 22° to 69°.

Based on the above analysis, the average attitude of the whole rock cut slope is NE80°∠59°, and the bed rock attitude could be chosen as SW70°∠56°. Stereo-analytical map can be made as Figure **5**. Obviously, from this point of view, the high artificial rock slope is very stable, not easy to slide. But it had actually slipped.

Figure 4: Photo of landslide after excavating superficial unstable materials.

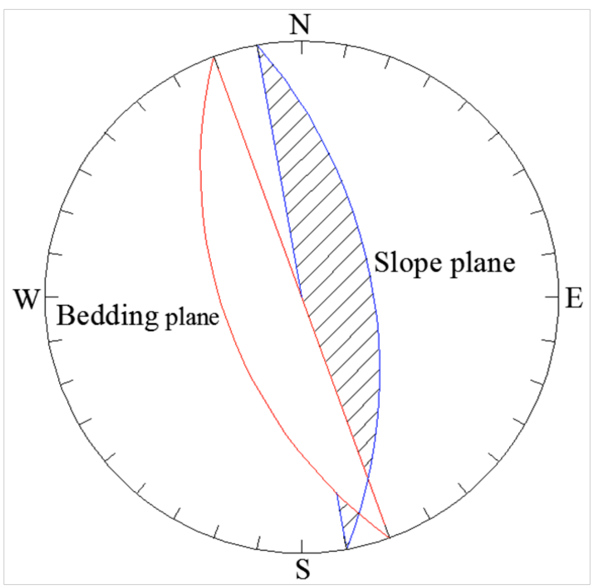

Figure 5: Stereographic projection map.

According to Figure **2**, the critical slip surface of the landslide was composed of three connected discontinuities from the toe to top of the slope. The results of geological drilling indicated that the sandstone, limestone and marlstone layers in the rock cut slope were weathered moderately to heavily. Some small cavities were present in limestone layers and the rock masses were highly fractured.

4. INITIAL EXCAVATION AND THE TIME SINCE EXCAVATION

Under the unloading action of excavation, the variation of rock properties (wave velocity) of the surrounding rock exhibits a certain regularity over time. In the first 3 years, the rate of variation of rock properties (wave velocity) of the cavity was very high, because the initial stage of rock excavation was the fastest period of stress release. After 3 years, the variation rate of the surrounding rock properties gradually stabilized, because the resilience and stress release of rock mass gradually weakened. Until 15 years, the variation rate of the surrounding rock properties (wave velocity) is very small, at this time the surrounding rock of the cavern is basically stable, because the rock surface has been completely relaxed, and its properties are no longer changing. These regularities indicate that the variation of rock properties (wave velocity) of the surrounding rock under excavation has a time effect, and this is not a short time (Yang and Zhang, 2016).

The excavations changed the natural slope surface and removed original supporting role of the excavated rock masses, which restricted deformation of the upper unexcavated rock masses. Vibratory action induced by the blasting during excavation might loosen the rock

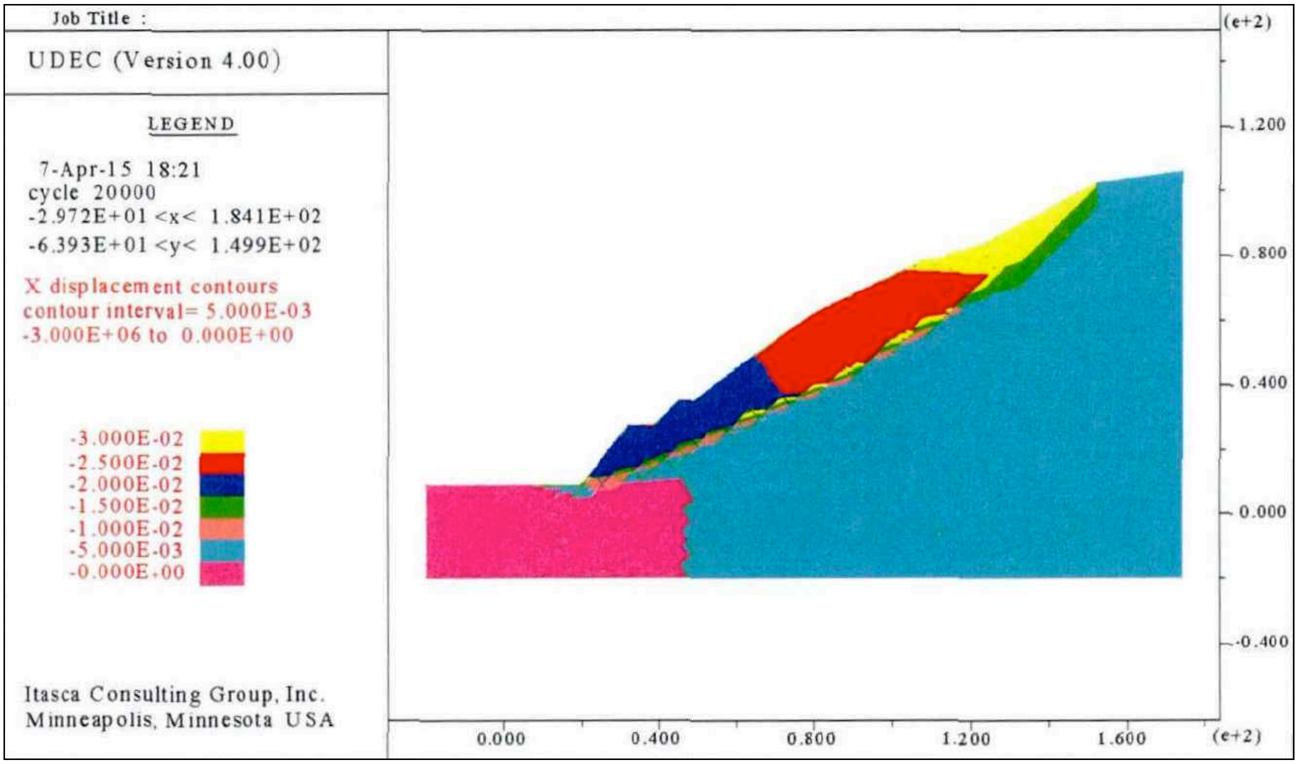

Figure 6: The horizontal displacement cloud image.

masses and even widen the existing cracks. The adjustment for stresses and strains of the rock masses result in the concentration of stress at the toe of slope, and the looseness of the rock masses. The looseness might accelerate the weathering process of the rock masses. The reinforcement measures after excavation are very weak and there is no compensation for the unloading force. Under the action of unloading rebound and creep, the internal stress of the retained slope is changed, and the joint fracture is fully developed. Compared with the time effect of unloading, the ten years may not exceed its time frame. Of course, the development of joints and fissures were accelerated by rainfall, groundwater and other factors. And the horizontal displacement cloud image is shown in Figure **6**.

According to Figure **6**, under the action of unloading rebound and creep, the strong weathered layer in the middle and upper part of the weak interlayer of the reserved slope body have obvious downward dislocation deformation, the middle and lower of the reserved slope rock masses are squeezed to a certain extent. At the foot of the reserved slope, there are squeezing phenomenon and bulging phenomenon. This indicates that the instability of high artificial rock slope is related to the unloading action caused by excavation.

The time since excavation (from slope excavation to slope failure), is about ten years. In this period of time, the deformation and displacement of this high artificial rock slope are on the increase. Some abnormal growth phenomenon of the plant and old cracks, behind the slope shoulder, could prove that the slope is in the process of dynamic change. Since the deformation and displacement of the high artificial rock slope, under the action of rainfall and groundwater, the weathering process of the internal slope was accelerated once again.

5. WEATHERING

During the ten years after excavation, the weathering on the rock masses of the slope was not step-down due to some protective measures carried out after excavation, but step-up due to the adjustment of stresses and strains in rock masses during and after excavation. In general, weathering includes three processes, i.e. physical, chemical and organic weathering. Physical weathering results in the disaggregation of rocks without mineralogical change, but chemical weathering results in the decomposition of the constituent minerals to stable secondary mineral products. Organic weathering often includes root wedging, animal activity and microorganisms. Weathering processes on the materials of the rock cut slope should be described as mainly physical and chemical weathering. Weathering, which might be an important factor affecting the stability of slopes, was reported by Mišcevic and Vlastelica (2014).

Due to weathering, the integrality and shearing strength of the rock masses were reduced. The whole failure started with the local failure at the toe of slopes. The stresses and strains at the toe of slopes varied with weathering, drying and wetting, freezing and thawing, etc. During and after rainfall, the local shear stress at the toe of slopes increased because of the increment of gravity. While the local shear stress exceeded the shearing strength of the local rock mass, local failure happened. Once the local failure happened, the stresses and strains of the rock masses redistributed, and new concentration of stress at new positions formed. If the local shear stress at the new positions exceeded still the shearing strength of the local rock masses, local failure happened again. The local failures happened gradually from the toe to top of slope, and then the whole failure of the rock cut slope happened. It is worth mentioning that the time of slope failure was in the rainy season.

6. OTHER MINOR FACTORS

There are many other factors which affect the stability of high artificial rock slopes, such as unfavorable geographical conditions, climatic conditions, the mistake of initial construction, management of operation period, traffic loads and so on. It is worth mentioning that unfavorable geographical conditions are the foundation of development for this landslide. The joints and fissures were found to be widely distributed in the body of this high artificial rock slope. there some small caverns were found in limestone layers. There is plenty of rain in this place where the high artificial rock slope is located, and the climate is humid. All these provide natural conditions for the formation of the landslide. Although, no artificial design mistakes have been found after the investigation, the high artificial rock slope was stable during the next ten years after construction, which does not mean that its initial design and construction are qualified, because the whole designed service life of this high artificial rock slope is much more than ten years. The existing theory of design is flawed, which does not take full account of various objective factors, for the time since excavation. As the record data of initial construction are incomplete, whether the mistake of initial construction exist or not, which cannot be judged. In the management of the operation period, traffic loads, especially the dynamic load of large transport vehicles have an adverse effect on the high artificial rock slope.

If these factors were all taken into account in the design and construction, landslides could be avoided. Therefore, the main subjective reasons of slope failure are analyzed, for example, the unloading action of initial excavation. Man-made causes and natural causes have led to this landslide, jointly.

7. STABILIZATION TREATMENT

After excavating partly superficial unstable rock masses and filling some excavated rock blocks at the toe of slope, the factor of safety for this high artificial rock slope might increase a little. Based on empirical estimation on the stability of the slope, the factor of safety at this time was about 1.02 to 1.04 under natural conditions, and very near 1.0 under saturated conditions. But the stability degree of the slope after stabilization must meet the safety requirement. The shearing strength of the critical slip surface (Figure **2**) might be back calculated by the limit equilibrium method, suggested in Chinese national code GB 50330-2002 (MOHURD 2002). The values of the shear parameters c_i and φ_i of the three connected discontinuities were back calculated (Table **1**).

Table 1: Values of Shear Strength Parameters of Slip Surface and Corresponding Factors of Safety

Conditions	Factors of Safety for Slope	Discontinuities	Shear Strength Parameters	
			Cohesion (kPa)	Frictional angle (°)
Natural	1.034	High-height discontinuity	0	40
		Hid-height discontinuity	15	34
		Low-height discontinuity	15	18
Saturated	1.009	High-height discontinuity	0	39.5
		Hid-height discontinuity	14	33.5
		Low-height discontinuity	14	17.5

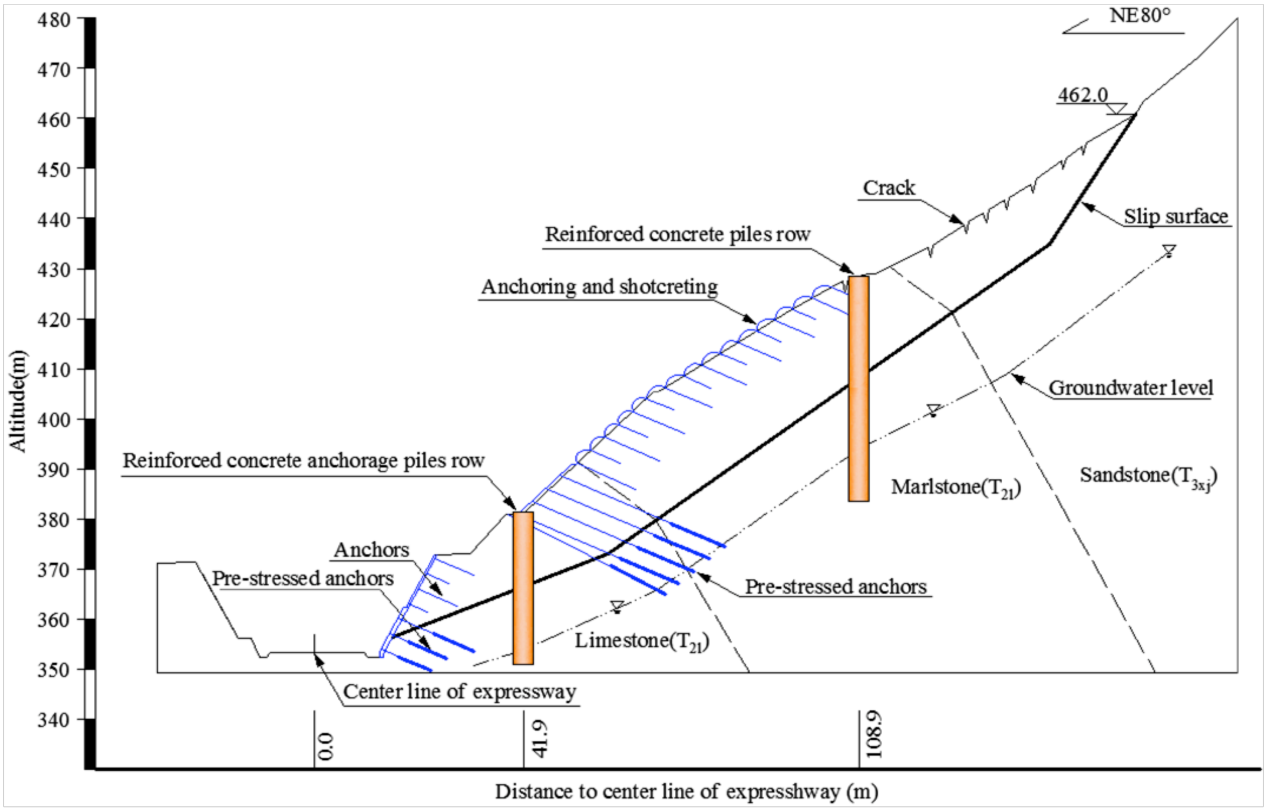

Figure 7: Stabilization methods (Section #3-3').

The stabilization methods included mainly seven parts from the toe to top of slope (Figure **7** and **8**). They were:

(1) Three-layer pre-stressed anchors with 15m to 18m in length located at the toe of slope;

(2) Four-layer anchors with 6m to 9m in length located at near the toe of slope;

(3) A reinforced concrete anchorage pile-row composed of 21 piles and located at right 41.9m from the center line of expressway, with about 3.4m×2.2m in section size and 34m in length of piles, and with 33m to 36m in length of 2 or 4 pre-stressed anchors per pile;

(4) Three-layer pre-stressed anchors with 34m to 36m in length located at above the reinforced concrete anchorage pile-row;

(5) Protection of anchoring and shotcreting located at the mid-height of the slope;

(6) A reinforced concrete pile-row composed of 7 piles and located at right 108.9m from the center line of expressway, with about 3.0m×2.0m in section size and 28m in length of piles;

(7) Interception and drainage of water (omitted from Figure **7**).

In the seven parts of the stabilization methods on the rock slope, the pile-rows (reinforced concrete anchorage pile row and reinforced concrete pile row), pre-stressed anchors (pre-stressed anchors located at the toe of slope and pre-stressed anchors located at above the reinforced concrete anchorage pile-row) and anchors (anchors located at near the toe of slope) were used to provide force systems to resist instability, the interception and drainage of water to improvement of strength, and the anchoring and shotcreting to protect the slope face against rainfall infiltration.

The stability degree of the slope after reinforcement must meet the safety requirement. According to Chinese specifications for design of highway subgrades JTG D30-2004 (MOHURD 2004), the required factor of safety is 1.20 to 1.30 in natural states, and 1.10 to 1.20 under saturated conditions. The design methods of the piles and anchors suggested by MOHURD (2004) and described by Wang et al. (2014) were used. The stabilization treatments of this high artificial rock slope have been carried out about three years ago. Now, this high artificial rock slope is stable (Figure **8**).

Figure 8: Photo of rock slope after near 3 years since stabilization.

DISCUSSION AND CONCLUSION

In this paper, an high artificial rock slope has been destroyed during its operation period. The specific reasons for the failure of this slope are analyzed one by one. According to geological exploration data and protective measures of the cut slope during the construction of the highway, the scope of stability analysis and reinforcement for slope are not sufficient. This slope belongs to the push-type slope, displacement and deformation of the front slope were produced by the thrust of mountain behind. The critical slip surface was composed of three connected discontinuities from the toe to top of slope. The initial excavation and the weathering were two key factors resulting in the failure. The initial excavation removed original supporting role of the excavated rock masses at the toe of slope. The survey results after failure indicated that the rock masses in the slope were highly fractured and heavily weathered. The weathering deteriorated mechanic properties of the rock masses. Based on stability analysis, an integrated stabilization treatment, which included mainly seven parts, was carried out on the rock slope. The pile-rows, pre-stressed anchors and anchors were used to provide force systems to resist instability; the interception and drainage of water to improve the strength, and the anchoring and shotcreting to protect the slope face against rainfall infiltration.

A wide variety of natural and artificial rock slopes are widely distributed in Southwest China, especially in Chongqing. Due to the influence of the Qinghai-Tibet Plateau continue to rise, the regional geological environment is complex and the rock stratum is broken, so the deformation and failure mechanism of the high artificial rock slope is complex. The safety of these high slopes during operation period is a matter of concern. The evolution of slope deformation and failure is a long-term process. The influence of geological structural features, unloading induced by excavation, groundwater and weathering on the stability of artificial high rock slope should be concerned. Through this case, it is clear that the stability of the high artificial rock slope during operation period should be taken seriously. The long-term stability analysis of slope includes these aspects: (a) Criterion of stability and instability criterion. (b) Process and law for the evolution of deformation and failure. (c) Main factors affecting progressive deformation and failure.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] Abbas M and Mehdi A. Analysis of geo-structural defects in flexural toppling failure. International Journal of Rock Mechanics and Mining Sciences 2011; 48: 175-186. https://doi.org/10.1016/j.ijrmms.2010.11.007

[2] Admassu Y, Shakoor A and Wells NA. Evaluating selected factors affecting the depth of undercutting in rocks subject to differential weathering. Engineering Geology 2012; 124: 1-11. https://doi.org/10.1016/j.enggeo.2011.09.007

[3] Benoît D. Numerical modeling of groundwater and air flow between compacted bentonite and fractured crystalline rock. Department of Physical Geography, Stockholm University, Holmbergs, Malmö 2016.

[4] Bouissou S, Darnault R, Chemenda A and Rolland Y. Evolution of gravity–driven rock slope failure and associated fracturing: Geological analysis and numerical modeling. Tectonophysics 2012; 526-529: 157-166. https://doi.org/10.1016/j.tecto.2011.12.010

[5] Hack R, Price D and Rengers N. A new approach to rock slope stability – a probability classification (SSPC). Bulletin of Engineering Geology and the Environment 2012; 62: 167-184.

[6] He JP and Wang YL. Stability Analysis and Evaluation of QingXi High-Cutting Slope. Applied Mechanics and Materials Vols 2013; 438-439: 1376-1379. https://doi.org/10.4028/www.scientific.net/AMM.438-439.1376

[7] Huang RQ. Geo-stress distribution and unloading fracturing mechanism of high rock slopes in western part of China. Journal of Engineering Geology 2004; 12(Suppl.): 7-13. (In Chinese)

[8] Huang RQ. Main characteristics of high rock slopes in southestern China and their dynamic evolution. Advances in earth science 2005; 20(3): 292-297. (In Chinese)

[9] Li XL, Tang HM, Xiong CR, et al. Dynamic Centrifuge Modelling Tests for Toppling Rock Slopes. Engineering Geology for Society and Territory 2015; 2: 769-774. https://doi.org/10.1007/978-3-319-09057-3_130

[10] Liu YC and Chen CS. A new approach for application of rock mass classification on rock slope stability assessment. Engineering Geology 2007; 89: 129-143. https://doi.org/10.1016/j.enggeo.2006.09.017

[11] Liu HY, Lv DW, et al. Engineering geological characteristics of one high cut slope in Chongqing Wanzhou. Advanced Materials Research Vols 2012; 368-373: 814-818.

[12] Mišcevic P and Vlastelica G. Impact of weathering on slope stability in soft rock mass. Journal of Rock Mechanics and Geotechnical Engineering 2014; 6: 240-250. https://doi.org/10.1016/j.jrmge.2014.03.006

[13] Ministry of Housing and Urban–Rural Development of the People's Republic of China (MOHURD). (2002). Technical code for building slope engineering. GB 50330-2002. (in Chinese).

[14] Neiman W. Lessons learned from rates of mudrock undercutting measured over two time periods. Environmental and Engineering Geoscience 2009; 15(3): 117-131. https://doi.org/10.2113/gseegeosci.15.3.117

[15] Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). (2004). Specifications for design of highway subgrades, JTG D30-2004. (in Chinese).

[16] Nicholson DT. Hazard assessment for progressive, weathering–related breakdown of excavated rock slopes. Quarterly Journal of Engineering Geology and Hydrogeology 2004; 37: 327-346. https://doi.org/10.1144/1470-9236/04-021

[17] Pantelidis L. Rock slope stability assessment through rock mass classification systems. International Journal of Rock Mechanics and Mining Sciences 2009; 46: 315-325. https://doi.org/10.1016/j.ijrmms.2008.06.003

[18] Stead D and Wolter A. A critical review of rock slope failure mechanisms: The importance of structural geology. Journal of Structural Geology 2015; 74: 1-23. https://doi.org/10.1016/j.jsg.2015.02.002

[19] Vyazmensky A, Stead D, Elmo D and Moss A. Numerical analysis of block caving-induced instability in large open pit slopes: a finite element/discrete element approach. Rock Mechanics and Rock Engineering 2010; 43: 21-39. https://doi.org/10.1007/s00603-009-0035-3

[20] Wang JJ, Liang Y, Zhang HP, Wu Y and Lin X. A loess landslide induced by excavation and rainfall. Landslides 2014; 11(1): 141-152. https://doi.org/10.1007/s10346-013-0418-0

[21] Wang JJ, Zhang HP, Deng DP and Liu MW. Effects of mudstone particle content on compaction behavior and particle crushing of a crushed sandstone–mudstone particle mixture. Engineering Geology 2013; 167: 1-5. https://doi.org/10.1016/j.enggeo.2013.10.004

[22] Yang JJ and Zhang J. Time effect of rock mass variation after excavation and unloading. Journal of Henan University of Urban Construction 2016; 25(1): 52-56.

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