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A dynamic comprehensive method for landslide control

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Abstract

A slope failure is developed due to progressive external loads and deteriorations of slope geomaterials, thus forming a progressive and dynamic development and occurrence of landslides. Site geological properties and other active factors such as hydrodynamic load and human activities are complex and usually unknown, thus this dynamic development and occurrence of landslides can only be understood through the progressive accumulation of knowledge on the landslides. For such a progressive process, this paper proposes a dynamic comprehensive control method for landslide control. This control method takes full advantage of updated monitoring data and site investigations of landslides, and emphasizes the implementation of possible measures for landslide control at reasonable stages and in different groups. These measures are to prevent the occurrence of a landslide disaster. As a case study, a landslide project at the Panluo open-pit iron mine is analyzed to illustrate this dynamic comprehensive control method.

Keywords: Landslide disaster; Progressive failure; Dynamic control; Engineering treatment

1. Introduction

China's ambitious Western Great Development Projects, especially the construction of the Three Gorges Dam in southwestern China and other large-scale engineering projects, have considerably disturbed the natural landscapes in that area. These disturbances have induced a large number of natural disasters including landslides (Liu et al., 2004). Southwestern China is a mountainous and high-rainfall area, thus landslides are serious problems every year. Landslides often result in extensive property damages and sometimes loss of human life. According to Chinese governmental statistical data, Chongqing city, which is located in southwestern China, had 29896 crags and landslides in 1998. Their total mud volume reaches 50×10^6 m^3. In order to prevent potential disastrous landslides in the Three Gorges Reservoir area, China has spent 4 billion RMB (approximately 500 million US dollars) in the first stage treatment. These landslides have also attracted the attention of Chinese and international scientists. They analyzed the key factors for the occurrence of landslides (Liu et al., 2004; Kwong et al., 2004; Xie and Xu, 1999; Zhang et al., 1999) and proposed many methods for stability assessment (Xia and Li, 2002).

The objective for the stability assessment of landslides is to find out a suitable control method to prevent or mitigate landslides (Segalini and Giani, 2004; Petley et al., 2005; Voight, 1988). A control method for landslides is based on either strengthening earth materials (increasing resisting forces) or reducing the

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mass weights within potential sliding mass (decreasing driving forces) or both. For a sliding mass, the control method requires halting or reversing those factors that worsen its instability. Current stabilization measures for landslides include: draining surface and underground water from the sliding area, excavating and redistributing sliding mass, and installing retaining facilities (Pipkin et al., 1997). For a sliding mass, some single measures, especially stabilizing piles as retaining facilities, have been studied in detail (Poulos, 1995; Hassiotos et al., 1997). However, potential or progressive failure of landslides (Miao et al., 1999; Petley et al., 2005) is evolving with the evolution of both external and internal loading factors. For such landslides, one or more measures must be applied in time to prevent further sliding development. These measures include not only traditional "hard" remedial treatments such as retaining facilities but also some "soft" measures such as the management of external loadings and internal factors. So far, no innovative method is available for landslide control except conventional methods. The conventional methods are suitable for those landslides already in their critical states and with fully known information. For potential landslides and progressive landslides, conventional methods are not suitable due to their technical demerits and high costs. Some examples are reported on the failures of those conventional landslide control methods (Zhang, 2000). In fact, a landslide is a complicated mechanical problem in its state evolution, risk assessment, and hazard mitigation (Feng et al., 2004). As a contrast, a large-scale landslide in Fujian province of China was successfully mitigated and controlled for nearly 10 years with a different landslide control method. In this report, we analyze the characteristics of the development and evolution of this landslide and summarize a new landslide control method called the dynamic comprehensive control method. We first discuss, in general, the geological background, content and the advantage of the dynamic comprehensive control method over conventional control methods. We further analyze the efficiency and the cost-effectiveness of this new method through a case study.

2. Dynamic comprehensive control method

2.1. Characteristics of the development and occurrence of landslides

The development and occurrence of landslides is usually a progressive and dynamic process. This feature was observed in many reports (Chen and Lee, 2003; Segalini and Giani, 2004). Babu and Murthy (2005) made a simple model to calculate the reliability for gradual failure of homogeneous soil slope. Tan et al. (2000) studied the mechanism on gradual breakage of rock slopes through physical models and numerical simulations with FLAC commercial software. Based on the development stages of landslide deformation, Zheng et al. (2003) proposed a classification of landslides. The development of a landslide usually experiences four stages: small deformation, large deformation, tiny sliding and strong sliding. Zheng et al. (2002) also numerically simulated the development of a slope sliding process with the reduced strength method. The gradual breakage was clearly observed from their numerical simulations. Another example is the Choja landslide (Hiura and Hiramatsu, 1999) located in Choja village of Japan. It has been moving for a long time, and the mean rate of the displacement from 1982 to 1996 was 2740 mm per year. Other examples include many old landslides in the Three Gorges area in China. These landslides gradually came in live due to geo-environmental changes (Zheng et al., 2003). Fig. 1 is a typical time versus displacement curve on a sliding body. This curve shows three stages of landslide development: initial stage, linear stage and accelerating stages. A landslide always occurs at the accelerating stage (Wang, 1991). Therefore, the development of landslides is progressive and dynamic.

Why is the development and occurrence of landslides progressive and dynamic? This can be analyzed from two aspects. Firstly, dynamic evolutions of external and internal factors affect the stability of slopes. An open-pit slope is typical in this class. Slope height, width and other geometries are dynamically evolving with the mining process, inducing the dynamic evolutions of stress distributions in soil or rock masses. Other

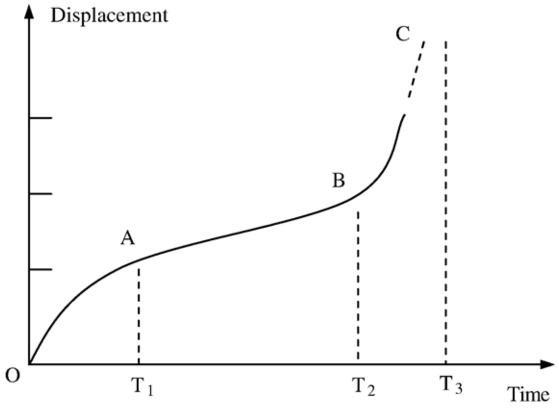


Fig. 1. Typical displacement for a landslide.

dynamic factors such as rainfall and groundwater fluctuate with seasons, affecting the stability of slopes. For example, the shear strength of soil or rock masses linearly descends with the increase of soil moisture (Hu et al., 2001). Therefore, the accumulation of soil moisture makes the development and occurrence of landslides progressive and dynamic (Tan et al., 2000). Secondly, with the development of a landslide, its scope, size-scale, depth and soil shear strength on the sliding surface are dynamically evolving. Even for a landslide near its critical state, its structure, material properties, external loads, and environments are still in their dynamic process. For example, when a sliding surface runs through from top to bottom and a landslide is entirely developed, in some cases, a landslide disaster would not happen immediately. The instability state of this landslide is still changing with the evolution of those influence factors. Our project practice shows that the key factors for landslides are not only complicated but also dynamic. They are changing with landslide development. Thus, a landslide movement is always in a dynamic balance as shown in Fig. 2.

2.2. Landslide control methods in practice

Landslide control methods should be adaptable for such a progressive process mentioned above. However, conventional landslide control methods in practice cannot adapt for such a process. They have some irremovable demerits such as high investment at one time, exclusion of the effects of some control measures such as drainage measures and other “soft” measures, and so on. These are due to their evaluation criterion. The current assessment criterion, Factor of Safety (FoS) for slope stability, brings in some demerits. As a quantitative index, FoS is obtained in practice by simply summing up all driving forces and resisting forces acting along a potential sliding surface and finding out their ratio. The stability of a slope is judged based on this FoS. When the FoS is greater than 1.0, the slope is considered relatively stable and when the FoS is less than 1.0, the slope is relatively unstable (Pipkin et al., 1997). For example, the current China practice codes for open pit require the FoS be 1.25 or bigger, otherwise, control measures are required. This evaluation criterion is based on the classical concept of limit equilibrium analysis. However, the FoS cannot completely include the effects of some control measures but these measures may have great effects on landslide control. A good example is the effect of ground water drainage measures. These measures are important and effective for landslide control, but cannot be completely included in the FoS. As a typical example, Fig. 3 shows the controlling of the Jipazi landslide at Yunyang County of Chongqing City (China) in 1982 (Zhang, 2000). The landslides volume was 1.5×10^7 m^3. Because this landslide occurred in an unpopulated mountainous area, considering the cost-effective factors, only a drainage system for ground and underground water was designed and completed as control measure in 1984. If conventional methods were used for this landslide control, retaining facilities such as piles should have been required to provide additional resistance for stability. This is because the drainage system does not improve the FoS value for this slope based on the current FoS evaluation criterion. However, the drainage system has made the slope stable for over 20 years up to now, thus being quite successful as a dynamic control measure. Those progressive and dynamic factors are difficultly included in the conventional landslide control methods through the FoS. This is that not all control measures can be quantified. In fact, the quantitative evaluations for some control measures are usually unknown beforehand in practice. How to evaluate the effect of every measure accurately is really a difficult task in conventional control methods.

In addition, our understanding and knowledge on landslide development should be dynamic. At the beginning, the engineering geological information of a landslide including the position of sliding surfaces, soil strength on the sliding surface, and so on is uncertain. With further development of landslides, information data on landslides are gradually accumulated and the understanding on the landslides is growing. Based on

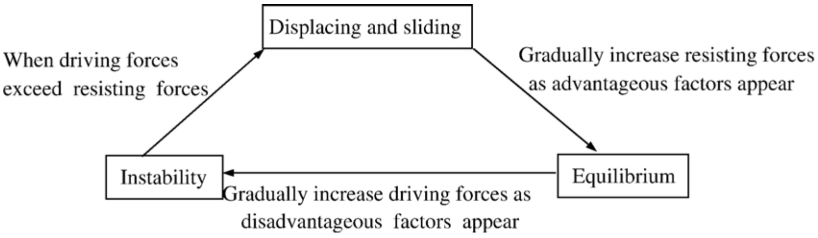


Fig. 2. Dynamic process of landslide development.

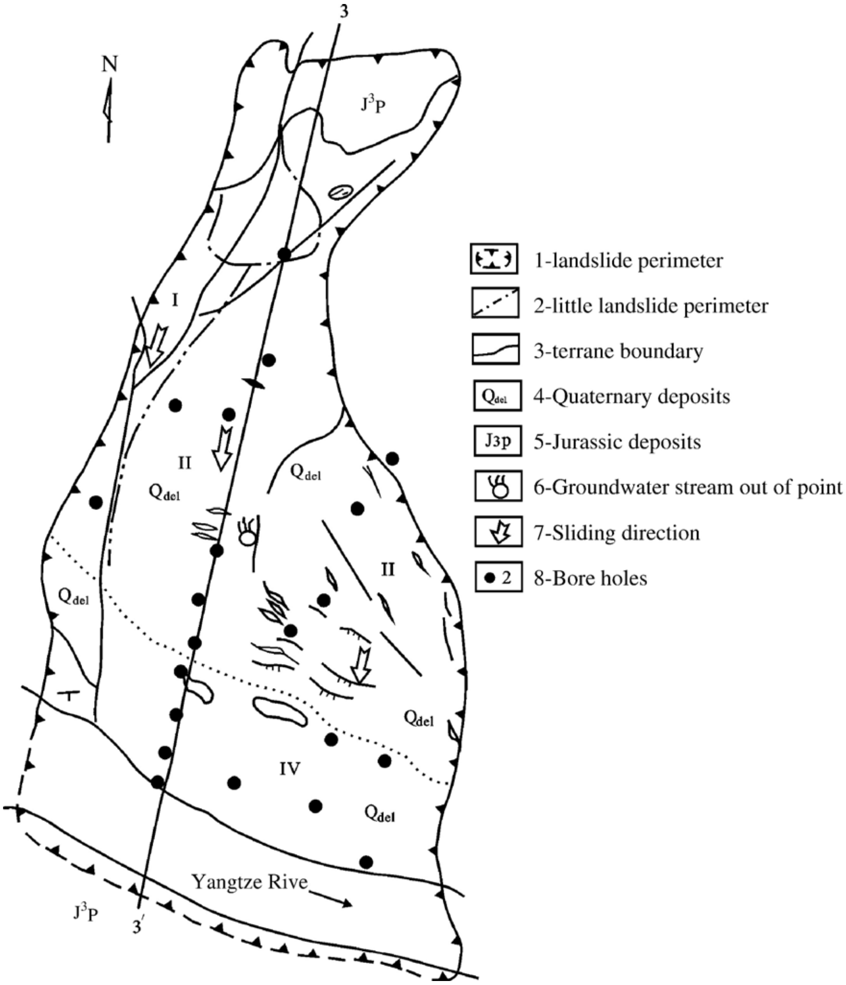


Fig. 3. Plane map of the Jipazi landslide, Chongqing, China.

these dynamic understanding and knowledge, any control measure should be dynamic. A dynamic comprehensive control method for landslide control can dynamically execute any control measure and evaluate its effects from site monitoring and investigations.

2.3. Dynamic comprehensive control method

Based on the above characteristics for the development and occurrence of landslides as well as our practical experiences, a dynamic comprehensive control method is proposed for landslide control. This control method is composed of following concepts: based on the monitoring data for landslides and the site investigations on landslide development, all measures for landslides control are reasonably organized at different stages and in different functional groups. One or more measures which may include “hard” and “soft” measures are applied to key positions of the landslides. These measures are to release or reduce sliding loads or enforce anti-sliding factors, thus preventing further risk of a landslide disaster in time. This method emphasizes that the organization of each control measure completely depends on the stage of landslide development. Therefore, the control method is dynamic and is to effectively prevent further development and occurrence of landslides.

2.4. Advantages of the dynamic comprehensive control method

Conventional methods assume that a landslide in its critical state (FoS is equal to or less than 1.0) has a sliding surface which has crossed through from top to bottom. There is no more space for further development in both sliding surface and soil/rock strength. This is an ideal and static situation. Furthermore, limit equilibrium analysis is usually applied to stability analysis, and any landslide control treatment is designed only based on the analysis results. Therefore, the design for landslide control is usually complex and expensive. In practice, the shear strength in the sliding surface is gradually developed with deformation, and sliding loads are progressively applied. Because of this progressive property some treatments are not effective immediately. The above arguments indicate that conventional methods are not suitable for those progressive landslides on either technical merits or cost-effectiveness. Compared with conventional methods, the current dynamic comprehensive control method has the following salient advantages:

1) Landslide control is always in a dynamic process, while conventional control methods are completely static. The current dynamic comprehensive control method does not only use pre-phase survey data, but also uses updated monitoring information. The more data available, the more clarity of understanding on this landslide, and the more accuracy of measures applied to the landslides control.
2) Multiple control measures are comprehensively applied to a landslide. All measures can be optimized through a feasible design system and the self-organizing ability of slope is fully explored.
3) The dynamic comprehensive control treatment is economical. It usually requires investments for landslide control at different stages and each investment is small. This can avoid a big amount of investment at one time contrary to conventional methods.

3. Case study on a open-pit landslide

This section will discuss the characteristics, content and application of the proposed dynamic comprehensive control method through a case study. Its applicability, efficiency and cost-effectiveness are evaluated through this example.

3.1. Geological and environmental conditions

Panluo iron ore mine is a middle-scale open-pit mine located in the western Fujian province of China. This mine was opened in 1965 and in full operation in 1978. Its annual production capacity is 3×10^5 tons. According to the original project plan and the current operation situation, the contour line at elevation of 920 m is the

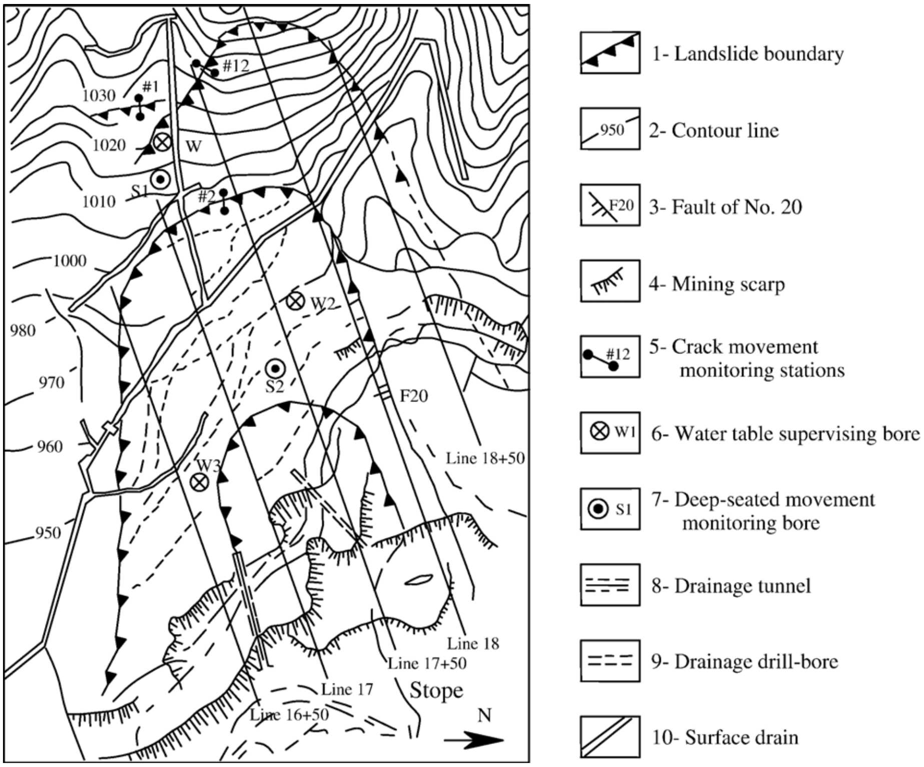


Fig. 4. Landslide scope, partial monitoring points and partial controlling treatments (a) annual rainfalls (b) displacement at key point #2.

Table 1
Rainfall and survey results at key points on the landslide during 1990 to 1996

Annual		1990	1991	1992	1993	1994	1995	1996	Total
Rainfall (mm)		2750.7	1341.8	2221.9	1784.2	1937.8	1487.0	1804.0	
Key point displacement (mm)	#1	50	120	0	80	120	100	134	604
	#2	500	190	2430	75	310	1980	730	6215
	#12	50	45	0	105	150	190	134	674

boundary to divide the pit into two parts: a mountain surface mine above 920 m, and a pit mine below 920 m. The pit is designed to dig down to 880 m. Because of the poor ore quality and the disturbance by local residents, the pit mine was closed at 887 m in 2000. While mining was executed up to 920 m on July 1990, the pit slope was already more than 100 m high and more than 300 m wide. This slope was then subjected to both an earthquake of magnitude 5.3 from Taiwan Straits and big rainstorms. Rather large-scale failures occurred, forming a U-shaped landslide as shown in Fig. 4. Tension cracks were also observed. The total latency volume was estimated up to 1.0×10^6 m^3.

As seen from Fig. 6, its ground conditions are as follows (from top to down):

(1) Overburden stratum of the Quaternary system: this stratum is mainly composed of eluvium, sliderock, and diluvium. Their geomaterials are mostly silty clay, with some quartzy sandstone detritus inside.
(2) Bedrock: there are three strata. The first stratum is completely and highly weathered mudstone, the second stratum is highly weathered sandstone, and the third stratum is middle weathered sandstone.

3.2. Cause and features about the landslide

In order to protect mine production and the safety for local residents, a landslide control team was immediately set up after the landslide was observed. This team carried out geotechnical and hydrological investigations, in situ tests, and stability analysis. They also installed a system to monitor the displacement of the sliding mass, local rainfall, and underground water. Based on these, a scheme for landslide control was proposed. Engineering geological investigations and field tests revealed that the poor strength of the slope mass is the main intrinsic cause of this slope instability, and the mining cutting at the slope toe, ground water and underground water (particularly due to rainfall) are external factors. Since the landslide occurred, the crack on the slope top had made a great adverse influence on the slope stability. The slope toe has no obvious appearance because the high-strength iron ore mass at the lower part supports the slope. This implies that a sliding surface has not been formed from top to toe. Based on the above information, this landslide has the following main characteristics:

(1) Geotechnical investigations show that this is a pre-existing landslide. It comes in live under combined actions of different factors.
(2) Slope instability is mainly induced by combined actions of earthquake and big rainfalls.
(3) Monitoring data (see Tables 1 and 2, and Fig. 5) show that the slope movement is closely related to rainfall. Stability analysis revealed that this slope was already in its critical state. When rain and rainstorm come, the slope soil is re-saturated and loses some shear strength, producing slope instability and sliding. Further analysis reveals that if mining continues up to 880 m, the new slope is unstable (See Fig. 6).
(4) Under combined actions of internal and external factors, the development and occurrence of the landslide is dynamic. Sliding is firstly developed in the shallow zone, then in the middle and finally in the deep zones. With further development, small landslides form a big landslide as shown in Fig. 7.

Table 2
Rainfall and displacements at key points of landslides in 1995

Months		1	2	3	4	5	6	7	8	9	10	11	12	Total
Rainfall (mm)		47.4	101.5	169.3	85.2	175.8	298.3	220.4	304.1	34.5	10.5	13.0	27.0	1487.0
Key point displacement (mm)	#1	0	0	30	0	0	30	0	30	0	0	10	0	100
	#2	0	0	40	30	0	215	155	1370	90	30	50	0	1980
	#12	0	0	10	0	1.0	20	0	120	0	10	20	0	190

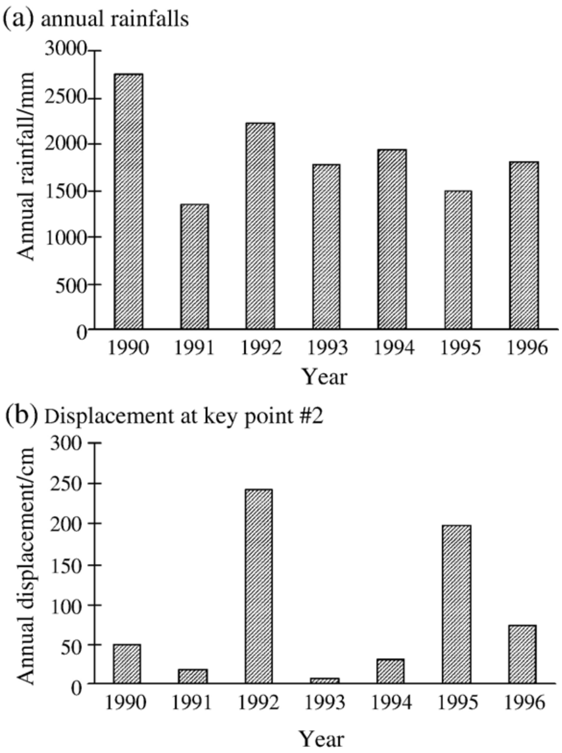


Fig. 5. Relationship of annual rainfall and displacement at key point #2.

3.3. Landslide control project

3.3.1. Landslide control scheme

Based on site investigations and in situ monitoring data, two schemes were proposed for landslide control: the first scheme is to use stabilizing piles. In this scheme, multi-ranks of stabilizing piles are used to support and hold back the sliding parts. This design is based on conventional control methods. The other scheme is to use the dynamic comprehensive control method. This scheme uses a comprehensive treatment to control further degradation of the sliding surface. These treatments include surface and underground water drainage, jambs of 10–20 m in width, subsection soil cutting (to reduce down-loads) in key sections if necessary, and some “soft” measures in the production management. In conventional control methods, stabilizing piles and backfilling soil in the slope toe would have been implemented to increase the weight of resistance. This requires a high investment (24 million RMB or 3 million US dollars) and is risky, because the stability analysis revealed that the sliding surface would develop gradually down to deeper levels if further mining were continued (see Fig. 6). After comparing the economical and technical merits, the dynamic comprehensive control scheme was finally adopted (Wei et al., 2003).

3.3.2. Measures and process in the dynamic comprehensive control method

As mentioned above, the dynamic comprehensive control method was finally adopted. The procedure as designed was basically implemented as shown in Fig. 8 in the landslide control. Details on the control measures and the implementation process were stated as follows.

3.3.2.1. Surface and underground water drainage. In 1991, early in the development of the landslide, a net system for monitoring the landslide was installed. As a first step, draining dykes were built along sliding boundaries and interiors (see Fig. 4). The cracks on the slope were backfilled and tamped to eliminate the effects of rainfall. Along with the measures finished at late 1991, the sliding movement became much slower (see Fig. 5 (b)). All-year displacement at key point #2 was only 190 mm. However, in the rainy season (from April to July) of 1992, there were many heavy storms and the annual rainfall was 2221.9 mm. The sliding rate increased rapidly. This information indicated that ground drainage might be the key measure to the stability of this slope. Site investigation shows that there is a lentoid plump area in the slope abdomen. This area is adverse to the stability of the slope. Based on the information of ground and underground water, a drainage system was constructed in the dry season of September of 1992. This system includes a drainage tunnel between line 17 and line 16+50 at 910 m and a horizontal drainage bore of 70 m long at line 17+50 (see Fig. 4). After the completion of this drainage system, the flow-out from the drainage bore reached 5 tons per day at beginning. Monitoring data (see Fig. 5(b)) showed that the landslide displacement rate had decelerated slowly in the year of 1993. Therefore, these drainage measures were effective to the stabilization of the slope.

3.3.2.2. Remaining ore jambs as supports. Site monitoring data showed that the landslides were still sliding all the time although their displacement rates changed slowly. A scheme for stabilizing piles was expensive and risky. The sliding depth increases with the development of landslides, thus the toe levels of pile foundations are difficult to be determined in the dynamic process of landslides. Furthermore, deep pile foundation is expensive. In the final scheme implemented, remaining jamb of 10 to 20 m wide along the landslide toe was made as retaining wall. Based on the limit equilibrium

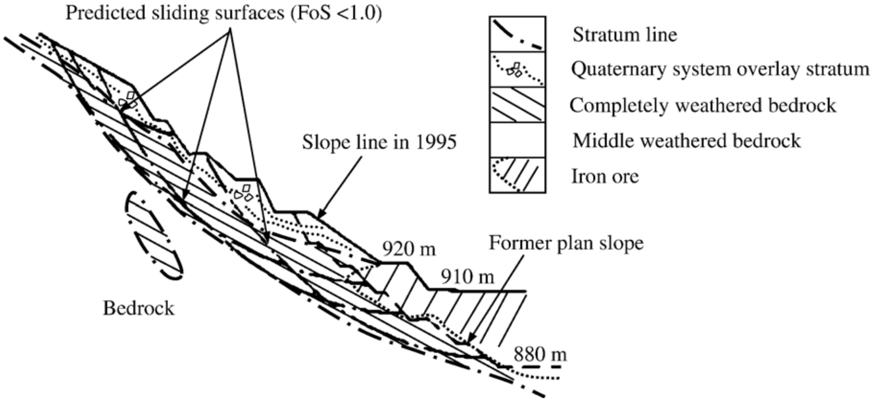


Fig. 6. Open-pit landslides containing multi-slip surfaces (from back-analysis).

method, this can improve the safety factor of this slope to 1.03 and the slope would be relatively stable. Site monitoring data showed that the displacement at key point #2 was less than before, indicating that this slope was being stabilized. In addition, this measure did not require any direct investment.

3.3.2.3. Cut soil on the slope top to reduce download. Although drainage and ores jamb measures to prevent the slope from further sliding had been implemented in time and got some effects on stabilization, the pit slope was still unstable with the down extension of the pit slope toe. In order to release the

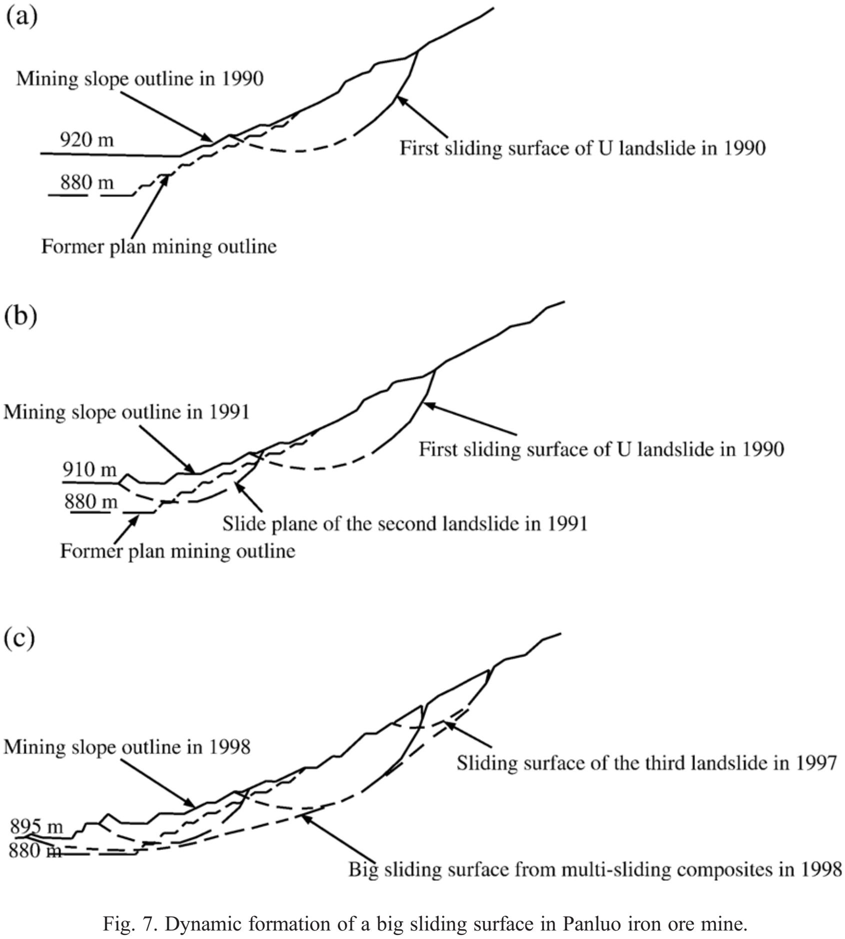
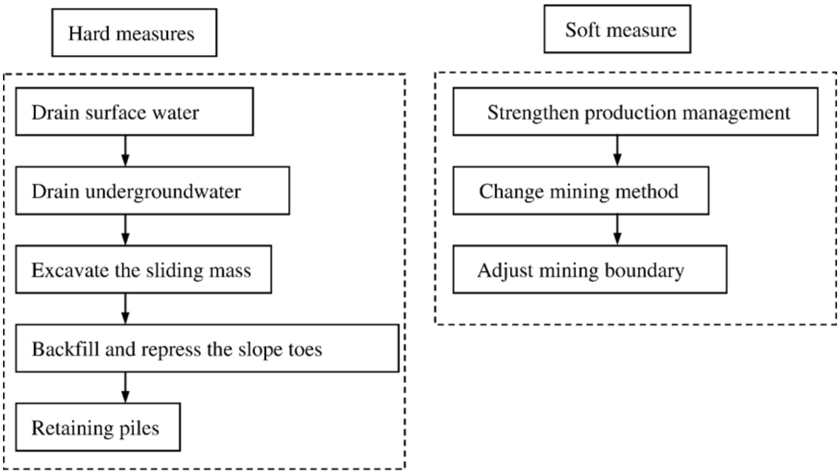


Fig. 7. Dynamic formation of a big sliding surface in Panluo iron ore mine.


(a) Measures for landslides control

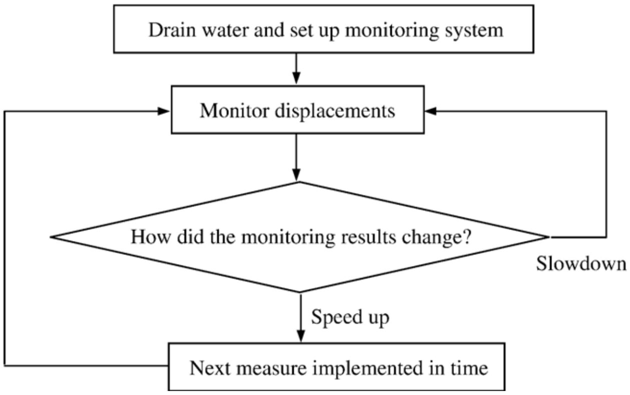

(b) Design procedures

Fig. 8. Control measures and design procedures to landslides control.

weight of the slope top and reduce downward forces, in every dry season from 1993 to 1998, the soil masses in the key part of slope were excavated and moved in three stages based on the results of limit equilibrium analysis. Cutting position and volume were then decided between line 17 and line 18+50 in horizon and from 1060 m to 940 m in elevation.

3.3.2.4. Adjust mining procedure and strengthen production management. According to the design plan in 1970s, the pit level descended uniformly. Since the slide occurred in 1990, mining procedures and production management were also adjusted to prevent further sliding. In 1995, an access method for ground mining was used to open the mine as "soft" measures for the landslide control. This method had the following procedures: Firstly, the slope was divided into many sections along horizontal directions of the slope. Secondly, stage mining and cutting were carried out. Thirdly, waste rocks were used to backfill the pit at the slope toe for slope stabilization (see Fig. 9). Finally, production management was strengthened, and the

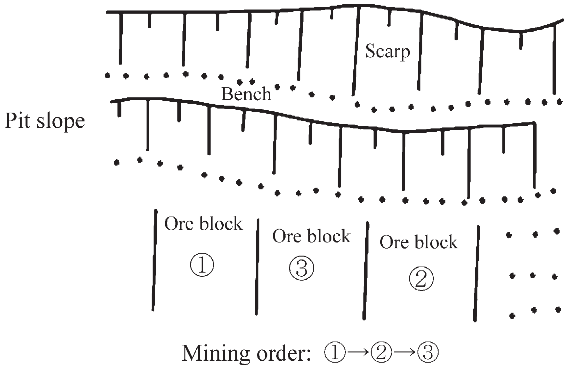


Fig. 9. A sketch of access method for mining.

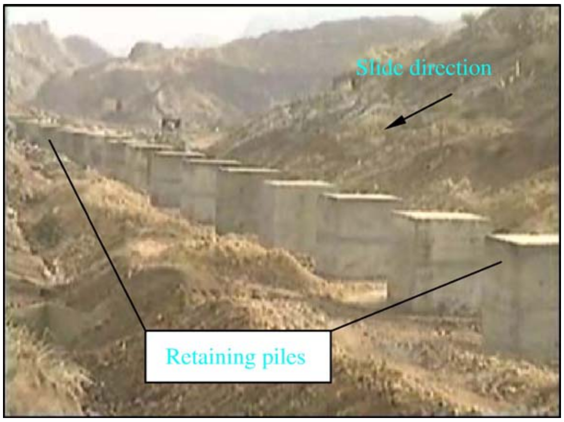


Fig. 10. Stabilizing piles for landslide control.

mining plan adjusted with season. For example, some preparation works such as cutting waste rock and reducing downloads were only done in rainy seasons. Cutting ore in dry seasons could avoid the adverse effect and potential accidents that may be induced by mining. Ore-mining zones were adjusted to prevent further deterioration. In order to meet market requirements, only high-grade ores were mined. The low-grade and poor quality ores were left there to heap the slope bottom. This method protected the resource, strengthened the slope stability and reduced the dump volume of wastes. The above measures were not only efficient, but also no direct investment was required.

3.3.2.5. Implement stabilizing piles, backfill the pit, and repress slope toe with waste rocks. Although the mine would close soon, a line of stabilizing piles (16 piles) was installed on the slope bottom in 1999 (see Fig. 10). The longest pile was 18 m in order to control a possible landslide radically. After the completion of stabilizing piles in 1999, the main parts of the pit (main sliding direction) were backfilled with waste rocks to keep the slope toe stability. Based on the analysis results of the limit equilibrium method, the pit slope has a FoS of 1.27 which is over 1.25 after these two measures were completed. The landslide toe had never been displaced again.

3.4. Evaluation of the dynamic comprehensive control method

Table 3 lists the main treatments during 1991–1999. Ten-years (From 1991 to 2000) monitoring data showed that the dynamic comprehensive control treatment had produced not only big economical benefit, but also an enormous benign society effect. The mine had produced 1.0×10^9 kg high-grade ores in these 10 years, producing a hundred million RMB income and prolonging the mine life. During the dynamic controlling process, the landslide was moving with seasons, but no safety accidents occurred due to sliding. Finally, after stabilizing piles and backfilling soil finished in 1999, two-years monitoring results showed that the landslide had been stabilized. For example, the displacement at key point #2 was only 14 mm in 2000. The efficiency was evaluated from site monitoring data and site records.

4. Conclusions

The external loading and deterioration of slope materials are progressive, forming a progressive and dynamic development and occurrence of landslides. For

Table 3
Main measures and execution time for landslide control

Mitigating measures	Execution time	Main objectives	FoS	Project's volumes	Cost (10^4 RMB)
Surface drainage tunnels	1991	Prevent surface water from infiltrating the slide mass.	/	800 m in length	16
Remain ore jambs		Stabilize the slope with stabilizing piles.	/	20.0×10^4 ton (ore)	/
Horizontal drainage tunnel	1992	Remove the groundwater within the slide mass.	/	40 m in length	60
Horizontal drainage bore				70 m in length	20
Cutting soil (first stage)	1993	Reduce driving forces of the slide mass.	1.07	9.0×10^4 m^3	180
Cutting soil (second stage)	1994~1995	Reduce driving forces of the slide mass.	1.05	7.0×10^4 m^3	140
Cutting soil (third stage)	1998	Reduce driving forces of the slide mass.	1.10	7.0×10^4 m^3	140
Stabilizing piles	1999	Further stabilize the slope.	1.27	16	180
Backfill the pit and repress slope toes		Increase resisting forces	1.27	8.0×10^4 m^3	Use waste rocks
					Total 736

Remark: (1) the mine was in half-production state due to disturbance by residents around during the second half year of 1996 and the first half year of 1997.
(2) Project-repairing fee is not included as investment in the table.
(3) Current currency ratio: 1 US dollar = 8.11 RMB.

such a progressive process, the current dynamic comprehensive control method is useful and economical for landslide control. This method is based on our accumulating knowledge on landslides including site investigations, site tests, and site monitoring data. The method emphasizes that multiple measures for landslide control are implemented in stage, in groups, and in time to prevent the occurrence of a landslide disaster. These measures may be "hard" and "soft" measures, including site drainage system, mining procedure, cutting and backfilling, stabilizing piles or jambs, production management, and so on. As a case study, the Panluo open-pit iron mine was analyzed. The details on the dynamic comprehensive control method were explained and its effect on landslides disaster control was verified through this case study.

Acknowledgements

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