Stability Analysis and Design of Open-Pit Mine Slope in China: A review

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ABSTRACT

Based on current researches and developments of open-pit mine slope in China, the engineering features of open-pit mine slopes are summarized. Mine slope is basically formed by dynamic excavation of multi-level and multi-type, and mining benefit is the purpose of mine slope engineering when using various schemes and/or methods. Thus, the issues of design and stability analyses are the main concerns in open-pit mine slope. Based on the experiences of a variety of projects, the development process of open-pit mine slope engineering in China can be divided into four phases: (1) experience-based analogical design; (2) design in combination of limit equilibrium analysis and experience; (3) quantitative analysis design; (4) dynamic design based on comprehensive analysis. In this regard, five key technologies of the mine slope stability analysis are proposed: (1) limit equilibrium analysis; (2) numerical simulations; (3) reliability analysis; (4) "3S" technology; (5) equivalent pattern recognition techniques. Finally, the difficulties and challenging issues in design and stability analysis of open-pit mine in China are presented accordingly.

KEYWORDS: Open-pit mine in China; slope stability analysis; research progress; prospect

INTRODUCTION

Development of open-pit mine slope project

The open-pit mining technique came into being when human beings began to use rock as the original tool about 450,000 years ago. The modern concept about open-pit mining was firstly proposed when the low-grade porphyry opencast copper mine in Utah Bingham Canyon was operated in 1903. After that, the open-pit mining technique entered an era of mechanized and large-scale mining activity. Since the 1950s, the open-pit mining projects have been frequently reported by virtue of its increasing production and intensification in association with improvement of labor productivity [1, 2]. Because of such characteristics as large-scale, high-effectiveness and high-productivity, the open-pit mining technology is commonly used in the solid mineral exploitation, including building materials; about 80% solid mineral was exploited with the open-pit mining
technique. Therefore, with the continuous increasing mining activity, the depth of many mines was deeper and deeper, such as Canada's Carol lake iron mine and Mont-Wright iron mine, whose mining depth was up to 400 m. In addition, the mining depth of Valley copper mine will reach 630 m, and the depth of the American's Empire iron mine is up to 455 m; the South Africa's Palabora copper mine will be up to 836 m, and the Chile's Chuquicamata copper mine is 1000 m\(^3\). In china, the mining depth is close to 700 m in ShuiChang iron mine. Obviously, the deep open-pit mining technique is main developmental trend in the near future. Therefore, the stability analysis and control technologies for open-pit mine slopes become critically important in strip mining engineering.

Engineering characteristics of open-pit slope

Ground surface associated with gradients is called slope or steep slope. The mining boundary formed by artificial excavation in open-pit mine is called ‘side slope’. The embankment slope formed in the railway and highway construction is called ‘road slope’. The slope formed in excavation road cutting is called ‘cutting slope’, and the slope formed by excavating during water conservancy construction is called ‘hydropower slope’. The open-pit slope engineering, a kind of geotechnical engineering, not only contains all of the engineering geological problems that are involved in geotechnical engineering, but also has its own characteristics compared with the hydropower slope and road side-slope [4].

1. The dynamic feature with mining

The open-pit slope is the important structure in open-pit mining. Because the mining process is conducted throughout the entire period of production services, the slope depth changes with continuous excavation (mining) process dynamically. In order to realize such a circumstance as early-producing and low-investment, the open-pit mining must reduce the early stripping as low as possible, so the initial slope is called as a ‘temporary slope’. Therefore, the steep slope is gradually formed in the middle and later period of the mining engineering.

2. Excavation engineering under specific geologic conditions

The purpose of mine production is to exploit useful minerals or mineral resources from underground. The mineral resources are not only a product of geologic process and geologic transition, but also buried in the geologic-specific surrounding and geologic structure. Dam site of the hydropower project is selected from several engineering geological conditions by feasibility analysis and comprehensive comparison. Compared with the hydropower engineering, the location of mining engineering has no choice to be selected, thus it must be mined under certain geological-specific conditions.

3. Mining economic benefits

The aim of slope excavation is to mine minerals in terms of the maximum mining benefits, thus it is rather different from the hydropower project which pays more attention to the stability and security of engineering operation. In order to reduce the overburden amount at the early stage, staged-excavation and steep-walled mining are implemented. At the same time, in order to explore the barrier pillar, it has to excavate slope angle, an adverse effect on the stability of slope.

4. Slope in terms of multi-step and multi-type
Slope of open-pit mine is much simple compared with underground mine engineering to some extent, but when compared with hydropower slope project, the open-pit slope is of a combination of structures in terms of multi-step and multi-type. In order to meet the need of production for open-pit mining, the transport platform, work platform, trenches and the pit-line access to open-pit must be employed. At the same time, the proper drainage tunnel and chambers in the slope must be excavated, which makes the structure of open-pit mine slope more complex.

5. Evaluation criteria for slope safety with the characteristics of multiplicity and complexity

The safety and stability of mining slopes vary with mining process and specific requirements. In general, the stability of slope only needs to meet the safety of mining, which ensures the stability in mining production period. Therefore, compared with the permanent work of hydroelectric project, mining slope is a kind of temporary project. When the deposit reserves, occurrence conditions, rock mass structure and mining scale are different, the period of service and stability demand of mine slope are also different. Usually, the service life of mine is shorter from tens of years to several decades, and the service life of sub-structure in mining slope is also different due to its different service object and application. Therefore, the safety evaluation criterion of mining slope is of multiplicity and complexity. If there are no structures and pipelines in influencing area of mine slope, the ultimate strength criterion is commonly used for safety evaluation; if there are structures and pipelines in influencing area of mine slope, the rock deformation must be strictly controlled; otherwise, the slope excavation will lead to damage of structures and pipelines by strata movement.

6. Slope project associated with maximum economic and social benefit

It is not necessary for mining slope to keep long-term stability, but it must keep safety production during the mining service period. Thus the principle that obtains the largest mining economic benefit and social benefit by using the smallest investment and maintenance cost is often employed. Then, the balance point between the mining safety and economic benefit by optimizing design and mining process should be focused on. Therefore, it is not an optimal design scheme for a slope that is still stable after mining is completed. It may be better while a slope fails within a short period of time after mining ending, which is the largest difference between mining slope and other permanent slope. Obviously this is also the maximum difficulty in the study and design of mine slope.

RESEARCH AND DEVELOPMENT OF OPEN-PIT SLOPES IN CHINA

Current situation of open-pit mining in China

Open-pit mining is widely used in China. The open-pit mining ratio of iron ore, non-ferrous, chemical industry and building materials is 90%, 50%, 70% and 50%, respectively [9]. It was estimated that about $4.9 \times 10^{10}$ ton coal reserves can be mined by open-pit mining in China. About 12%-14% of the total coal production will be mined by open-pit mining in 2020 [10].
Since the 1970s, a lot of open-pit mines in China had entered the deep concave region from hillside, as the height and angle of slope increased sharply. In this case, increasing landslide accidents were frequently reported, i.e. not only the probability of damage was increasing, but also the landslide scale was increasingly larger. Statistics indicates that when the slope height is more than 100-150 m, the frequency of landslide hazards is more obviously increased, which was confirmed by the cases including the landslide of Nanshan, Haizhou, Hainan, Daye, Blue Edge and Baguanhe. The investigation results of 12 large open-pit mine slopes in China showed that some mining slopes had potentially serious instability factors [11]. A case of the West Fushun Open-pit Mine, there were totally 70 landslide occurrences during the last 70 years from production to 1990, causing the rock volume nearly 1.0×10^8 m^3 to be cut to reduce the loading weight. Bedding landslide in 1959 destroyed the main transportation and lifting system of west alleys, whose recovering production lasted for three years, and the cost was more than RMB 2×10^7. In 1979, a large scale landslide occurred in the west slope of the open-pit mine again, which buried the main transportation system of the west alleys and mining production stopped. When the mining of Dagushan iron mine entered deep, partial subsidence and sliding happened in the east and west slopes. Since 1972, there were 19 slope sliding incidents in Daye iron mine and the landslide volumes accumulated to almost 1.4×10^7 m^3. In 1979 the landslide failed with rock mass value of 2×10^4 m^3. The length of unstable slope was 890 m, accounting for 19.8% of the total length. There were also two landslides occurring at Baguanhe limestone mine, and the weight of landslide body was 2×10^7 and 8×10^6 ton, respectively, which in turn had serious effect on mining production. The landslide volume of Baiyin open-pit mine was about 6.5×10^5 m^3. The upper part of the slope was exposed for more than 20 years, and more than 10 landslide accidents happened, of which 8 were the larger scale landslide. From 1975 to 1982, the sliding volumes in the upper wall and footwall were 1.48×10^6 m^3 in Jinchuan open-pit mine. The landslide body was piled up in the level 1514 m in March 1990 with collapse value about 4×10^5 m^3, leading to mine closure in July 1990. In Nanshan iron mine, 21 landslides were recorded from 1979 to 1990. The largest landslide recorded in 1980 had the volume of 2232 m^3. In Haizhou open-pit mine, the slope height has been nearly 240 m since 1952 and 73 landslides occurred, including three larger-scaled landslides, i.e. one landslide with volume of 3×10^6 m^3 in 1977, one with volume of 3×10^5 m^3 in 1986 and one in 1989 [12].

The potential instability of high-steep slope severely threatened the mining safety production and economic benefits, which remains the biggest obstacle to open-pit mining. Thus more and more potentially serious security problems in China[13, 14] can be observed with increasing open-pit mine depth. On the other hand, the angle of open-pit slope is above 45° in foreign countries, but it is immoral for the angle of open-pit slope higher than 40°-45° in China. Research results show that the stripped amount will greatly decrease for a large open-pit mine if slope angle is increased by 1°. For example, 1° increasing for the slope with angle 30°-60°can decrease the stripped amount by 3.43%-3.91%. When angle of slope with height of 500 m increases from 40° to 45°, stripped amount reduction per 1000 m length will reach 4.8×10^7 m^3 [15]. So the key technology for improving the mining efficiency is to increase the slope angle, which is also an important issue for a large open-pit slope.
Design stages of open-pit slope

Aiming at existing problems in open-pit mine in China, comprehensive key researches on deep open-pit mine mining were carried out during the "Eighth Five-Year Plan", "Ninth Five-Year Plan" and "Fifteenth Five-Year Plan" periods in China. The researches were involved in transport process, high-steps mining technology, high-steep slope stability, comprehensive technology of ventilation and dust prevention, which had made great progress in science and technology [16]. However, because of the inherent complexity and uncertainty in high steep mine slope design and analysis in mining process, it is more difficult for researchers to carry out stability analysis and to predict instability of high-steep open-pit slope. Therefore, it is necessary to successively carry out extensive and in-depth studies on the high-steep slope of open-pit mine.

According to the research and development of the mine slopes in China, the mining slope design development process is roughly divided into four phases as follows [15]:

1. Analogue design

From 1949 to the mid-1970s, the mining slope design was basically the copy of the pattern of former Soviet Union, or referenced to the primary experience to select slope angle by the designer's personal experience.

2. Analogy design combined with ultimate balance analysis

From the mid-1970s to mid-1980s, part of the open-pit mines in China had turned into deep mining. Then landslide disasters attracted the attention from the mining industry. On the basis of the experiences of large open-pit mine in mining, the analysis and design of the mine slope gradually entered the stage of engineering analogy combined with ultimate balance analysis and rock construction method from single analogy design. In this regard, the slope design was somewhat improved and slope angle was also increased. A typical case was east slope in Baiyunebo mine. The slope angle in the deep mining design increased 2°53 compared with the analogy method, which reduced stripping rock amount of 118.5 million ton [15].

3. Comprehensive quantitative design

From the mid-1980s to the 1990s, the metallurgical mine and coal mine slope became the hot issues in China. Our country carried out slope engineering science and technology research in the"Seventh-five" and" Eighth-five "period, the slope engineering research level increased significantly, especially the application of the rock mass structure mechanics on slope engineering. Mr. Gu Dezhen, from Chinese Academy of Sciences, who first proposed the concept of rock mass structure, put into effect the classification of rock mass structure revealing that the geological structural plane plays an important role in slope engineering stability analysis. On this basis, Wang Sijing academician and Sun Guangzhong professor established the slope geological structure model and rock mass structure mechanics theory according to different rock mass structure type, which laid theory foundation for numerical analysis and design optimization. At the same time, the slope engineering analysis method ,such as ultimate balance analysis, finite element analysis, discrete element analysis, DDA, and other technology program were rapidly developed, thus further promoted the numerical analysis of slope engineering, objectively reflect research of rock mass structure and comprehensive evaluation of slope engineering stability, All of these had established
the solid foundation for stability quantitative analysis and optimization design of complex slope engineering.

4. Dynamic design with comprehensive analysis of slope system

At the beginning of 21st century, many open-pit mines turn into deeper, higher and steeper slope open-pit mining in our country. For example, the slope height of Shuichang iron mine is close to 700m. Stability of high and steep slope is extremely sensitive to influence factors, and usually have "butterfly effect" and "chaotic effect", as a result, reliability analysis and risk prediction of slope are more difficulty. Therefore, the theories and methods of dynamic comprehensive analysis and optimum design, which integrate the engineering experience, numerical analysis and deformation monitoring, become the only way of slope stability analysis and catastrophe instability prediction. Deformation monitoring is the basis of dynamic analysis, limit equilibrium analysis; numerical simulation and engineering experience are the basis of comprehensive analysis. Through the deformation monitoring, dynamic feedback and comprehensive analysis of slope rock mass, the slope engineering stability analysis gradually close to actual engineering condition, provide technical support for optimization design, disaster prevention and control of slope engineering.

The development stage of open-pit slope stability analysis

Stability analysis of slope engineering is an important basis of slope design and optimization decision. Obviously, the reliability of analysis results is directly related to the safe production and mining efficiency of slope design. With the development of open-pit mining technology, the study on slope engineering stability undergoes four periods [4]:

1. Initiative stage

In 1950s, due to the limited open-pit mine scale and its development level, the traditional engineering geology and soil mechanics were adopted for mine slope stability analysis to study the reasons caused the landslide and corresponding prevention measures, the geological characteristics and structural effect of rock slope were neglected. Therefore, slope engineering stability research of this period is the beginning stage of qualitative analysis.

2. Phases of slope engineering analysis, monitoring and comprehensive evaluation

In 1960s, the stability of open-pit slope has entered comprehensive development period in our country. The representative work was stability research of Daye Iron Mine slope that conducted by Geotechnical Institute of Chinese Academy of Sciences and University of Science and Technology Beijing. Under the guidance of professor Chen Zongji, who began paying more attention to the effect of rock mass structure characteristics and rock rheological mechanics, in-situ test, indoor test, rock mechanics test, rheological test, structural plane test and dynamic test, were carried out which fully revealed the creep mechanism and instability failure mode of high-steep slope under high stress for slope engineering rock mass. At the same time, in-situ stress measurement techniques and deformation monitoring methods, were developed which not only realized the effect of in-situ stresses on the slope stability analysis, but also improved the slope deformation monitoring accuracy; promoted the numerical analysis technology advancement of slope engineering. This stage was the most active period of mining slope stability study in our country.

3. Breakthrough stage of rock mass structure effect and mechanics theory
In 1980s, Geological Institute under Chinese Academy of Sciences used the Jinchuan Open-pit Nickel Mine as engineering background, carried out a comprehensive, systematic and deep study on the mining slope stability. The engineering geology, rock mechanics and rock mass structure were comprehensive analyzed, which realized the combination and mutual infiltration between multi-discipline and multi-field. The results emphasized that geology is the basis of slope engineering analysis, stability is controlled by geological structure, the in-situ stress is the internal force and the slope excavation is outside power, the slope engineering stability depends on the interaction and coordination of internal and external force. Thus the theory and method of geological mechanics analysis in slope rock mass engineering were founded, the rock mass structure classification methods and mechanics theory system were established, which enriched and developed rock mass mechanics, made a major contribution to the slope engineering stability study.

4. Gradual perfect stage of slope engineering theory analysis

Since 1980s, combining with the theory study breakthrough of numerous large open-pit slope engineering in our country, slope stability theoretical analysis turned into the development and perfection stage. Its main signs were the establishment of rock slope typical geological model, the application of numerical analysis with CAD technology in engineering design, the reliability analysis and risk assessment of slope stability. In engineering practice, the founding of slope angle exploration, drilling core orientation technology and rock mass structure mechanics theory, which laid the research foundation for the our country’s open-pit slope engineering, perfected the slope engineering analysis theory [17-22]: the unique rock slope stability analysis and design methods were formed according to the engineering geology, the rock mass structure theory as well as geological structure.

RESEARCH ADVANCEMENT OF MINE ENGINEERING IN CHINA

Stability evaluation and instability risk prediction are the core theme of slope engineering; slope stability analysis techniques mainly include limit equilibrium analysis, graphic analytic method, numerical simulation and the reliability analysis and so on. The application of comprehensive system method, fuzzy mathematics, grey theory, neural network, genetic algorithm, chaos, evolutionary algorithm, nonlinear and uncertainty analysis technology enriched analysis theory of mine slope engineering.

Limit equilibrium analysis

Limit equilibrium analysis theory is a slope stability analysis technology with the longest development time, in 1950s and 1960s, this analysis technology was widely used in our country’s open-pit slope. Compared with the early empirical method, limit equilibrium analysis technology can quantitatively evaluate the slope stability and enhance the reliability design of slope angle. For example, the Original Anshan Metallurgy Research Institute used the engineering analogy and limit equilibrium analysis technology to improve the overall slope angle 2°53′, which decreases the stripped amount to 118.5325 million ton (see Table 1 and Table 2 [15]) in the deep mining design.
of East Baiyunebo Mine. Limit equilibrium analysis is still an important analysis technologies in slope design until now.

**Table 1:** The slope angles of the East mining in Baiyun mine

<table>
<thead>
<tr>
<th>Design partitions</th>
<th>Design of slope angle</th>
<th>Slope Angle increase value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feasibility studies</td>
<td>Preliminary design</td>
</tr>
<tr>
<td>I、Ⅱ</td>
<td>38°24′</td>
<td>41°11′</td>
</tr>
<tr>
<td>Ⅲ</td>
<td>41°03′</td>
<td>43°39′</td>
</tr>
<tr>
<td>Ⅳ</td>
<td>36°21′</td>
<td>39°32′</td>
</tr>
<tr>
<td>Ⅴ</td>
<td>37°57′</td>
<td>41°43′</td>
</tr>
<tr>
<td>Ⅵ</td>
<td>39°17′</td>
<td>41°44′</td>
</tr>
<tr>
<td>Ⅶ</td>
<td>27°42′</td>
<td>30°11′</td>
</tr>
</tbody>
</table>

**Table 2:** The results of improving slope angle in the East mining Baiyun design

<table>
<thead>
<tr>
<th>No</th>
<th>Project name</th>
<th>Feasibility studies</th>
<th>Preliminary design</th>
<th>Reduce value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rock volume in mining bounds /10^3m³</td>
<td>13727.78</td>
<td>9632.83</td>
<td>4094.95</td>
</tr>
<tr>
<td>2</td>
<td>Rock weight in mining bounds /10^4 t</td>
<td>39414.29</td>
<td>27561.04</td>
<td>11853.25</td>
</tr>
<tr>
<td>3</td>
<td>Average stripping ratio /t⁻¹</td>
<td>2.73</td>
<td>1.95</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>Practical stripping ratio /t⁻¹</td>
<td>3.50</td>
<td>2.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Numerical simulation technology**

Many researchers use finite element method to carry out the numerical analysis of mine slope engineering. Zhou Quwei et al, used the finite element method to simulate the stress concentration of excavated slope rock mass [23]. Shi Jianjun et al, simulated the feasibility of open mined-out area that will be constructed as tailings reservoir based on the finite element software ANSYS[24]. Fu Xudong with others adopted the self-compiling program for the numerical analysis of slope reliability[25-27], which laid a foundation for slope stability quantitative evaluation. Ceng Sheng et al, adopted ABAQUS-ANFIS program for the reliability analysis of open-pit mine slope [28]. Sun Shiguo et al, combined the finite element numerical simulation with the measured data analysis to study the superposition characteristic of combined mining and its influence on slope engineering, and quantitatively research the interaction and interference mechanism between two excavation systems based on the combined underground mining and open mining West Fushun Open-Pit Mine [29]. Aiming at the limitation of finite element method to simulate of the geotechnical materials in nonlinearity, joint fissure and other discontinuity, Tang Chunan et al, carried out "RFPA (Rock Failure Process Analysis) theory research and application development" in 1995. Li Changwen et al, applied the RFPA2D in the numerical simulation of NanFen open-pit mine slope instability. By analyzing typical profiles, obtained a conclusion in conformity with the actual landslide, provided an intuitive, realistic and more reliable analysis method for slope research [30].

The FLAC software was developed by the ITASCA Company, which is an explicit finite difference program. Compared with previous difference analysis, it not only can deal with general large deformation, but also can simulate the sliding deformation along a weak plane. There can successfully simulate the mechanical behavior of damage or plastic flow when geological materials up to the ultimate strength or yield limit and reveal the slope progressive failure process or the
instability mode of slope engineering for different material properties. Tan Wenhui and others taken physical simulated of slope progressive while carried out the numerical simulation analysis of slope progressive failure by using FLAC software, who used the the south working wall slope in a Henan mine as engineering background. The results shown that the combination of physical analysis and FLAC numerical simulation could expose the mechanical of rock slope progressive destruction on both surface and essence[31]. Hou Kepeng carried out a dynamic, visual simulation, which were the motion state and stress, displacement and block’s movement speed of ZhuJiabao Iron Mine slope by using the large deformation of discrete element method and CAD technology. The analysis provided theory basis for mine engineering design, slope reinforcement, and safety production. Meanwhile, the results shown that the slope stability results by discrete element analysis were suitable and reliable [32].

Zhungeer Heidaigou Open-pit Coal Mine is a modern large open-pit mine designed and constructed by China, its west dump is located in the ancient landslide development zone. Due to the dump’s particularity, it is difficult to detect deformation. Once found the deformation of slope, The destruction is unavoidable, because the force enhanced dramatically and sliding speed increased rapidly in short-term. This landslide engineering puts forward a new research subject for our country open-pit mine dump’s design, construction, stability analysis and the control aspect of dumping program. Considering the dynamic loading process of dump engineering, discrete element method is used for the stability analysis of Heidaigou open-pit mine dump slope, which provide a theoretical basement for the safety production and risk control of open-pit mine slope engineering [33].

Reliability analysis

A large number of random variables involve during the analysis of slope stability, so state parameters of mass engineering have random distribution properties, destruction mode and failure process of slope also have obvious randomness. The numerical analysis represented by finite element cannot reveal the influence of parameters randomness on the analytical results, which has not considered the variability of its parameters, so the results obtained by using numerical simulation analysis are often inaccurate. On the basis of probability theory and mathematical statistics, reliability theory can compensate the inadequacy of numerical analysis to some extent. Reliability analysis can reflect the actual state of rock mass engineering well by considering the parameters random distribution. The reliability analysis technology combining numerical simulation is a kind of the effective way to solve the complex rock mass stability analysis.

The reliability theory gets rapid development in the mining slope stability analysis, and explores a new road for mining slope stability analysis and risk prediction. The geotechnical engineering reconnaissance specification (GB50021-94) has pointed out that in addition to the stability coefficient to calculate slope stability for large slope design, it is appropriate to analyze the slope reliability, and carry out the sensitivity analysis on the influence factors of slope stability. The common methods of reliability analysis are Monte Carlo Simulation (Monte-Carlo Method), first order second moment (FOSM), Rosenblue Method and the improved first order second moment method, etc [28].
Since the early 1970s, the reliability theory had been used in mine slope engineering, which attracted universal attention in rock and soil engineering. Slope reliability analysis studies the security issue of slope under the action of all sorts of certainty and uncertainty factors, taken the uncertainty of slope engineering geological properties and working status into quantification, thus the uncertainties were included into slope design process. Qiu Xiande et al, by using Monte Carlo Simulation Method, finished the reliability analysis results of the northwest slope exploration in Lanjian Iron Mine (see table 3). It pointed out that the failure or reliability probability obtained from slope reliability analysis is different from the safety coefficient in the value analytical method, higher safety coefficient doesn't mean the lower slope failure probability, Sometimes, the safety coefficient meet the requirements of allowable safety coefficient, but failure probabilities can't be accepted [34]. Wang Jiachen and others researcher applied the Monte - Carlo method to calculate the reliability of A- section in Yanqianshan open-pit mine slope whose results show that the slope reliability of mining has the dynamic decrease trend (see table 4 and figure 1) [35].

Table 3: The results of reliability for the 3 and 4 test in the Lanjian mine slope

<table>
<thead>
<tr>
<th>Profiles</th>
<th>Ave.safety coefficient CSF</th>
<th>Reliability Index β</th>
<th>Instability probability Pf</th>
<th>Ave.safety coefficient CSF</th>
<th>Reliability Index β</th>
<th>Instability probability Pf</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-6</td>
<td>1.19</td>
<td>1.957</td>
<td>2.51×10⁻²</td>
<td>1.23</td>
<td>2.152</td>
<td>1.57×10⁻²</td>
</tr>
<tr>
<td>5-5</td>
<td>1.75</td>
<td>4.680</td>
<td>1.43×10⁻⁶</td>
<td>1.32</td>
<td>2.238</td>
<td>1.26×10⁻²</td>
</tr>
<tr>
<td>4-4</td>
<td>1.57</td>
<td>2.871</td>
<td>2.04×10⁻²</td>
<td>1.40</td>
<td>2.565</td>
<td>5.16×10⁻³</td>
</tr>
<tr>
<td>3-3</td>
<td>1.31</td>
<td>1.850</td>
<td>3.21×10⁻²</td>
<td>1.34</td>
<td>2.082</td>
<td>1.87×10⁻²</td>
</tr>
<tr>
<td>7-7</td>
<td>1.17</td>
<td>1.931</td>
<td>2.67×10⁻²</td>
<td>1.36</td>
<td>2.897</td>
<td>1.88×10⁻³</td>
</tr>
<tr>
<td>2-2</td>
<td>1.29</td>
<td>1.970</td>
<td>2.44×10⁻²</td>
<td>1.55</td>
<td>3.604</td>
<td>1.57×10⁻⁴</td>
</tr>
<tr>
<td>13-13</td>
<td>1.05</td>
<td>1.264</td>
<td>10.4×10⁻²</td>
<td>1.13</td>
<td>2.686</td>
<td>3.62×10⁻³</td>
</tr>
</tbody>
</table>

Table 4: The calculation results of 2D reliability of the A profile in the surface slope of Yanqian mountain mine

<table>
<thead>
<tr>
<th>Mining level /m</th>
<th>Ave.safety coefficient</th>
<th>Standard deviation of safety Coef.</th>
<th>Reliability Index</th>
<th>Instability probability %</th>
</tr>
</thead>
<tbody>
<tr>
<td>-195</td>
<td>1.3804</td>
<td>0.1367</td>
<td>2.7819</td>
<td>0.2702</td>
</tr>
<tr>
<td>-147</td>
<td>1.4004</td>
<td>0.1416</td>
<td>2.8275</td>
<td>0.2346</td>
</tr>
<tr>
<td>-99</td>
<td>1.4084</td>
<td>0.1423</td>
<td>2.8694</td>
<td>0.2056</td>
</tr>
<tr>
<td>-51</td>
<td>1.4182</td>
<td>0.1425</td>
<td>2.9354</td>
<td>0.1666</td>
</tr>
</tbody>
</table>
For the north high-00 steep slope of Changba Lead-zinc Mine, Gao Qian and others conducted the reliability analysis and risk prediction of slope stability in 1253m level. The results shown that slope was more sensitive to rainfall and dynamic loading. Considering the effects of seepage pressure, blasting, rainfall and blasting dynamic load, the instability probability under the most unfavorable factors were obtained, the risk prediction of slope stability under the strong mining condition were carried out [36].

**Applied technology**

With the development of computer hardware and software technology, "3S" (GPS, GIS, RS) technology are widely used in many engineering. GPS technology is developed by the department of defense, which makes up of 24 satellites; they are distributed in six orbit planes, the height of orbit plane is about 20183km. The positioning of GPS technology has high precision, fast, easy to operate and full-weather observation characteristics, three dimensional displacement coordinates (X, Y, Z) are measured at the same time, which can accurately measure the rate of a moving point, and not be restricted by visibility conditions for continuous monitoring. GPS technology is applicable to the horizontal displacement and vertical displacement monitoring of different deformation stages. The Institute of Geology, China Seismological Bureau, the ministry of natural resources, the Yangtze River Water Resources Commission and other units used GPS technology for landslide monitoring in three gorges reservoir area [37,38]. Institute of Geology and Geophysics, Chinese Academy of Sciences used GPS technology for the surface subsidence observation in Jinchuan Nickel Mine; University of Science and Technology Beijing used GPS technology for the slope deformation monitoring in Shuichang Iron Mine and Changba Lead-zinc Mine, and has achieved better results(see Fig.2) [39].
Figure 2: The plane map of 3D dangerous sliding in the I and II mining area in Shuichang iron ore

GIS (Geographic Information Systems) provides a public platform and general data structure for space science, has been more and more widely used in civil engineering in recent years. GIS is an integrated information system that including data capture, input, manipulation, transformation, visualization, merger, retrieval, analysis, modeling and output. GIS provides the multi-functional spatial data analysis ability and spatial display function, and the required data stored in spatial database. GIS greatly shortens the preparation and processing time of data, and can handle information from different sources. Predictably, the GIS data form will become the basic data form of spatial data process. Although many engineers and researchers understand the GIS technology, the personnel who can discover the potential strong analysis ability is not much, mostly applications are limited to the large regional analysis, such as land-use, environmental analysis and hydrological analysis, etc. In fact, small-scale applications have become possible, such as the large open-pit mine slope.

The application of GIS technology on mining starts relatively late in our country, by means of one of the Ministry of Science and Technology major projects, Changsha Institute of Mining Research undertake the GIS research on metal mine engineering geological disaster prevention and cure technology, University of Science and Technology Beijing successfully applied 3DSlopeGIS to the three-dimensional limit equilibrium analysis of Shuichang Iron Mine slope to carry out the stability analysis under various load conditions by two schemes including original design and optimization design, thus determined the rationality and reliability of optimization design scheme.
Figure 3: The flow chart of equivalent pattern recognition for slope stability analysis in Changba mine

The analysis steps based on GIS technology include: Firstly, to collect data to build the needed GIS database of slope stability analysis, dynamic monitoring and evaluation and control management system. The data need to be collected include: (large-scale) location plan (1:10000~1:50000 topographic map and comprehensive chart), correlation diagram (range is bigger than mining scope over 400m), topographic map (1:2000), engineering geological zoning map (1:2000), engineering geological profile, fault, structural plane and other information; mine design drawing (1:2000), engineering geology, hydrogeology and slope failure investigation report, test report of rock physical and mechanical properties, the seismic design data, preliminary slope analysis report and information. Then import the collected data into established GIS database and map digitize of the original data, which can form a three-dimensional dangerous sliding surface search area plan (see figure 4). Secondly, to search the sliding zone one by one, get the dangerous sliding surface, and follow three three-dimensional slope stability analysis models based on cylinder unit to analyze the model: (1) The classic model based on cylinder unit, this model has the same assumption as Hovland model, and considering the effect of seismic load. (2) The second
model is three-dimensional model proposed based on Hungr in 1987, this model is the three-dimensional extension of two-dimensional Bishop Model. (3) The third model is the three-dimensional extension of Janbu two-dimensional model, it was proposed by Hungr in 1989, which can calculate the slope stability safety coefficient under different earthquake and groundwater combined conditions. Finally, compares the safety factor decrease range of the applied approach and the original design scheme, confirms the slope stability and rationality of applied approach. Using GIS technology to optimize the design of Shuichang Iron Mine slope, make the mining area slope angle increased 1°~6°, decrease stripping 30~50 million ton, thus obtain remarkable economic benefit and social benefit[40].

The application of Remote Sensing technology (Remote Sensing System) on slope engineering began in 1950s, its application field has been developed from original geological mining and mapping to geological mining and mapping, agriculture, forestry, land, sea and transportation departments, and play an important role in those departments. The RS and GIS have been applied to the slope stability analysis and safety evaluation.

So the "3S" technology combining GIS, GPS, RS, are the development direction of open-pit mine slope engineering research. The increasingly fusion of RS and GIS data structure, make it possible to convert RS grid information and GIS vector information. Therefore the "3S" technology will play more and more important role in our country’s open-pit mine slope engineering in the future.

### Equivalent model recognition technology

Slope equivalent model recognition technology is based on the monitoring rock mass displacement in actual engineering stage (the current slope height), the equivalence model identify of the current stage of practical engineering’s numerical model is established (equivalent parameters and boundary conditions), thus the rock mass equivalent parameters are identified. According to the rock mass equivalent model, numerical analysis and stability evaluation of current engineering are made. Based on the achieved rock mass equivalent parameters, the dynamic prediction of the next construction stage is conducted. At the same time, according to the displacement monitored in the next step engineering construction, rock mass parameters corresponding to the current engineering stage is identified, thus the corresponding equivalent parameters are gained. Implement this circle until the end of mining. For Changba Open-pit Mine slope, the research technical route of slope equivalent identify model is shown in Figure 3, which was conducted by University of Science and Technology Beijing. By using the GPS monitoring data the equivalent model recognition was adopted to analysis the dynamic excavation slope based on orthogonal numerical testing(Fig.3) [36].

It should be pointed out that the combination of information technical development and numerical calculation technology provide the new approach for the stability analysis of dynamic excavation and complex features mining engineering slope, the optimization design, the disaster prevention and control research. Therefore, new theory, method and technology should be used for the requirement of mine slope engineering characteristics and stability, modern information platform should be used to develop and perfect the system integrating the mining slope information storage and management, analysis and synthesis, forecasting and prevention and control, thus
improving the slope design and analysis ability. The analysis and research methods must be closely combined with slope geological conditions and engineering practices that may effectively push forward the mine slope research.

**CHALLENGES OF MINE SLOPE SLOPE RESEARCH**

With the continual exploitation of mineral resources, mining slope around safety, efficient, environmental and sustainable development goal, and deeply research, has made significant progress in China. However, at present many large-scale iron mines including Dagushan, Daye, Nanshan, BaiyunObo and a large number of open-pit coal mines and nonferrous metal mines have been transferred or transferred into deep open-pit mining, which make the research of mine slope engineering faced with severe challenge. The Mining slope is generally designed to 300~500m, with individual case reach above 700m. Slope stability is related to the mine safety production and economic benefits, and also affects the mine production capacity and the sustainable development of the enterprise. So the mines take reasonable measures to maintain slope under the premise of ensuring mining safety, which is an important topic of the high steep slope faced [5].

Most of large and middle-scaled mines in China were established in the 1950s and 1960s. After decades of exploitation, 80% of the iron mines had entered into middle and late stage, and faced with the problem of closed pit [6,7]. For these mine development status, making full use of existing production system and equipment to obtain the maximize recovery of mineral resources and extend the mine life before mine transition from open pit to underground, to relieve the pressure from mine production in short period and arrange a large number of idle staff are the realistic problem faced by mine enterprise[8]. On the other hand, some new open-pit mines are located in plain country and near to city, so the issues of mining safety and environment become increasingly prominent. For example, Heshangqiao Open-pit Iron Mine located in Xiangshan City with 5 km distance from southwest Jiashan township and 12 km distance away from Ma On Shan, produce 5 million tons of ore per year. Therefore, the mine development put forward more strict requirements for digging environment, the ecological construction plan, environment impact assessment and corresponding control measures must be carried. Sijiaying Iron Mine affiliated Hebei Iron and Steel Group also faces environmental protection and ecological restoration problems.

At present, in China, the open-pit coal mines are mainly distributed in the areas of western and northwestern loess plateau, and most of them are nearly horizontal and gently inclined coal seam, such as Pingshuo Antaibao open pit coal mine, Pingshuo Anjialing open pit coal mine and Heidaigou Open Cast Coal Mine in Inner Mongolia Zhungeer, etc. Because of extremely complex geological conditions and occurrence characteristics of coal seam in loess plateau region, mining in this area has its particularity. The combined mining method of open pit and underground is widely used, a new research subject about slope came into being: how will the two mining methods interact with each other under the influence of combining mining of open-pit with underground mining, we need to establish a new evaluation criterion and analysis method. Now our country’s Daye Iron Mine, Shirengou Iron Mine, Baoguo Iron Mine, Heiwang Iron Mine, Changba Pb-Zn Mine, West Open-pit Coal Mine of Fushun, Xingcheng Gold Mine and other large open-pit mines turn into underground mining. The large-scale excavation blasting of open-pit mining period has a significant impact on the rock mass of slope, and produces higher stress concentration at the foot of
slope. On this basis, if we go on underground mining, especially when the mining of the barrier pillar, stress disturbance and landslide will be caused, which bring great difficulties to the transition from open-pit to underground mining and have potential risk of slope instability[41,42].

CONCLUSIONS AND PROSPECTS

With the exploitation of mineral resources in China, mining slope engineering around the safety, efficient, environmental and sustainable development goal, has made great improvements and gets some valuable progresses. However, open-pit mining has entered complex mining environment in high and steep, deep, surface and underground combined mining, the mine slope engineering research still face with severe challenges. Researchers and managers of mine slope engineering should have the scientific development outlook to treat and estimate the development process and shortcomings of slope engineering in our country. From a higher strategic height, they should prospect the development trends of open-pit mine slope engineering, put forward a malleable research topic as well as push the research and develop in mine slope engineering.

Mine slope is a complicated open system composed of many subsystems. The complexity refers to the system dynamic change, and the interaction between different factors in the system. It is a nonlinear system including uncertainty, fuzziness and incompleteness. Therefore, system analysis method is one of the significant ways to research and solve complex slope engineering in the future.

The key point of mine slope optimum design and stability control research is to reasonable evaluate and quantitative express the engineering characteristics and influence factors. In fact, people has realized that the slope stability mainly depends on two aspects: Firstly, the geological condition and occurrence environment of slope rock mass (ground stress, groundwater, etc.); Secondly, the engineering factors influencing on slope stability, such as rock mass excavation, blasting vibration, and maintenance measures, etc. Though the existing analysis methods consider the interaction between influencing factors and their contributions to slope stability, but corresponding theory and concepts are vacant.

The research of engineering geology [54], discusses the interaction of human engineering activities and geological environment and its impact on the environment, has identify that geodynamics is the basis of the geological environment, disaster and engineering research [55]. For the single function of influence factor, the research puts forward the comprehensive analysis and the coupling effect of internal and external motivation factors. This is the first study to investigate the coupling effect of internal and external motivation factors and the cause analysis of major geological disasters [56]. The suggestion to carry out the theory research of internal and external motivation factors focused on coupling effect will be a new way to the research of mine slope engineering.

At present, "3S" technology, mostly based on GIS, RS and GPS, have play important role in resource development and environmental protection. GPS has been applied in many open-pit mines slope deformation monitoring in our country, which improves the economic benefit and social benefit to mining area. However, the open-pit mine engineering face even greater difficulties in landslide instability, environmental protection and high efficient mining, so the development and application of "3S" technology in slope engineering become more important. The application of
"3S" technology not only can conduct mine slope engineering information acquisition, analysis and process, realize the stability evaluation and instability prediction of high-steep mine slope, even more important, it also can realize the mine environment monitoring and the comprehensive evaluation of mining environment. As may be expected, the application of "3S" technology in the open-pit mine slope engineering is bound to further research and development \cite{57-60}. Today, with the emergence of globalization of knowledge, the research is not a country or region can independently complete. Mine slope research in China sincerely look forward to the cooperation with the international mining industry, make joint efforts to push the mine slope research into a new stage of development, make greater contribution to the rational and efficient development of mineral resources.

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