CrossMark

sciendo Applied Mathematics and Nonlinear Sciences 6(1) (2021) 319–334

Applied Mathematics and Nonlinear Sciences

https://www.sciendo.com

Research progress in the mining technology of the slowly inclined, thin to medium thick phosphate rock transition from open-pit to underground mine

Xiaoshuang Li[1,2,3], Yunming Wang[2,3], Shun Yang[1,4,†], Jun Xiong[5], Kui Zhao[4]

[1] School of Civil Engineering, Shaoxing University, Shaoxing Zhejiang 312000, China

[2] Sinosteel Maanshan General Institute of Mining Research Co. Ltd, Maanshan 400045, China

[3] State Key Laboratory of Safety and Health in Metal Mines, Jiangxi University of Science and Technology, Ganzhou, Jiangxi 341000, China

[4] Jiangxi Key Laboratory of Mining Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China

[5] Department of Civil and Environmental Engineering, University of Alberta, Alberta, Edmonton, T6 G 1H9, Canada

Submission Info

Communicated by Juan Luis García Guirao
Received December 24th 2020
Accepted January 31st 2021
Available online May 25th 2021

Abstract

This paper takes the deep ore body of Yunnan Phosphate Group Co. Ltd, the largest open-pit chemical mining enterprise in China, as the research background, and systematically introduces the technical problems recognised by many Chinese researchers in the past eight years on the open-pit to underground mining of gently inclined thin to medium-thick ore bodies with a soft interlayer. It shows that the mining of open-pit transferred to underground is a complex engineering system, and the underground stope surrounding rock and overlying strata present a nonlinear failure process. Through mining process innovation, mining method innovation and improvement, research was undertaken on new processes and technologies for phosphorus mining under complex conditions. The relevant research results not only have important economic value and academic significance for Yunnan Phosphate Group Co. Ltd. but also have important guidance and impetus to the exploitation of a large number of similar phosphate resources in China.

Keywords: gently inclined thin to medium-thick phosphate rock; convert from open-pit to underground mining; gently inclined thin to medium-thick ore bodies with soft interlayer; new mining technology and new technology

†Corresponding author.
Email address: 18720720706@163.com

sciendo ISSN 2444-8656 doi:10.2478/amns.2021.2.00017 sciendo

1 Introduction

The gently inclined orebody with thin-medium thickness occupies a considerable proportion in phosphate mining in China. Out of the estimated 16.786 billion tons of phosphate rock resources, more than about 75% of the seam is gently inclined orebody with thin-medium thickness. Gently inclined orebody with thin-medium thickness means the dip angle of 5°-30°, the thickness of the orebody is 1.0–15 m. Gently inclined orebody with thin-medium thickness has the typical characteristics of the gentle dip angle, the shape of the orebody changes greatly, and the ore boundary is unclear. Comprehensive analysis of the existing research results shows that the existing open-pit to underground mining research is mainly concentrated on iron ore, copper ore and other vein-like metal mines, while non-metallic gently inclined orebody with thin-medium thickness phosphate ore is rarely involved as shown in Figure 1.

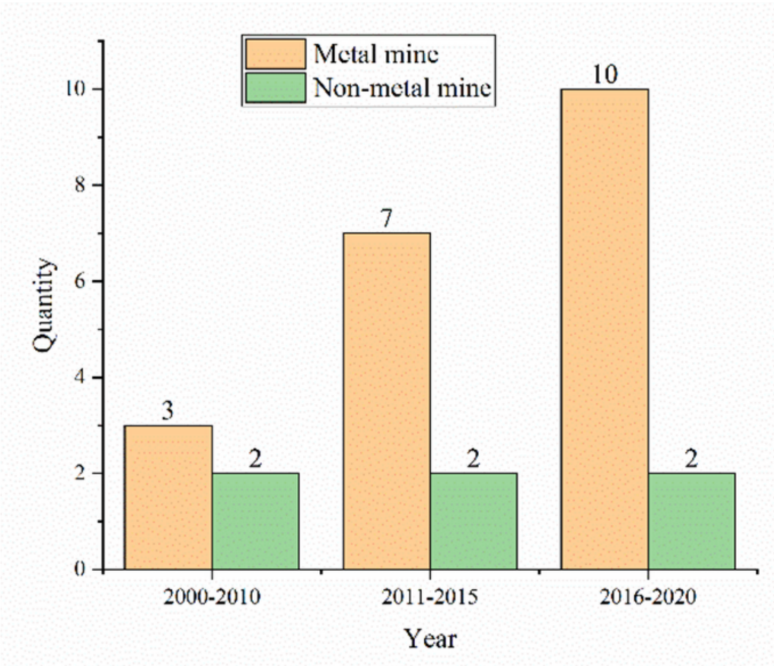


Fig. 1 Metal and non-metal open pit to underground mining research in recent years.

The output characteristics of gently inclined orebody will bring a series of technical problems to open and underground mining. The problems of high loss rate, high dilution rate and low resources recovery which it causes seriously restrict the development of phosphate mining technology in China. Up to now, the mining of gently inclined phosphate orebody with thin-medium thickness is still a problem faced by mining companies all over the world [1-8].

Currently, the problems of efficient and safe mining of gently inclined/thin-medium thickness phosphate orebody are as follows [9-33]:

(1) The dip angle of gently inclined phosphate orebody with thin-medium thickness is gentle, and the caving ore cannot be completely discharged at the bottom by means of its deadweight. It requires mechanical handling or manual transportation, which causes high loss rate, high dilution rate and low resources recovery. Currently we are unable to find any mechanical equipment, mining methods and mining technology matching the underground mining of this orebody;

(2) Gently inclined phosphate orebody with thin-medium thickness, especially after underground mining the broken unstable orebody, the suspending roof of the stope is high, it is difficult to control the roof, and it brings production safety with serious security risks. At present, it rarely reports the research on support measures

and the law of confining pressure activities and the stope, which is gently inclined phosphate orebody with thin-medium thickness especially which is broken and unstable, it urgently needs to be carried out;

(3) Strata movement and surface subsidence caused by underground mining of phosphate rock is a very serious underground engineering problem. During the underground mining process, the balance of primary rock stress is destroyed, the surrounding rock is deformed and moved, and even produces large area movement. With the increase of mining depth, the mining strength becomes heavy, the mining time has increased continuously, the ore is mined continuously, and the deformation, movement and destruction of the surrounding rock are gradually intensified. At the same time, it causes surface subsidence, destruction of cultivated land, and soil erosion. Therefore, to achieve safe mining, it is necessary to study the deformation and failure characteristics of overlying strata in mining areas caused by underground mining. Currently, although the research on strata and surface movement of metal or non-metal mine has achieved certain results, there is no great achievement. While the relevant theoretical system is far from mature and perfect, it is still in the preliminary research stage, and hence the research on underground mining subsidence of phosphate rock is almost blank;

(4) At present, people have done a lot of research and practical work on single open pit mining and single underground mining, having obtained a series of great research results and accumulated many successful experiences. People have a deep understanding of the stability of the slope rock of single open pit mining and the deformation and failure mechanism of the surrounding rock of single underground mining, but there are few studies on slope stability and deformation and failure mechanism of surrounding rock in underground stope after open-pit into underground mining, and the existing related research mainly concentrates on a small part of iron mines, copper mines and individual open-pit coal mines in metal mines, for the research on gently inclined thin-medium thick troublesome phosphate rock in metal and non-metal mine transferring open pit into underground mining is almost blank.

This paper takes deep orebody, which is obtained from Yunnan Phosphating Group Corporation Limited Jinning Phosphate Mine No. 2 and No. 6 pitheads, Jianshan Phosphate Mine, Kunyang Phosphate Mine No.4 mining area, as the engineering background, for gently inclined orebody with thin-medium thickness containing soft interlayer transferring open pit into underground mining, it is a recognised technical problem in the mining industry, through some comprehensive research methods like the investigation of relevant literature, site investigation of similar phosphate mines at home and abroad, theoretical analysis, similarity simulation experiment, three-dimensional numerical calculation and engineering analogy, etc. We have done systematic research on the key technical problems of inclined thin-medium thick troublesome phosphate rock and gently inclined thin-medium thick phosphate rock containing soft interlayer transferring open pit into underground mining in Dianchi area, Yunnan province. Efforts are on to develop safe and efficient new mining processes and technologies for difficult mining phosphate deposits, and to provide strong technical support for the technological development of the mining industry in China.

2 Research progress

2.1 Theoretical and experimental research on different mining methods and processes of inclined medium thick and gently inclined thin-medium thick phosphate rock

a. According to the requirements of the project document, we have done a fully systematic investigation on the geological data and production materials of the inclined medium-thick phosphate orebody of No. 2 pit of Jinning Mine and the gently inclined thin-medium thick phosphate orebody of No. 4 mining area of Kunyang Phosphate Mine, and fully grasped the geological characteristics of the deposit and mining status of the two mining areas.

b. The samples were obtained by density from the inclined medium-thick phosphate orebody of No. 2 pit of Jinning Mine and the gently inclined thin-medium thick phosphate orebody of No. 4 mining area of Kunyang Phosphate Mine, and processed into standard cubes in the laboratory. Triaxial, uniaxial, shear and rheological tests were then conducted to obtain the mechanical properties and deformation characteristics of the orebody and surrounding rock.

c. This paper has used ICT tomography technology to make a systematic analysis of the fracture distribution in ore samples and rock samples, and to study the mechanical relationship between the fracture distribution and the deformation features.

d. We have used the Digital Panoramic Borehole Camera System (DPBCS) to study the distribution of broken rock around the stope, and determine the distribution of the fracture zone and the deformation zone.

e. This paper has done a theoretical research on the different mining techniques and processes of the underground mining of the inclined medium-thick phosphate orebody of No. 2 pit of Jinning Mine and the gently inclined thin-medium thick phosphate orebody of No. 4 mining area of Kunyang Phosphate Mine.

f. The study used the gently inclined thin-medium thick phosphate orebody of No. 4 mining area of Kunyang Phosphate Mine as the engineering background, and used the large similar material simulation experiment to simulate the underground mining process of gently inclined thin-medium thick difficult mining phosphate rock containing soft interlayer in the room, and researched the influence of underground mining on the surrounding rock movement and the breaking rules of underground overlying strata as shown in Figure 2.

Fig. 2 Similar material simulation experiment of mining and pillar recovery.

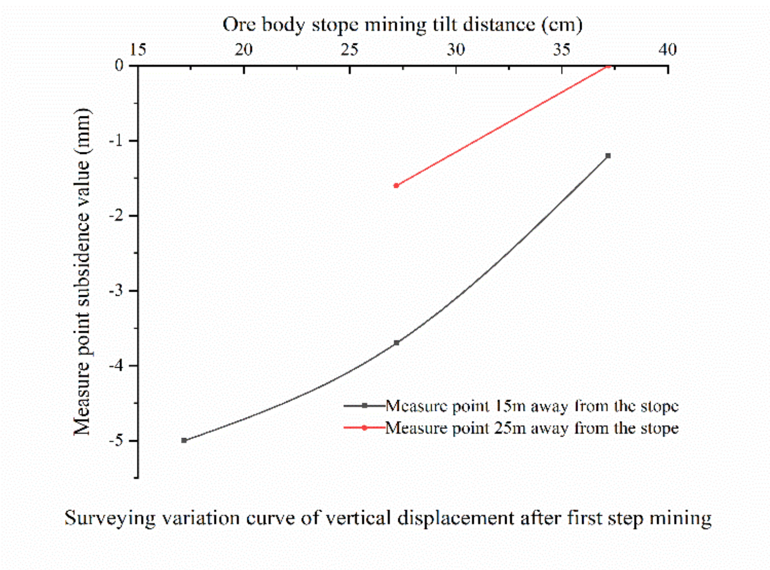
According to the subsidence displacements of the similar material model at different excavation stages (Figure 3), The mining deformation of the surrounding rock underground, and of the overlying strata develops in three stages, namely: 1) small and local deformation, 2) continuous linear increase, and 3) the violent nonlinear collapse of the entire system. Finally, the global subsidence curve is in asymmetrical trough shape and presents a nonlinear failure characteristics.

g. The study used the gently inclined thin-medium thick phosphate orebody of No. 4 mining area of Kunyang Phosphate Mine as the engineering background and used the large numerical simulation software to build a mathematic model on the underground mining of gently inclined thin-medium thick difficult mining phosphate rock containing soft interlayer. To reveal the failure law of primary rock stress, and the deformation law of surrounding rock, simulating the underground mining process and quantitatively researching the deformation and failure characteristics of the surrounding rock, the moving law of rock under different mining methods.

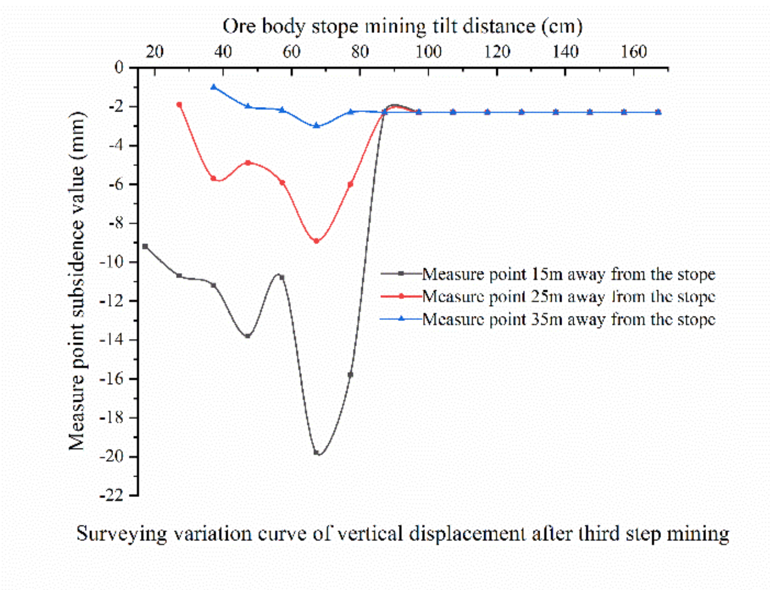
h. The study took the deep orebody which was in the north mining area of Yunnan Phosphating Group Corporation Limited Jinning Phosphate Mine No. 2 pithead as the engineering background, and used theoretical analysis, indoor similar material simulation experiments, FLAC3D numerical simulation (Figure 4) and other comprehensive research methods. Then from the perspective of engineering mechanics, having systematically researched the deformation characteristics of overlying strata and the activity law of ground pressure during the underground mining process of inclined thin-medium thick phosphate orebody for different dip angles, different mining layers, different mining methods, different mining thicknesses, different roof hardness and different interlayer thicknesses. At the same time, it has analysed the hidden danger and disaster prevention measures in the underground mining process.

i. Choosing the better mining methods to be suitable for the inclined thin-medium thick phosphate orebody of No. 2 pit of Jinning Mine by studying the degree of damage to rock by different mining methods, then determining the mining methods and mining technologies corresponding to the underground mining of inclined thin-medium thick phosphate orebody.

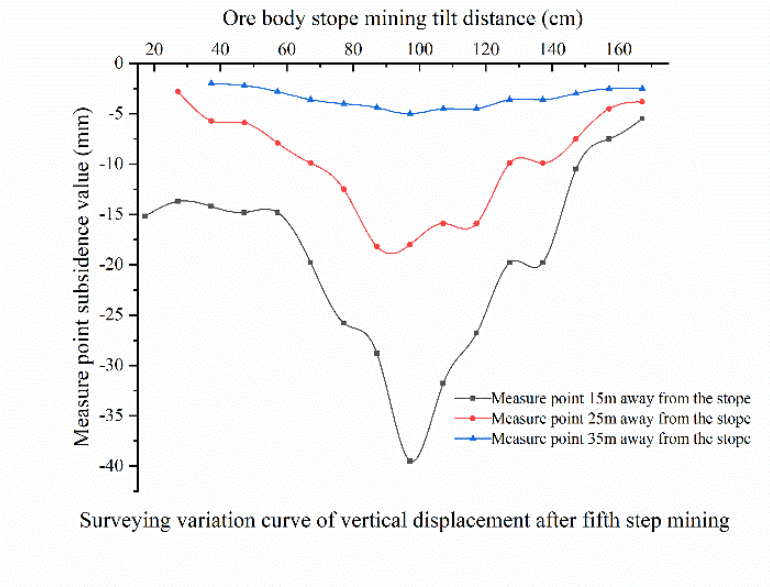
j. After the open-pit mining is transferred to underground mining, the open-pit end slope, surrounding rock mass and underground mining constitute a compound mining system. During the period of open-pit mining, the rock mass around the end of the open-pit slope and the bottom of pit was disturbed. On this basis, the secondary disturbance is caused by the excavation of underground, and with the advance of excavation space, the dynamic superposition of the secondary disturbance effect influences and changes the state of stress and deformation.



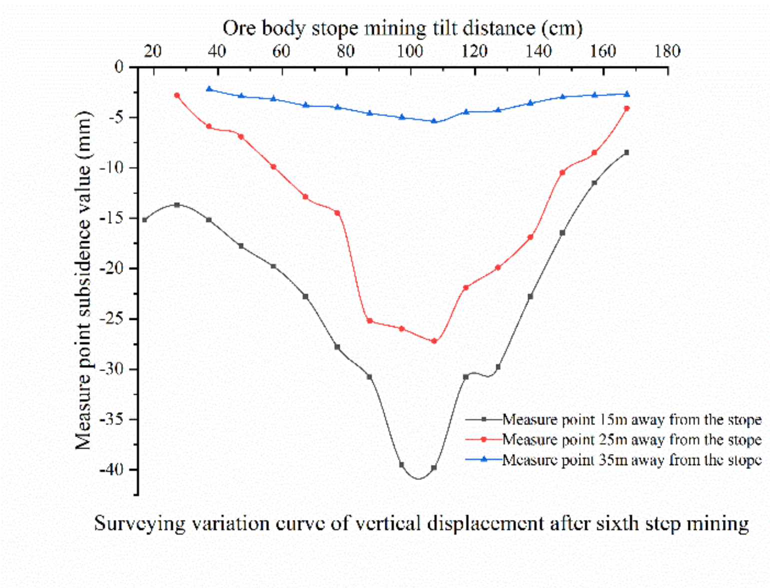
(a) First step mining



(b) Third step mining



(c) Fifth step Mining



(d) Sixth step mining

Fig. 3 Subsidence displacements after the first (a), third (b), fifth (c), sixth (d) excavation steps of the similar material model.

At the same time, the stress redistribution and the deformation and failure change of the rock mass around the open-pit slope and the bottom of the pit after being disturbed also have an important influence on underground mining, making the hazards between the two systems induced each other, thus, a composite dynamic change system is formed.

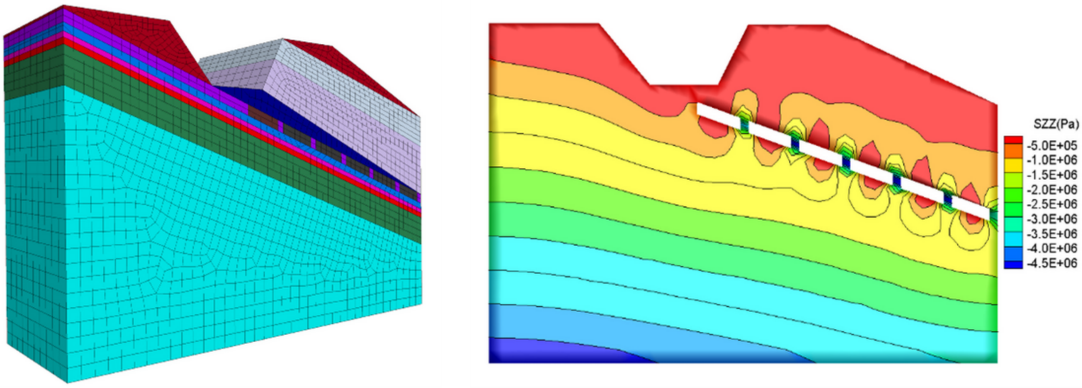


Fig. 4 FLAC^{3D} model.

2.2 Study on characteristics of open-well composite mining slope, rock movement and subsidence on earth's surface and ground pressure in phosphorus mine

a. According to the requirements of the project assignment paper, the engineering geological conditions and hydrogeological conditions in the eastern mining area of No. 6 pit of Jinning Phosphorus Mine were systematically investigated. The physical and mechanical properties of the ore and rock body in this area were tested in the laboratory and the physical and mechanical parameters of these were obtained. Meanwhile, theoretically, the mechanical mechanism of the instability and failure of the slope after the mining method is converted from open-pit to underground and its main influencing factors are analysed.

b. According to the specific occurrence conditions of the deep gently inclined medium-thick difficult-mining ore body in the eastern mining area of No. 6 pit of Jinning Phosphorus Mine of Yunnan Phosphate Group, a typical 114 geological exploration line section is selected along with the decline of the ore body. And according to the similar theory, a similar material physical model test in the laboratory is carried out to investigate the stress, deformation and fracture response characteristics and slumping form under the influence of open-pit slope and underground mining face overlying strata mining after mining method of phosphorus mine convert from open-pit to underground. At the same time, according to the results of similar model tests, combined with relevant theories, the mechanical mechanism of the mining failure of the slope rock mass after mining method of it convert from open-pit to underground is analysed. Based on the results of similar simulation model tests, the concept of 'mining impact factor' considering the factors such as slope and underground mining excavation disturbance is proposed, and the theoretical calculation formula of the 'mining disturbance coefficient' reflecting the mine pressure characteristics such as deformation and failure of slope and underground mining face overlying strata after mining method of phosphorus mine convert from open-pit to underground, which is defined as the ratio of the maximum variation in stress to the initial stress for each excavation in the stope structure and given as follows (Eq. 1):

$$K_{max} = \left| \frac{(\sigma_i - \sigma_1)_{max}}{\sigma_0} \right| \square[0, +\square) \tag{1}$$

where K_{max} is the mining disturbance coefficient, σ_i is the stress of each excavation step (MPa), σ_1 is the stress of the first excavation step (MPa), and σ_1 is the initial stress (MPa).

The subsidence coefficient is the ratio of the maximum subsidence of the overlying strata to the mining thickness of the phosphate rock under the full mining of the stope structure, which reflects the degree of influence the mining disturbance has on the overlying rock (Eq. 2).

$$W = \frac{W_{max}}{D} \tag{2}$$

where W is the maximum subsidence of the overlying rock (m), and D is the thickness of the orebody mined (m).

c. According to the similarity theory, the deep gently inclined medium-thick difficult-mining ore body in the eastern mining area of No. 6 pit of Jinning Phosphorus Mine of Yunnan Phosphate Group is used as the engineering background. The indoor bottom friction model simulation test under the conditions of top pillar thickness in different realms (10 m, 20 m, 30 m) and different slope heights (65 m, 108 m) is used to investigate the mining response characteristics, deformation failure mechanism and mode of the slope body above the goaf after mining method of phosphorus mine convert from open-pit to underground. The mining response characteristics, deformation failure mechanism and mode were studied. Meanwhile, the influence of the thickness of the top pillar in the realm and the slope height on the stability of the mining slope was analysed.

d. Using the deep gently inclined medium-thick difficult-mining ore body in the eastern mining area of No. 6 pit of Jinning Phosphorus Mine of Yunnan Phosphate Group as the engineering background, a +2150 m ore excavation geological section was selected along the strike as the model simulation plane. Through the simulation experiment of similar materials, the deformation and fracture law of the roof surrounding rock of the mining face when mining by chamber and pillar method with different structural parameters (Figure 5, bord 10 m, pillar 3 m; Fig. 6, bord 10 m, pillar 5 m; bord 10 m, pillar 8 m) of mining face after mining method of phosphorus mine convert from open-pit to underground was studied and the structural parameters of mining face were optimised. According to the results of the model test, combined with the relevant theory, the mechanical characteristics, instability failure mode and mechanism of the pillar in the mining face were systematically analysed. Finally, using the cusp catastrophe theory, a simplified mechanical model system for the pillars when mining by chamber and pillar method is established. The mechanism and conditions of the sudden failure of the pillars are studied and analysed.

e. Based on the Lagrange finite difference method, the FLAC^{3D} numerical simulation method is used to study the chamber and pillar method mining parameters such as the reasonable thickness of the top pillar of the open-pit mine realm and the waste rock cover layer at the bottom of the open-pit, optimal structure size of underground bord and pillar, and ore mining order after the mining method of the deep gently inclined medium-thick difficult-mining ore body in the eastern mining area of No. 6 pit of Jinning Mine convert from open-pit to underground.

2.3 Study on underground pressure control technology of mining face in inclined medium-thick phosphorus mine

a. Taking the inclined medium-thick phosphorus ore body of No. 2 pit of Jinning Phosphorus Mine as the research object, based on the site investigation, the review of previous research results and theoretical analysis, the theoretical calculation and FLAC^{3D} numerical simulation tests for mine pressure law during single segmentation mining were carried out. The results show that the numerical simulation results are similar to the theoretical solution. The vertical stress peak caused by the mining of the working face gradually moves away from the working surface with the increase of the burial depth, and the vertical stress concentration factor gradually decreases with the increase of the burial depth. A stress-increasing zone is formed within 13 m of the floor rock stratum in front of the working face, and a stress-decreasing zone is formed in the floor rock stratum below the goaf, and its influence depth can reach 30-40 m. During single segmentation mining, the roof rock stratum is plastically damaged. The plastic zone area of the roof above the working face is the largest, and the plastic zone runs from the working face to the earth surface. Plastic failure also occurred in the stress rise zone below the working face. The damage zone is 5-10 m in front of the working face, and the maximum depth is 12 m.

b. Taking the inclined medium-thick phosphorus ore body of No. 2 pit of Jinning Phosphorus Mine as the research object, based on the site investigation, the review of previous research results and theoretical analysis, the theoretical calculation and FLAC^{3D} numerical simulation tests for mine pressure law during multiple segmentation mining were carried out. The results show that the stress state of the floor and the surrounding rock of the roadway is a dynamic process with underground mining. When multiple working sites are mined

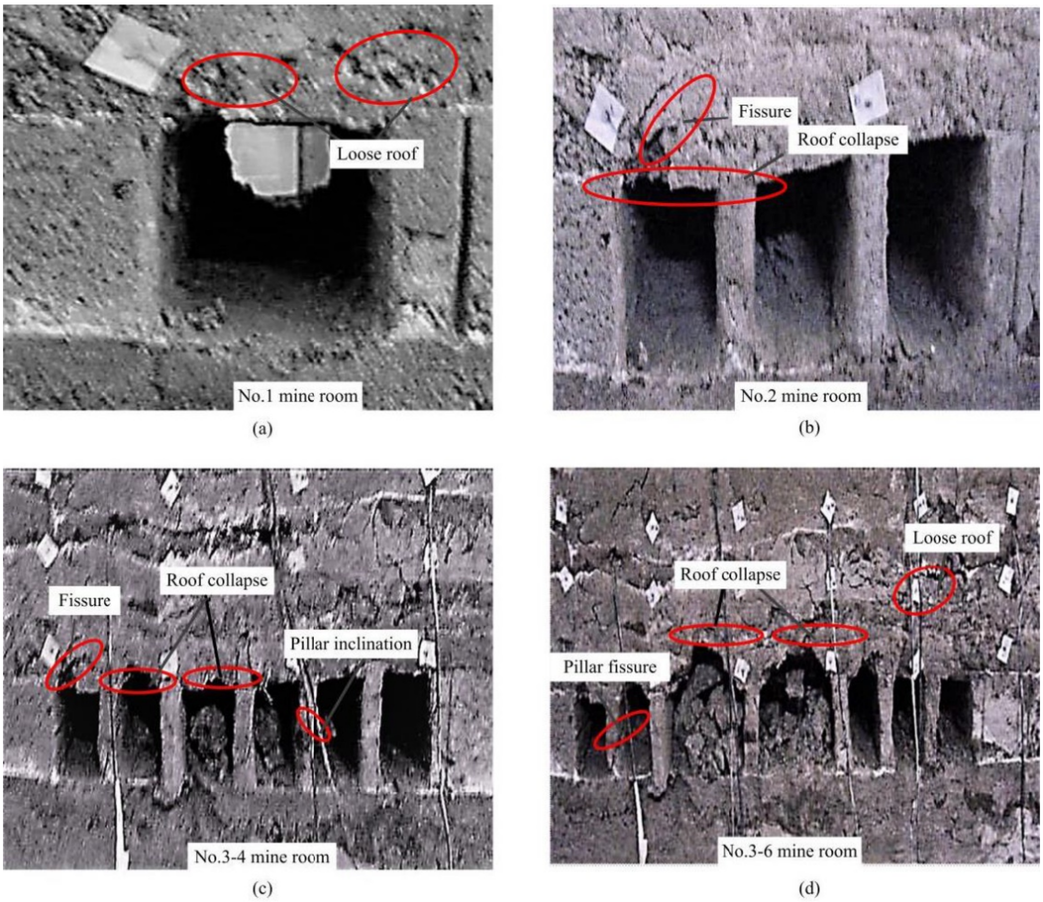


Fig. 5 Deformation and Failure Characteristics of the Roof for the 3-m Ore Pillars.

simultaneously, the stability of the surrounding rock of the lower segmentation roadway is affected by the upper segmentation mining. The vertical stress concentration factor and the influence range of the lower segmentation roadway are increased compared with the single segmentation mining.

When multiple working sites are mined simultaneously, the vertical stress of the lower segmentation roadway is affected by the mining. The range of stress concentration and the value of stress concentration factor are increased compared with the single segmentation mining, and the maximum principal stress value is smaller than the tensile strength of rock mass. The rock mass will not have fracture failure, but the roof of the roadway may be partially collapsed. The theoretical solution of the stress increase concentration coefficient during the different segmentation mining simultaneously is smaller than the single segmentation mining, On the one hand, it's because when digging the segmented roadway in the development project, the segmental roadway stress is released in advance. On the other hand, the reason for that is the segmented roadway in the inclined phosphorus rock layer is distributed along with the phosphorus rock layer which causes the distance between the segmented roadways which is relatively long, and the vertical stress attenuation is greater.

c. Taking the inclined medium-thick phosphorus ore body of No. 2 pit of Jinning Phosphorus Mine as the research object, based on the site investigation, the review of previous research results and theoretical analysis, the theoretical calculation and FLAC^{3D} numerical simulation tests for mine pressure law during mining different layers, in turn, were carried out. The results show that when the hanging side seam is mined, the stress of the roof above the goaf will be released, and the principal stress of the roof is positive, that is, tensile stress appears on the roof. As the mining progresses, the degree of stress release gradually increases, and the maximum principal stress peak of the roof is greater than the tensile strength of the roof rock mass. After the phosphorus ore body is mined to form a goaf, the stress concentration is concentrated at the top and bottom of the interlayer, and the

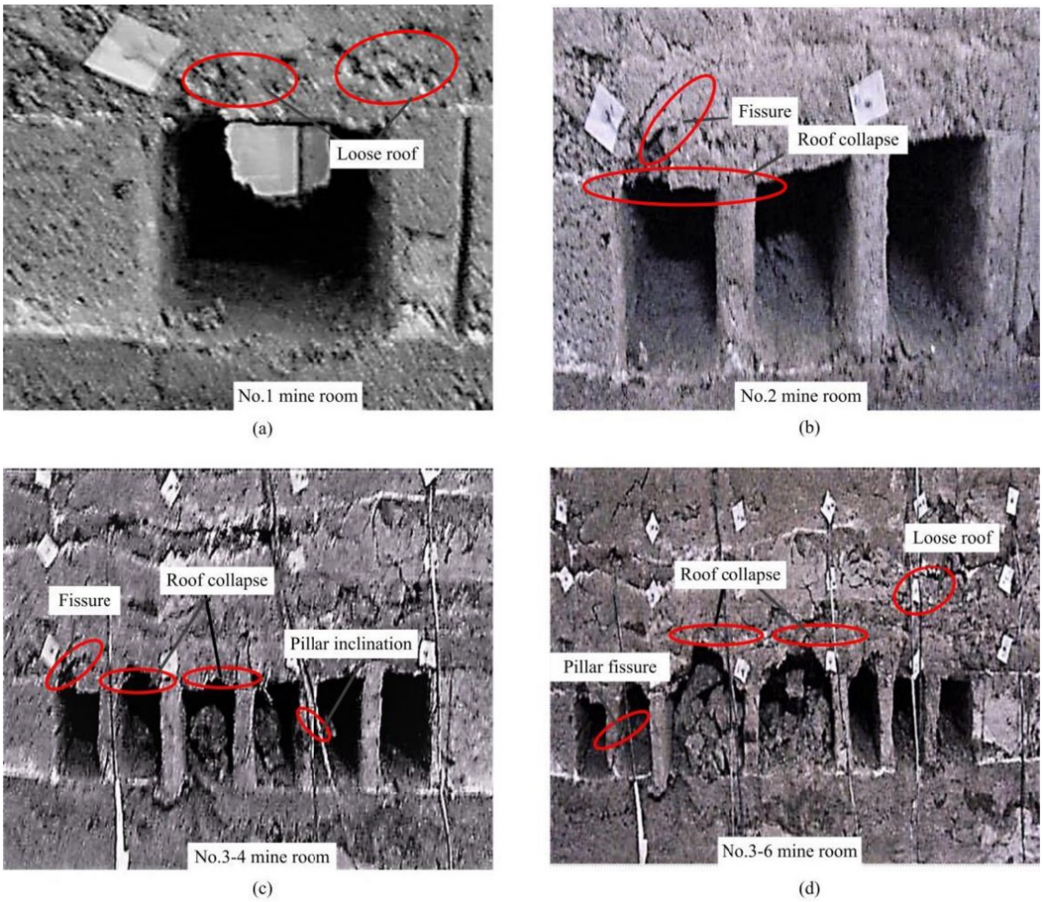


Fig. 6 Deformation and Failure Characteristics of the Roof for the 5-m Ore Pillars.

bottom is mainly composed of compressive stress. Due to the geostatic stress, the middle part tends to move to the lower goaf. As the mining progresses, the zone of tensile stress in the interlayer increases continuously, and the stress concentration at the top gradually weakens. The maximum tensile stress generally appears in the top middle part of the lower goaf. At the end of the mining of the phosphate rock layer in the footwall, attention should be paid to the stability of the roof of the lower ore layer. If the stability of the ore layer is poor, there will be occurrence such as falling and wall caving, which are prone to accidents.

After the mining of the upper ore layer, a large-scale plastic failure zone appeared in the roof of the goaf, and the top pillar of the hanging side phosphorus seam mined by the sectional shrinkage stoping-caving method collapsed and then fell. In the lower mining layer, the location and area of the plastic zone continuously change dynamically as the mining progresses. After the early shallow-hole shrinkage mining in the lower ore layer, the newly added plastic zone mainly appears on the top and bottom of the roof of the hanging side seam, and there is no plastic failure in the interlayer. After the later mining of the lower ore layer, the plastic zones appear in the top middle and top parts of the goaf. After further mining, the plastic zone is further expanded, mainly concentrated in the middle and top of the goaf. Because the dolomite of the Meicun formation is hard and complete, the rock strength is large, and there is no plastic zone on the bottom plate.

d. Taking the deep inclined medium-thick phosphorus ore body in the northern mining area of No. 2 pit of Jinning Phosphorus Mine of Yunnan Phosphorus Group as the research object. Through the site investigation, theoretical calculation, FLAC^{3D} numerical simulation and other comprehensive research methods, a systematic study on the rock mass displacement law of single segmentation mining, simultaneous mining of different segmentations and mining of different ore layers were conducted. The results show that with the increasing depth of underground mining, the mining impact range and the displacement value of the roof continuously change dynamically. The displacement variation law is analysed from three aspects: roof, interlayer and surface. After the phosphate ore body is mined to form a goaf, the upper part of the goaf becomes a pressure relief zone, and the roof appears in different degrees of subsidence. The maximum sinking area is located in the upper-middle part of the goaf and dynamically moves down as the mining level continues to advance. As the mining continues downwards, the vertical distance of the goaf continues to increase, and the amount of subsidence of the roof of the stope gradually increases.

When the hanging side seam is mined, a bottom drum phenomenon occurs on the bottom plate. When the lower phosphorus rock layer is mined, the interlayer rock mass of the bottom drum sinks in the direction of the bottom plate goaf. The position of the maximum displacement value is gradually moved downwards from the point at the first mining of the lower plate, and the maximum values are 0.68 m and 0.92 m, respectively. Influenced by the mining of the phosphorus rock layer on the upper and lower plates, the maximum and influence range of surface subsidence increases. The position of the maximum displacement value is gradually moved from the middle of the goaf to the mining direction, and the maximum value is increased from 0.11 m to 0.40 m. The mining impact range also increases with the excavation, increasing from 7.2 m to 22.7 m.

2.4 Study on stability and strengthening control technology of composite mining slope of surface mine and underground mine

a. Taking the multiple cracks gently inclined slope in the east mining area of No. 6 pit of Jinning Phosphate Mine containing soft interlayer as the research object, through some comprehensive research methods such as site investigation, laboratory test, in-situ test, numerical calculation of rigid body limit equilibrium method and engineering analogy,. there has been a systematic analysis of engineering overview, geological survey and exploration in the early stage, stability analysis, the treatment scheme and the monitoring measurement plan of phosphate rock high slope. The results showed that the rock of slope surface had 3 groups of main structural planes, two groups of them are jointed planes, the other one is bedding plane. Jointed planes were mainly concentrated in $220 \sim 265^\circ \angle 70 \sim 78^\circ$ and $305 \sim 354^\circ \angle 82 \sim 89^\circ$, bedding plane was mainly concentrated in the range of $60 \sim 80^\circ \angle 20 \sim 30^\circ$ landslide boundary was mainly controlled by these two groups of joints, and the bottom plane slid along the bedding plane. The three groups of structural planes cut the rock into blocks, the strength of potential sliding plane would be reduced under the heavy rainfall and blasting load, and it would easily form the pulling type, multistage sliding pull crack type failure under the condition of the perimeter rock cut by the crack. Currently, the most possible potential sliding surface was white (yellow) phosphorus-containing clay rock in the second member of Meishu Village Group ($\in$1m2), the buried depth of this layer was about 5–20 m, and the thickness was uneven. It generally showed increasing thickness from north to south, and this layer was the main control plane of the middle-shallow layer landslide in the slope.

If the slope adopts a single-slope type, as long as the excavation did not cut the rock layer in the process of continuing mining for 100 m, the strata had no obvious shear outlet, the possibility of sliding pull crack type failure was small. But with the increase of rheological displacement and the gravity function of slope, the rock layer would generate shear slip along the weak interlayer or bedding, the middle and lower rock layer may have slight uplift along the free face. When the bending and the uplift raise to a certain stage, the slope had the possibility of buckling or bending failure.

The slope was almost impossible to generate deep slip, as long as the deep bedding structural plane was not cut off to form a free face during the excavation process, but the slope still could undergo middle layer sliding and shallow sliding. The possibility of of occurrence of middle layer sliding was small for the slopes of I-I' and III-III' sections, so the shallow sliding needed to be reinforced. However, the possibility of occurrence of middle layer sliding was large for the slope body of II–II' section, and it similarly needed to be reinforced to prevent slope failure. Currently, many places of shallow landslides were in the critical state or partial slip state, if it does not consider the weakening phenomenon of rock parameters with water and time, but consider the reduced situation of mechanical parameters with long-term creep after the landslides slid, the landslides would continue to slide, so it was necessary to strengthen monitoring and partial reinforcement treatment.

According to the characteristics of bedding high slope of phosphate rock, making a feasibility and economic contrast of several schemes such as anti-slide pile and anchor cable (rod) reinforcement, this paper thought that it could take several measures such as anchor cable (rod) combined reinforcement, slope cutting, lay down the anti-seepage geomembrane and gunite in this slope treatment project. To effectively predict the trend of slope deformation, at the same time, made the slope normal construction and provided a basis for dynamic design. All-round and multi-angle monitoring and arranging of surface displacement, deep displacement and supporting structure stress are carried out during the slope construction period. As for the construction period and heavy rain period, the shallow displacement was initially determined once a day, the deep displacement was once every two days, anchor cable monitoring was once a week, crack monitoring was once every two days; it was usually once a week for normal observation, and the threshold was 3-5 mm/day for early-warming standard. Besides, as for the frequency of monitoring and early-warning standards, it was necessary to adjust the frequency and warning threshold combined with specific engineering conditions.

b. Taking the oversize high-steep slope of Jianshan Phosphate Mine as the research object, combining site investigation and indoor analysis, qualitative analysis and quantitative analysis, engineering geology and rock mechanics, theoretical analysis and laboratory test, this paper emphasised the technical conditions of open-pit mining and the analysis of mechanical properties of slope rock mass, and paid attention to the study of deformation failure mechanism and instability mode of slope excavation, we have done a systematic research on the stability and control technology of the slope, which was excavated layer by layer in Jianshan Phosphate Mine. The main research results are as follows: Based on field investigation, theoretical analysis, experimental research and simulation calculation, put forward the ‘plane mixed-mode’ of deformation failure of the slope, which was excavated layer by layer in Jianshan Phosphate Mine, the shape of slip surface was linear type in the upper and circular arc type in the lower. By analysing the corresponding engineering geological conditions, we obtained that changes of occurrence in the deep ore body were the main reasons for the cause of the instability of slope excavation, and due to the above reason and the cutting of dominant structural plane to the slope rock, it is easy to form unstable landslides.

c. Based on the results of laboratory tests, results of field rock shear tests, back analysis of slope geotechnical parameters, we have determined the macroscopic rock mechanics parameters of slope rock in the study area. Then we used the analysis method of catastrophe theory, studying the slope disaster mechanism, the necessary and sufficient conditions for slope instability were pointed out, and the stability of slope excavation has been verified. Besides, we used FLAC3D numerical calculation software to establish a 3D geomechanics model and analysed the dynamic evolution process of slope excavation in Jianshan Phosphate Mine, and the simulation results showed that the slope would be unstable if we continue to extend mining under the existing mining technology, and the potential slip instability of slope was a slip-compression-bending failure. Based on the occurrence characteristics of deep orebody, the study has compared anchor cable reinforcement to slope cutting and press stand, and put forward that the comprehensive technical measure for the stability of extended mining was slope cutting and press stand.

d. With the implementation of research results, it could effectively solve the problem of stability of deep mining in the high-steep slope of Jianshan Phosphate Mine, and it could add 800,000 tons of deep orebody in the eastern mining area of Jianshan Phosphate Mine. If the unit price was 100 yuan per ton, and the mining cost increased by 4 yuan per ton due to the governance cost (The total amount of orebody was 7.5 million tons during the period of 2011.07-2013.10), it would bring a direct economic benefit of 50 million yuan in total.

3 Current problems and countermeasures

3.1 Problems

Using the traditional caving method and the empty field method to mine the gently inclined thin to medium-thick phosphate ore body with 3-5 m thick soft interlayer, there are problems of high ore depletion rate and large loss rate, and it is difficult to guarantee safety.

Using the traditional filling method to mine the gently inclined thin to medium thick phosphate ore body with 3-5 m thick soft interlayer, it can solve the problem of high ore depletion rate, large loss rate and safety, but due to the lower grade of phosphate rock and the increase of impurity content, the economic value is lower and cannot withstand the mining cost of traditional filling method. And the production capacity of the filling method cannot meet the requirements of large-scale mining.

Overall transition of open-pit mining, underground mining, open pit and underground combined mining, isolation roof thickness, influences separately and each other on blasting vibration on open pit and underground mining, and the relationship between slope stability and stability of underground roadway, surrounding rock and stope need to perform quantitative analysis to establish a system balance. The experience of existing metal mines cannot be copied and applied because of the different occurrence states and conditions of the ore body.

3.2 Countermeasures

It is necessary to find a filling material that is relatively inexpensive and easy to localise in the mine. From the perspective of the two large systems in the open and underground, the engineering practice of open-pit and underground mining with overall benefit and safety optimisation is achieved through the low-cost filling method to solve the mining problem of gently inclined thin to medium thick phosphate deposit with a soft interlayer.

It is imperative to accelerate the development progress of complete sets of equipment suitable for large-scale filling system technology, and there should be focus on automation, mechanisation and high efficiency so that the failure rate of filling mining can be reduced, and the filling scale can reach 2-3 million square metrer per year to adapt to capacity requirements after the open-pit mines are converted to underground mining.

It is important to strengthen the links between universities, enterprises, design institutes, professional technology and engineering companies, and carry out joint research in three stages of open-pit, underground and open-pit mining. From the four aspects of theoretical research, practical application research, engineering experiment and verification research, and industrialisation, we can gradually solve the overall transition of open-pit mining, underground mining, open pit and underground combined mining in the process of mining method convert from open-pit to underground of gently inclined phosphate deposits with soft interlayer; isolation roof thickness; the influences separately and each other on blasting vibration on open pit and underground mining; slope stability and stability of underground roadway, surrounding rock and stope and other issues.

4 Discussion

The phosphorus deposits near the Dianchi area in Yunnan generally have the following characteristics: the inclination angle is gently inclined, and most of them are between 20 and 35; the deposit is a sedimentary layered stable ore body with a large area; the thickness of the ore body is thin to medium thickness and the thickness is between 3 m and 12 m; 0.5-3.0 m soft interlayer in the middle of the ore body; the cleavage fractures of the ore body are relatively developed; and the top and bottom plates are very broken. As the depth increases the grade of the ore body gradually decreases, the impurity content increases, the cost of downstream beneficiation and rogueing for fertiliser preparation process increases and the economic value gradually reduces.

Based on the above characteristics, there are currently two views on deep mining of phosphate ore bodies: one is deep and extremely deep open-pit mining, reason is that the large-scale, automatic and continuous and semi-continuous development of open-pit mining process systems could greatly prolong the service life of open-pit mining, and avoids the problems of a large reduction in the recovery rate after convert to the underground mining, a sharp increase in the dilution ratio, and a rapid decline in production capacity; the other is through the optimisation of the filling mining process and the development of large-scale filling system equipment, to find a new filling mining process system with low filling materials and filling capacity to meet the production capacity requirements, to achieve efficient and safe mining for open-pit transfer to underground mining.

5 Conclusion

Taking the gently inclined thin to medium-thickness phosphate deposit with soft interlayer in near the Dianchi Lake in Yunnan as the research object, through mining process innovation, technological innovation and improvement, to research new processes and technologies suitable for mining technical conditions under the new situation. The relevant research results not only have important economic, environmental and social significance for Yunnan Phosphate Group Co. Ltd, but also have important guidance and impetus to the exploitation of a large number of similar phosphate resources in China.

Acknowledgments

The research work described herein was funded by the National Nature Science Foundation of China (NSFC) (Grant No.: 41702327,41867033), China Postdoctoral Science Foundation (Grant number: 2019M650144), State Key Laboratory of Safety and Health of Metal Mines (Grant number: zdsys2019-005). These financial supports are gratefully acknowledged.

References

[1] Wang T, Zhao X, Hu W, et al., Investigation of mine pressure and deformation due to phosphate ore body excavation based on Hoek-Brown model. Journal of Unconventional Oil and Gas Resources, 2016, 15, pp. 158-164.
[2] Li X X,Li K G, Optimisation of Stope Structural Parameters in Phosphorite Mine and its Stability Analysis. Applied Mechanics and Materials, 2015, 3307(580-583), pp. 1268-1272.
[3] Wang F, Zou P, Meng Z, et al., Study on Stability of Goaf Pillars in Daqiao Phosphate Mine: Theoretical Calculation and Field Investigation. Geotechnical and Geological Engineering, 2019, 37(3), pp. 1483-1492.
[4] Du F B,Guo W, Stability analysis on boundary pillar during open-pit to underground mining based on catastrophe theory. Chinese Journal of Underground Space and Engineering, 2018, 14(2), pp. 552-557.
[5] Zhang X, Jiang Y, Wang G, et al., Mechanism of shear deformation, failure and energy dissipation of artificial rock joint in terms of physical and numerical consideration. Geosciences Journal, 2019, 23(3), pp. 519-529.
[6] Yanhai Z, Shuren W, Zhengsheng Z, et al., Instability characteristics of the cracked roof rock beam under shallow mining conditions. International Journal of Mining Science and Technology, 2018, 28(03), pp. 437-444.
[7] Chen S, Wu A, Wang Y, et al., Study on repair control technology of soft surrounding rock roadway and its application. Engineering Failure Analysis, 2018, 92, pp. 443-455.
[8] Cheng G W, Chen C X, Li L C, et al., Numerical modelling of strata movement at footwall induced by underground mining. International Journal of Rock Mechanics and Mining Sciences, 2018, 108, pp. 142-156.
[9] Bakhtavar E, The practicable combination of open pit with underground mining methods- A decade's experience. Proceedings of the 24th International Mining Congress of Turkey, IMCET 2015, 2015, pp. 704-709.
[10] Fan X M, Ren F Y, Xiao D, et al., Opencast to underground iron ore mining method. Journal of Central South University. Science & Technology of Mining and Metallurg, 2018, 25(7), pp. 1813-1824.
[11] Zhang D B, Zhang Y, Cheng T, et al., Measurement of displacement for open pit to underground mining transition using digital photogrammetry. Measurement, 2017, 109, pp. 187-199.
[12] P.,Balamadeswaran, Open pit to underground mine transition - no simple recipe! Journal of Mines Metals & Fuels, 2015, 63(1-2), pp. 10-16.
[13] Tan B, Ren F, Ning Y, et al., A New Mining Scheme for Hanging-Wall Ore-Body during the Transition from Open Pit to Underground Mining: A Numerical Study. Advances in Civil Engineering, 2018, 2018(9), pp. 1-17.
[14] Jiang N, Zhou C B, Lu S W, et al., Propagation and prediction of blasting vibration on slope in an open pit during underground mining. Tunnelling and Underground Space Technology, 2017, 70(1), pp. 409-421.
[15] Xia K Z, Chen C X, Deng Y Y, et al., In situ monitoring and analysis of the mining-induced deep ground movement in a metal mine. International Journal of Rock Mechanics and Mining Sciences, 2018, 109, pp. 32-51.
[16] Li X S, Zhao K, Zhang D M, et al., Research on deformation and failure character of underground surrounding rock and overlying strata transition from open pit to underground mining. Journal of Engineering Geology, 2018, 14(5), pp. 1359-1371.
[17] Sun S, Zhang J, Liu Y, et al., The Study on Optimisation of Treatment Plan for Slope in a Transition from Open-pit to Underground Mining. Manufacturing, Design Science And Information Engineering, 2015, pp. 452-457.
[18] King B, Goycoolea M,Newman A, Optimising the open pit-to-underground mining transition. European Journal of

Operational Research, 2017, 257(1), pp. 297-309.
[19] MacNeil J A L,Dimitrakopoulos R G, A stochastic optimisation formulation for the transition from open pit to underground mining. Optimisation and Engineering, 2017, 18(3), pp. 793-813.
[20] Zhao Y, Yang T H, Bohnhoff M, et al., Study of the Rock Mass Failure Process and Mechanisms During the Transformation from Open-Pit to Underground Mining Based on Microseismic. Rock Mechanics and Rock Engineering, 2018, 51(5), pp. 1473-1493.
[21] Li X S, Zhao K, Zhang D, et al., Research on deformation and failure character of underground surrounding rock and overlying strata transition from open pit to underground mining. Chinese Journal of Underground Space and Engineering, 2018, 5(14), pp. 1359-13711386.
[22] Sun S, Tian B,Fan Y, Deformation Mechanism and Disaster Analysis of Covering Rock in Mining with Transition from Pit to Underground. international conference on simulation, modelling and mathematical statistics (SMMS 2015), 2015, pp. 511-515.
[23] Sun S, Zhang Y, Zhang H, et al., Stability analysis of overlying rock mass of L working face moving from open-pit to underground mining and slope treatment schemes. Safety in Coal Mines, 2016, 9(47), pp. 158-161.
[24] Fang Z, Wang L, Jia M, et al., Analysis of effect of open pit to underground mining on overlying structures safety. China Safety Science Journal, 2015, 2(25), pp. 83-88.
[25] Yang H, Zhang Z, Wang H, et al., Study on Capacity Connecting Technology of Open-pit Changing to Underground of Miaogou Iron Ore. Mining Engineering, 2015, 2, pp. 15-17.
[26] Jia T, The Dynamic prediction of environment damage induced by the excavation from open-pit into underground mine. Journal of Safety Science and Technology, 2015, 3(11), pp. 99-104.
[27] Zhang Y, Hou Y,Gan D, Experimental study on mine slope stability in transferring open-pit into underground mining. Industrial Minerals and Processing, 2016, 5(4), pp. 48-51.
[28] Wang Y, Jiao H, Wang L, et al., Study on deformation and stress characteristics of slope in transition from open-pit to underground mining. Mining and Metallurgy, 2016, 1(25), pp. 5-9.
[29] Deng Q, Cao J, Zhang L, et al., Uplift mechanism of the bottom of open pit after the transition from open-pit mining to underground mining in Longshou mine. Journal of Mining and Safety Engineering, 2015, 4(32), pp. 677-682.
[30] Sun S G, Guo W, Liu W, et al., Study on high slope sliding deformation mechanism induced by transiting from opencast into underground mining. Metal Mine, 2015, 5(44), pp. 162-165.
[31] Ding X P, Wang Z W,Li W, Dynamic process and typical deformation-failure mechanism of mining slope. Journal of China Coal Society, 2016, 41(10), pp. 2606-2611.
[32] Wang D, Wang Q L, Cao L Z, et al., Simulated study on the stability of countertilt slope in the combined open-pit and underground mining condition. Journal of Safety and Environment, 2015, 15(1), pp. 14-20.
[33] Sun S G, Zhang Y J, Zhang Y H, et al., Research on Influencing Mechanism of the Synchronous Mining of Open-pit and Underground on Slope Deformation. Metal Mine, 2016, 2016(11), pp. 58-62.