

## Cancelling ore pillars in large-scale coastal gold deposit: A case study in Sanshandao gold mine, China

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**Abstract:** According to the actual conditions in Sanshandao Gold Mine, the cancelling ore pillars mining method was researched. Firstly, a series of tests for the physical and mechanical characteristics of rock mass were carried out and a quality classification system of rock mass applied in coastal metal deposit was established. Secondly, the reasonable demarcation depth of cancelling ore pillars was simulated using the finite element method, and the simulation results show that the ore pillars can be cancelled below the level of  $-555$  m. Thirdly, a novel layer-backfill mining method of room-pillar alternation was designed to reduce the disturbance and settlement of terrain in mining area. Engineering practice shows that the new mining method enhanced the mining output and relieved rock disturbance. Furthermore, the settlement of the roof strata was small and no disaster occurred. The new mining technology effectively controlled the deformation of the terrain, indicating that the mining of the large-scale gold coastal deposit in Sanshandao Gold Mine was achieved safely, efficiently, and with a low loss rate.

**Key words:** coastal deposit; rock quality evaluation; numerical simulation; layer-backfill mining method of room-pillar alternation; monitoring system

### 1 Introduction

Considering the severe situation of limited land resources, people have shifted to exploit the coastal and undersea resources which are abundant for human beings [1–5]. Especially in China, the coastal gold mining is becoming the main objective of gold mining industry. Sanshandao Gold Mine is the first coastal metal mine in China, and is located in the seaside of Bohai bay. Its south side is a gold coast and holiday village, and its north neighbor is national megatonic open port which is named Wharf Laizhou. The ore body lies along the coast and under the seawater. The mining conditions are very complicated and thus the point-pillar layer-backfill mining method was adopted. In order to ensure the safe mining, the stope column, point pillar, roof-bottom pillar and roof protection pillar were kept during mining, so the total mining loss rate exceeded 22.60% per year. Or rather, when 1 million ton ores were exploited, 0.3 million ton ores were lost. To reduce the mining loss rates [6,7], taking the mining method into account, the optimization of configuration parameters becomes the

most important work [8,9].

In recent years, with the improvement of the rock mechanics, mining design work becomes more and more advanced [10–13] and it provides theoretical basis for mining optimization. To assure the safe working conditions, numerical simulation and displacement monitoring technology is used frequently [14–18]. Some scholars had researched the undersea mining technology, which look into the relationship between the mining depth and the mining security [19,20]. At present, the mining depth is below the level of  $-465$  m in Sanshandao Gold Mine, and the ore body's in-situ stress is getting higher and higher with the increase of mining depth. At the same time, the fragmental degree of rock mass is becoming more and more serious and the stope stability is getting worse, so the mining engineers had to narrow the mining stope span, increase the number of ore pillars and reduce the space between the pillars to realize safe production. As a result, the production capacity and efficiency were declined, and the dilution and loss rate were increased. Moreover, these problems existing in Sanshandao Gold Mine would badly affect the enterprise benefits and the mining life, so we can see that the point

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pillar layer-backfill method was inappropriate to mine the deep resources.

Therefore, how to safely exploit the coastal resources with low settlement, low ore loss, and high efficiency become the new research subjects in Sanshandao Gold Mine. Here, a quality classification system that is suitable for rock mass of coastal deposit is established by testing the physical and mechanical parameters of rock mass and surveying the joints and fissures in engineering rock mass, numerical simulation method is used to detect the reasonable demarcation depth of cancelling ore pillars in deep level mining. A novel room-pillar alternation layer-backfill method is put forward. In addition, the deformation monitoring system in terrane is established, and the settlement law of the ground surface is investigated. Also, the mining technology is used to actualize mining in large-scale coastal deposit safely, effectively and with low ore loss.

## 2 Parameters and quality evaluation of rock mass

### 2.1 Physical mechanics parameters of rock mass

The ore body in Sanshandao Gold Mine is thick and fractured with extremely developed faults in the northeast direction. Sanshandao and Jiaojia faults, for example, are the biggest ones. Their strikes are mostly parallel but tendency opposite. The secondary branch faults are also developed, forming a fracture zone which is the main ore-control geological structure. The fracture zones are started from Sanshandao in the northeast to Panjiawuzi in the southwest and their ends are both extended into the Bohai Sea. Only parts of the fracture zones are outcrops with 12 km in both length and width, extending from 50 to 200 m in the shape of “S”. The general trend is 40°, local trend 70° to 80°, and inclination angle is 45° to 75° in the southeast direction. After the fracture zone formation, compress-shear fault and compressive rupture zone are caused by the geological tectonic movement and side pressure with the direction of SE to NW. Major fracture plane with the shape of slow wave belongs to compressional-tortive fracture, and possesses black fault mud with thickness of 50–100 mm. The representative rock masses were sampled in situ in Sanshandao Gold Mine. Hanging wall

is beresitization granite, orebody is granite, and footwall is sericitization granite. The basic physical–mechanical parameters of the rock are shown in Table 1.

Test results show that the hanging wall rock with abundant joints and fissures was fragmentized, and was endowed with the characteristics of low cohesion strength, small compressive strength and low Poisson ratio; the ore body with few joints and fissures had high strength and generated rock burst when compression test proceeded; the rock strength of the footwall was lower than that of the ore body and also displayed rock-burst damage phenomena.

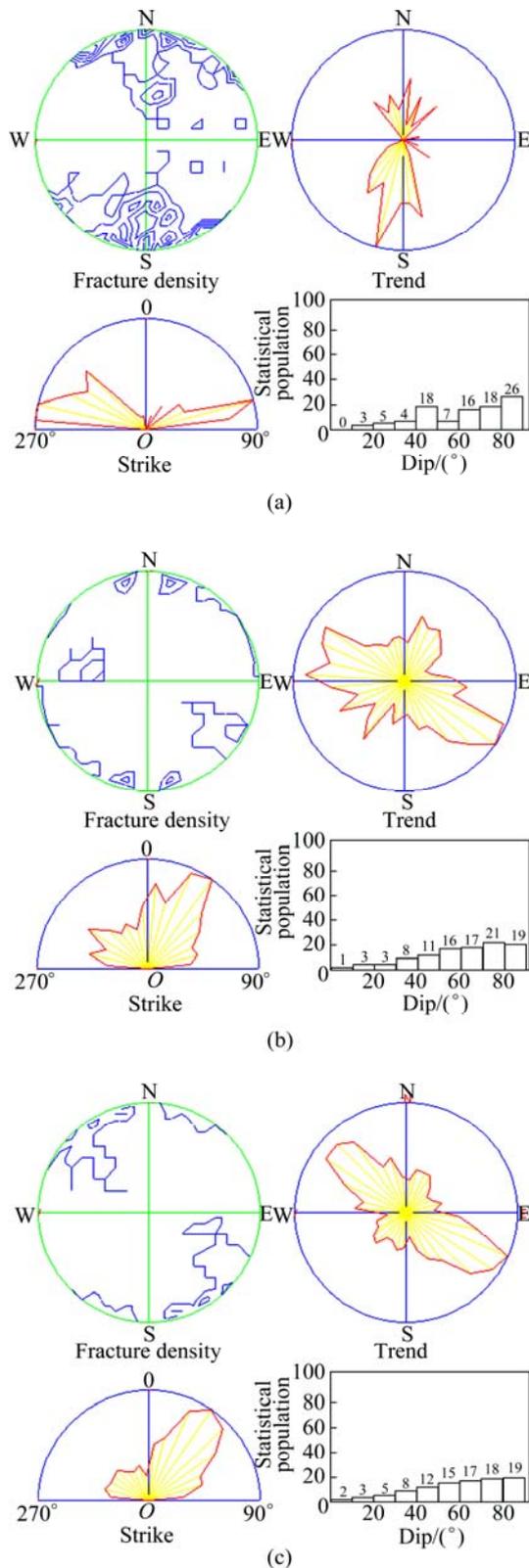
### 2.2 Joints and fissures investigation of rock mass

The structural joint–fissure planes are one kind of structural faults and result from the in situ stress. The stability, failure mode and damage degree of the ore body and surrounding rocks vary when the fissures differ in their direction, number, size and form. At the same time, joints and fissures are one kind of geological structures, reflecting the outline of the main structure and the characteristics of the tectonic movement in the mining area. Most joints, fissures and tectonic stress are constantly interacting one another. The tectonic stress field and its movement way can be speculated through the joints and fissures, so the tectonic stress field and tectonic system provide original data for the mechanical analysis. Therefore, in order to study coastal mining in Sanshandao Gold Mine, the joint–fissure investigations of the hanging wall, ore body and footwall were carried out in the levels of –465, –510, –555 and –600 m.

1592 stripes of rock joints were surveyed by measuring line method in the mining area. Joint rose diagrams are shown in Fig. 1. The results show that the joints and fissures were developed in the hanging wall near  $F_1$  fault. In the ore body and footwall terrane, the joints and fissures were not very developed, and most of them were randomly distributed, so their advantage direction was not obvious. By analyzing the joints and fissures in the hanging wall, ore body and footwall, advantage strikes were 30° and 300°, and advantage tendency were 30°, 200° and 300°. Compared with the above four surveying places, joints and fissures were developed with increasing depth. The common advantage strikes were in the spectra of 30° to 50° and

**Table 1** Physical–mechanical parameters of ore body and wall rock (Specimens with (49.00±0.05) mm in diameter and (100.00±0.05) mm height)

Item	Density/ (g·cm <sup>-3</sup> )	Cohesion/ MPa	Internal friction angle/(°)	Tensile strength/MPa	Compressive strength/MPa	Elastic module/GPa	Poisson ratio
Hanging wall	2.717	19.40	33.2°	4.129	72.30	49.88	0.223
Ore body	2.754	19.41	36.7°	3.849	106.46	69.12	0.242
Footwall	2.757	15.63	41.4°	3.900	93.46	42.57	0.246



**Fig. 1** Joint rose diagrams: (a) Hanging wall; (b) Ore body; (c) Footwall

280° to 330°, and advantage tendency of 100° to 130°, 200° to 300° and 300° to 330°, respectively. Advantage tendencies totaled 3 to 4 groups, and joint densities were

almost the same, 3–4 m<sup>-1</sup>. Joint–fissure survey results provided the basic data for stability evaluation and quality classification of rock mass.

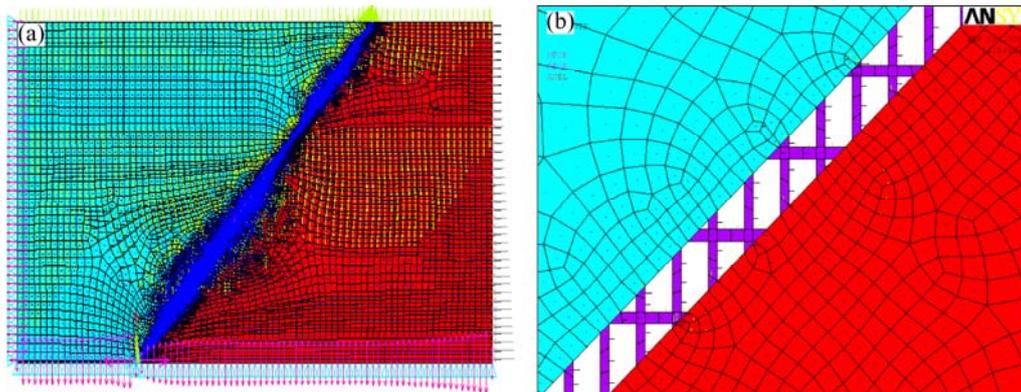
**2.3 Quality evaluation of rock mass**

At present, quality evaluation of rock mass is popularized in rock engineering [21–23]. There are many classification methods for rock mass, such as Barton rock quality Q system classification, soil mechanical classification rock mass rating (RMR) classification, engineering rock mass BQ grading standards (GB50218—94) and water resources and hydropower engineering geological investigation standard underground cavern HC classification. Q classification method emphasizes on the number, roughness and alteration of the joints; therefore, if considering the direction of the joint, this method was not very suitable. RMR method better reflects the medium solid rock quality, but not suitable for poor rock mass, and the evaluation results are conservative. BQ classification method is mainly based on saturated compressive strength and integrity of rock mass which judges the quality of the rock mass coefficient of main factors, and the groundwater, main structure surface, and the ground stress are correction factors. But the classification results are too sensitive to the rock mass strength. HC classification method is based on the rock strength, integrity of the rock mass and structure of the state, and the ground stress, groundwater, structure surface position correction factors, and is used in the classification of surrounding rock in low stress, but in high stress area, i.e., the rock burst area, the classification results are infeasible.

As Sanshandao Gold Mine belongs to coastal mine, it is necessary to put forward a new rock engineering quality evaluation method, and built a new rock quality evaluation system based on the special features of coastal deposit. Thus, mining modification of rock mass rating (M-IRMR) rock evaluation system was established based on the actual engineering situation, groundwater, ground stress and rock blasting vibration on the stability of rock mass. M-IRMR evaluation system includes 9 evaluation indexes: R1 was rock compressive strength, R2 was RQD, R3 was joints spacing, R4 was joints state, R5 was groundwater state, R6 was corrective parameter of joints of the influence of engineering direction, R7 was fixed parameters of in-situ stress, R8 was blasting vibration effect coefficient, and R9 was exposed areas for rock mass. M-IRMR accurately reflects the comprehensive quality of engineering rock mass index, available for undersea rock ore deposit quality evaluation.

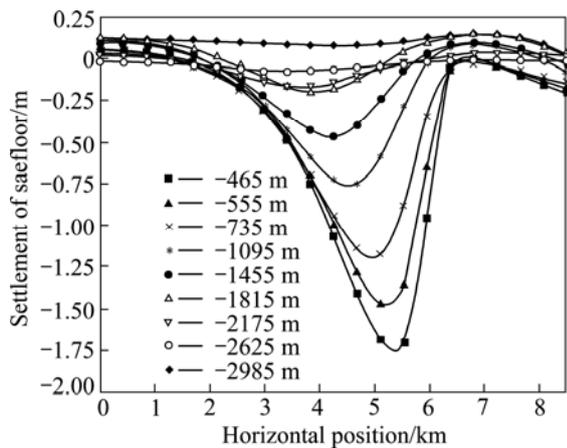
RMR method was used to evaluate rock quality in a deep level, combined with actual situation in the mining



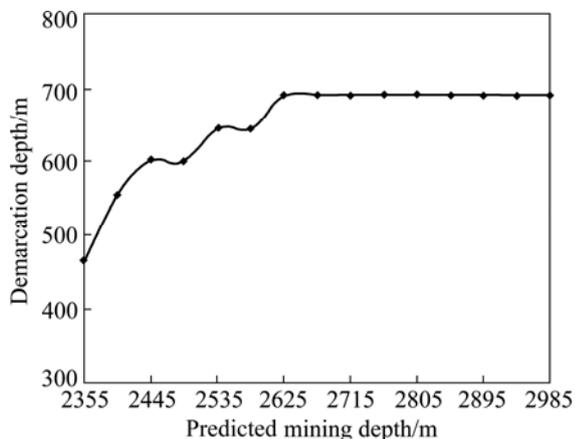


**Fig. 3** Finite element numerical model: (a) Whole stope; (b) Surrounding rock, ore pillar, roof and floor

Rock mechanics parameters are listed in Table 2. The relationships between different demarcation depth and settlement of the surface are shown in Fig. 4. After studying the settlement of ground surface, equivalent stress and plastic zone distribution of the mining area, the reasonable demarcation depth of cancelling the ore pillars was obtained and shown in Fig. 5.



**Fig. 4** Relationship between settlement of seafloor and demarcation depth



**Fig. 5** Relationship between demarcation depth and predicted mining depth

The simulation results show that, when the mining depth reached 2.5 km, the undersea settlement was 1.75 m in the worst working condition. Except the total mining depth, the demarcation depth, the maximum mining rate, the surrounding rock stress, the terrane deformation and the safe coefficient presented complicated relationship. As the mining depth increased, the subsidence of the seafloor reduced significantly (from Fig. 4). Combined with the actual situation (the mining depth was 2400 m in Xinli Zone of Sanshandao Gold Mine), the ore pillars below the  $-510$  m level were likely to be cancelled (from Fig. 5).

According to the numerical simulation results and combined with the actual mining conditions, the mining method was changed as follows: from the level of  $-465$  m to  $-555$  m, the ore pillars were canceled gradually, and all the ore pillars should be canceled below the level of  $-555$  m.

#### 4 Room-pillar alternation backfill method

With mining depth continuously increasing, geological conditions became more and more complicated. The point-pillar mining method was not suited for deep mining any more. According to the actual mining conditions in Sanshandao Gold Mine, the room-pillar alternation level backfill method was designed and used in 553# stope. As the new mining method implied in Fig. 6, all the ore pillars were cancelled and the stope was disposed vertically to the ore body, which was divided into the first step stope and the second step stope along the strike. The length of the stope was the same as the thickness of the ore body. For the rock mass of grade II, the width of the room or pillar was 10 m to 12 m. For the rock mass of grade III, its width became 8 m to 10 m. The first step stope was supported by anchor bolt, local broken area was reinforced by metal nets. The second step stope was supported by the combination of anchor cable and bolt.

Actually, the essence was that the ore body was divided into many rooms and pillars along the strike, forming a mining panel. Trackless mining preparation system was adopted, consisting of the ramp, sublevel roadway, layered crossheading and ore pass. By the mining method of mechanization upward stratified backfill, when a layer was exploited about 2.5 m in the stope, the stope was backfilled in time. The suitable compensation space was kept about 1.5 m. The mining sequence proceeded as follows: the rooms were mined at first, and all the rooms were exploited at one time. After the room was exploited upwards 8 m to 10 m, roof-connected filling was carried out. Then the pillars were recovered. Likewise, the connected-filling was adopted when the pillars was exploited upwards 16 m to 18 m. In the next

step, the rooms were mined again. The process was repeated until the whole ore blocks were exploited (Fig. 7). This new mining method enhanced the safety working conditions and reduced the resources loss and thus improved the mining benefits.

The room-pillar alternation layered backfill method was used in 553# panel area. Industrial practice results show that the new mining method greatly improved the mining output, with small disturbance in the rock stratum, and effectively controlled the dangerous faults in the hanging wall during the mining process. Mining dilution rate was 4.71%, and mining loss was only 4.97%. The production capacity of a stope was averaged to be 258 t/d and production capacity of a panel area was averaged to be 1025 t/d. Compared with the point-pillar upward

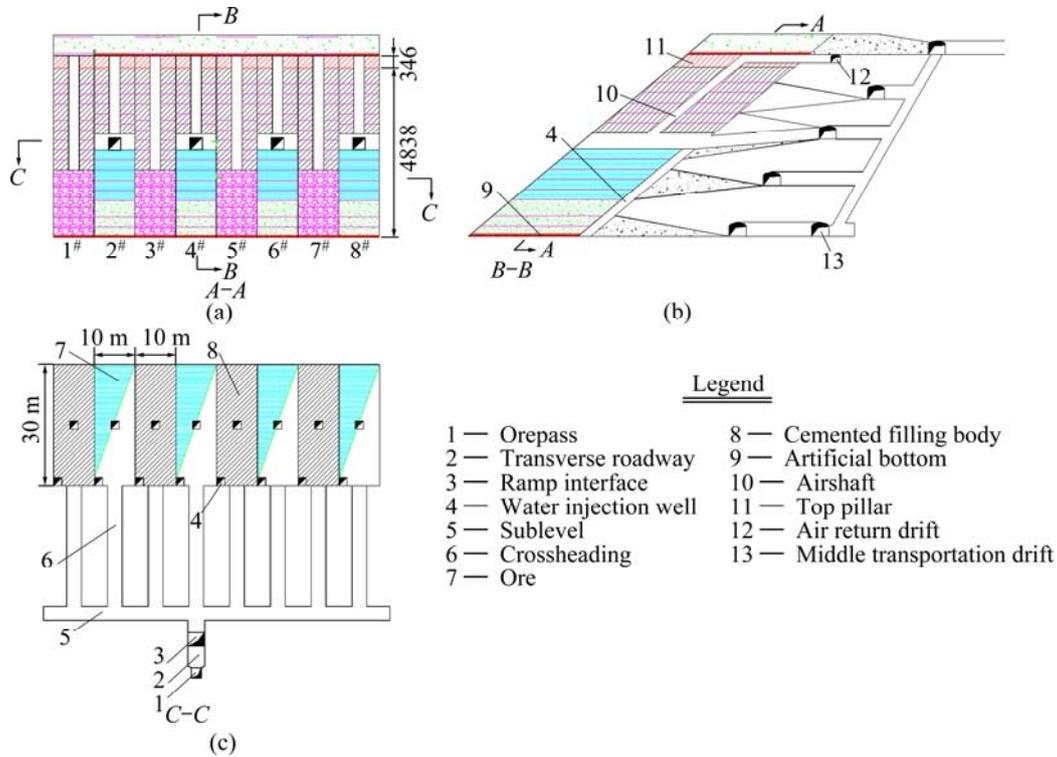


Fig. 6 Room-pillar alternation level backfill method

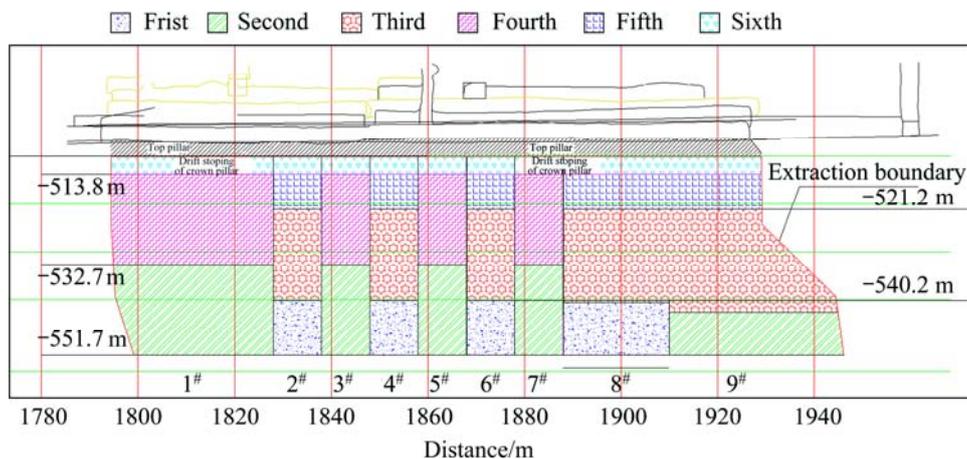


Fig. 7 Mining sequence in 553# panel area

layer-backfill mining method whose mining dilution and loss rate were 8.2% and 22.6%, respectively, the dilution and loss rate were considerably reduced. With the new mining method in 553<sup>#</sup> test stope, 537100 t of ore were mined out, and economic benefits of 394.3646 million Yuan were obtained.

The production capacity in Sanshadao Gold Mine was 8000 t/d before. While after popularizing the new technology, the mining dilution was reduced from 8.2% to 5.45%, and mining loss was reduced from 22.6% to 5.99% so the economic benefit of 516 million Yuan per year was achieved. Besides, the geological reserves consumption was reduced by 476100 t per year, thus prolonging the mine service life more than five years.

## 5 Ground surface settlement simulation and safety monitoring

### 5.1 Numerical simulation

To ensure the safety mining conditions, detecting the deformation of rocks and surface settlement after cancelling ore pillars during deep level mining in coastal deposit was important. Therefore, the numerical simulation with finite-element analysis software ANSYS was adopted to study the influence of the surface subsidence and rock deformation.

The parameters of the model are shown as follows: the direction of model length was along strike of ore body, and its length, width and depth of the model were 1230, 500, and 1000 m, respectively. The dimensions of the ore pillars were 4 m×4 m, and their net dimensions were 15 m×15 m in the upper mining. In the deep mining (down the level of -550 m), all the ore pillars were cancelled. The minimum safe thickness near surface was 60 m, and the height with point-pillar mining method was above the level of -550 m. There were 1100 m toward the land and 100 m toward the seawater in the calculation model. The finite element meshes are shown in Figs. 8 and 9, and the calculation mechanical parameters are shown in Table 2.

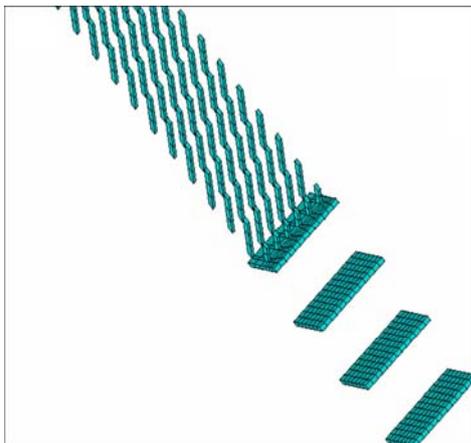


Fig. 8 Meshes of point-pillar, roof and floor

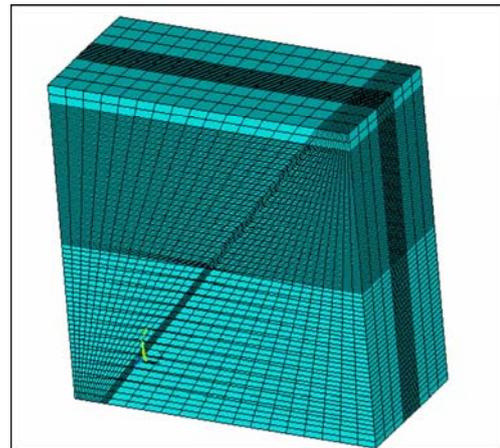


Fig. 9 Meshes of model

Simulation results show that the largest settlement was at the length of 430m vertical to the strike, and the maximum settlement was 140.642 mm (Fig. 10). The mining disturbance settlement is shown in Fig. 11.

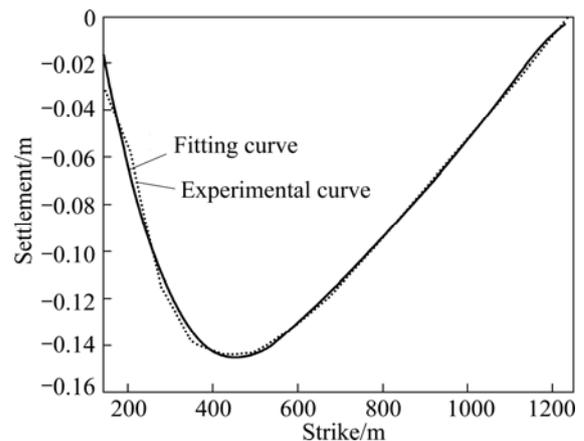


Fig. 10 Settlement curve along strike of orebody

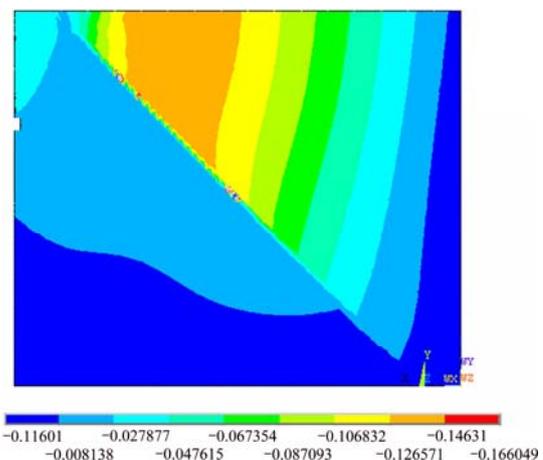


Fig. 11 Planar graph of disturbance settlement (unit: mm)

The settlement points of the ore body were fitted along the strike, and the fitting curve is shown in Fig. 10. Fitting function is obtained as follows:

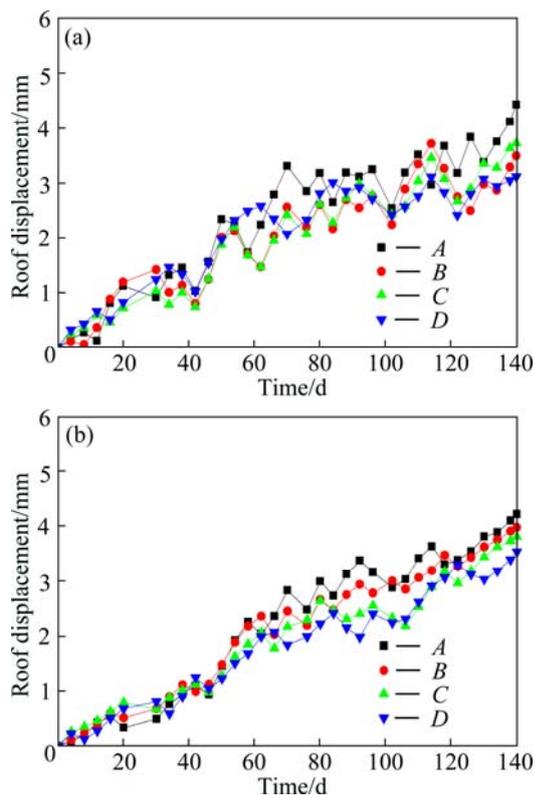
$$y = -2.089 \times 10^{-18} x^6 + 8.378 \times 10^{-15} x^5 - 1.237 \times 10^{-11} x^4 + 7.463 \times 10^{-9} x^3 - 4.765 \times 10^{-7} x^2 - 0.0010^9 x + 0.130988$$

The fitting coefficient of the above equation was 0.9974, so the fitting degree was higher.

Calculating by the fitting curve in Fig. 10, the maximum horizontal deformation was 0.4 mm/m, the largest curvature was  $0.003 \times 10^{-3} \text{ m}^{-1}$ , and the largest tilt was 0.011 mm/m. According to the national classification regulation, the damage degree of the building was at the grade I, and only about 1 mm crack natural brick might appear in the wall, so the influence on the coastal houses was limited.

## 5.2 Safety monitoring

Inspecting the effect of room-pillar alternative layer-backfill method to control the deformation of terrane, a transport roadway in -540 m level was chosen as the test site, which was divided into four points (A, B, C and D) using SWJ-IV tunnel convergence. The deformation of the roadway was measured in 140 d and the results are shown in Fig. 12.



**Fig. 12** Displacement sedimentation curve: (a) Vertical direction; (b) Horizontal direction

Monitoring results show that the deformation was smaller during the mining process. The maximum deformation was less than 5 mm after 140 d, and the deformation in general point was less than 4 mm. The deformation of the roadway and the settlement of the roof terrane were larger in the early time, with a high

growing rate. But, its growing rate reduced with time gradually. These results show that the new mining method effectively controlled the deformation of terrane and ground pressure, realizing the safety of coastal mining.

## 6 Conclusions

1) A system of rock mass quality classification that is suited to coastal deposit is put forward. In addition, to ensure security and the biggest mining rate, the feasibility of cancelling the ore pillars in deep level is estimated using numerical simulation method. The results indicate that the ore pillars can be cancelled below the level of -555 m in Sanshandao Gold Mine.

2) The room-pillar alternative layer-backfill mining method is presented to use in 553# panel area in Sanshandao Gold Mine. Industrial practices show that the new mining method is able to improve the mining output. The terrane disturbance in mining area is small. In the same time, mining efficiency is enhanced by 3 to 4 times and over 5 times of reduction is the mining loss rate. So, significant economic benefits are obtained.

3) By analyzing the laws of surface subsidence and deformation, the influence of the surface deformation to coastal buildings is evaluated and is small after cancelling the ore pillars in deep level. The rock mass deformation monitoring system is designed and the monitoring data show that the room-pillar alternative layer-backfill method can effectively control the terrane deformation. Therefore, all ore pillars can be cancelled in deep level mining.

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## 滨海大型金矿床取消矿柱及房柱交替采矿的新工艺

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**摘要:** 针对三山岛金矿条件, 研究了深部开采取消点柱的工艺技术。首先, 调查测试了矿岩物理力学参数, 并对矿岩质量进行了分级。其次, 在详细分析上下盘及矿体的物理力学特性的基础上, 对三山岛金矿深部开采取消矿柱进行了有限元数值模拟, 研究得出-555 m 水平以下矿体的开采可全面取消矿柱。最后, 结合矿床条件, 提出了房柱交替式盘区上向分层充填采矿新工艺。工业试验结果显示, 该新工艺大幅度提高了单位面积开采强度, 对岩层扰动小, 盘区生产能力大, 矿石损失贫化小, 获得了显著的经济效益。此外, 对三山岛金矿由于深部开采而导致的地表沉降利用 ANSYS 软件进行分析, 同时对岩层变形进行了监测。结果表明, 三山岛金矿深部开采取消矿柱和采用房柱交替采矿新工艺后能够有效控制岩层变形, 从而可实现滨海大型金矿床安全高效低贫损开采。

**关键词:** 滨海矿床; 岩石质量评价; 数值模拟; 房柱交替充填采矿法; 监测系统

(Edited by Hua YANG)