Engineering 3 (2017) 559–566

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Efficient Exploitation of Deep Mineral Resources—Article

Key Technology Research on the Efficient Exploitation and Comprehensive Utilization of Resources in the Deep Jinchuan Nickel Deposit

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ARTICLE INFO

Article history:
Received 10 April 2017
Revised 1 August 2017
Accepted 2 August 2017
Available online 23 August 2017

Keywords:
Deep mining
Efficient exploitation
Comprehensive utilization
Key technology

ABSTRACT

To understand the resource features and geology in the deep Jinchuan nickel deposit, difficult geological conditions were systematically analyzed, including high stress, fragmentized ore rock, prevalent deformation, difficult tunnel support, complicated rock mechanics, and low mining recovery. An integrated technology package was built for safe, efficient, and continuous mining in a deep, massive, and complex nickel and cobalt mine. This was done by the invention of a large-area continuous mining method with honeycomb drives; the establishment of ground control theory and a technology package for high-stress and fragmented ore rock; and the development of a new type of backfilling cement material, along with a deep backfilling technology that comprises the pipeline transport of high-density slurry with coarse aggregates. In this way, good solutions to existing problems were found to permit the efficient exploitation and comprehensive utilization of the resources in the deep Jinchuan nickel mine. In addition, a technological demonstration in an underground mine was performed using the cemented undercut-and-fill mining method for stressful, fragmented, and rheological rock.

1. Introduction

The Jinchuan nickel mine is a world-renowned multi-metal-associated sulfide deposit with nickel and copper as the dominant elements. Discovered in 1958, this deposit lies at the foot of Mount Longshou, and is 6.5 km long and 500 m wide. The proven reserve is 5.6×10^8 t, which includes 6.03×10^6 t of nickel, 3.89×10^6 t of copper, and more than 20 other valuable elements such as cobalt, silver, and platinum group metals. The deposit ranks the third globally in terms of size. It plays a vital role in China's nonferrous metal resource structure, with its nickel reserve accounting for 79% of the total nickel reserves in China, its cobalt ranking the second in China, and its platinum group metals topping China's reserve list; thus, it accounts for more than 80% of the domestic reserve. However, the mining conditions in the mine are quite complicated [1]. After many tectonic movements, the joint fissures have become well developed, and the orebodies are buried deep in the earth. A number of disadvantages make this deposit unusual in terms of high stress, a large scale, and difficult mining; these issues include high ground stress, fragmented ore rock, massive deformation, difficult tunnel support, and complex rock mechanics.

Work at the Jinchuan nickel mine has become deep mining, as the current operation is over 1000 m beneath the surface. The total mining area is more than 570 000 m^2, and the geological conditions are deteriorating, as indicated by an increasing mining area, more fragmented ore rock, further developed joint fissures, and higher ground stress. Serious deformation and rheology are causing instable stope wall rock and tunnels, presenting increasing challenges to mining operations in the depths of the Jinchuan nickel mine, and leading to a higher risk of geological disasters.

Experience with many deep metal mines at home and abroad has shown that conventional development, support methods, mining theory, and technology are not suitable for deep mining because of the special conditions that occur, including high ground stress,

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http://dx.doi.org/10.1016/J.ENG.2017.04.021

high temperature, seepage pressure, and complicated geology. In comparison with shallow mining, problems affecting deep mining include not only higher ground stress and difficult support, but also issues with personal and equipment safety, harsher work conditions, lower productivity, higher mining costs, and operation over a large area [2]. Thus, realizing efficient, safe, and economical mining and taking full advantage of the mineral resources in deep mines are a major research subject.

To resolve the problems related to deep mining at Jinchuan and to achieve safe, efficient, and economical mining in an environmentally friendly way, it is necessary to study the resource features and characteristics of the Jinchuan nickel mine. It is also necessary to develop a technology package for continuous deep mining and backfilling at Jinchuan through theoretical guidance, technological research, operation practice, process improvement, system integration, and information sharing; such a package will have a profound significance for mining the deep resources at the Jinchuan nickel mine.

2. Resource features and geology of the Jinchuan nickel deposit

The Jinchuan nickel deposit is located at the uplift belt at the edge of the Alxa platform block—that is, at the uplift belt of Mount Longshou. It is south of a tidewater basin and north of the geosyncline of the Qilian Mountains. There are large, deep faults along both sides of the uplift belt of Mount Longshou; the northern fault is called Fault F1. Tectonic signs are apparent, mostly in the form of fractures; these are due to tectonic movements since the Lüliang Movement, with well-developed fractures occurring across the entire mine [2].

The ore-bearing rock mass at the Jinchuan nickel deposit is 6.5 km long and 20–527 m wide, with depths ranging from several hundred meters to over 1000 m, and a maximum depth of more than 1100 m (as shown in Fig. 1). Both the eastern and western sides are covered by Quaternary rock, with outcrops in the middle and denudation at the top. The rock mass strikes northwest at 50° and inclines southwest at 50°–80°. It is divided into four sections from west to east; these are the No. 3, No. 1, No. 2, and No. 4 mining areas.

The outcrop stratum at the Jinchuan nickel deposit is simple, mainly comprising Pre-Sinian Baijiazuizi group mesometamorphic rock, including banded migmatite, chlorite quartz schist, serpentined marble, marble with agmatite, pomegranate mica gneiss, and biotite plagioclase gneiss. The stratum inclines to the southwest. In addition to ultramafic rock, pinkish red granite and alaskite are present. The ultramafic-induced dikes are aplite, diabase, lamprophyre, fine-grained diorite, and so forth.

Ore-bearing ultrabasic rock mass has intruded into marble and migmatite as irregular dikes, with main lithofacies of dunite, pyroxene peridotite, lherzolite, plagioclase lherzolite, and pyroxene, the first three of which are dominant ore-bearing lithofacies. The distribution of rock has obvious control over mineralization. The specific characteristics of the deposit are described below.

(1) There are complicated tectonic movements and high tectonic stress throughout the mine. The strata has experienced many geotectonic movements, metamorphism, and the multiple intrusion of magma since the Lüliang Movement. The lower Proterozoic metamorphic rocks show multi-period deformation, metamorphism, and strong tectonic replacement, indicating a fierce transformation effect and mutual superposition. Magmatic rock, including ore-bearing ultramafic rock, has generally been strongly transformed into a lentoid structure during a series of deformations and metamorphisms after the magma period, resulting in the extreme development of tectonic fractures and joints. The ore rock shows poor stability due to the frequent cutting of geologic structural planes, including fault planes, inter-fault compressive planes and joints, complex rock combinations, and the frequent cutting of soft structural planes (i.e., fault planes and inter-fault compressive planes and joints). The stability has been further weakened by serpentine, tremolite, and chlorite schist zones at the contact area of the ore and the surrounding rock, as well as by fragmented rock mass, water muddying, expansion, dilatancy, and creep [3].

Tectonic stress is high in the Jinchuan nickel deposit, and is complicated and diversified due to repeated tectonic superposition, traction, and transformation. Horizontal tectonic stress prevails in the deep Jinchuan nickel mine; it increases linearly into the depth of the mine, generally reaching from around 30 MPa to over 50 MPa and thus falling into the range of mid-high to super-high stress, and is closely related to tectonic denudation. Both vertical original rock stress caused by gravity and horizontal stress caused by excavation increase dramatically at deeper levels in the mine. According to ground stress data from deep site monitoring, deep rocks present obvious traces of ancient tectonic movements. The congruent tectonic stress field and residual tectonic stress field result in anisotropy and inhomogeneity in the ground stress field of the deep rock mass. Compared with the area close to the ground surface at the mine, the maximum principal stress deep in the mine is deflected, and its angle with the

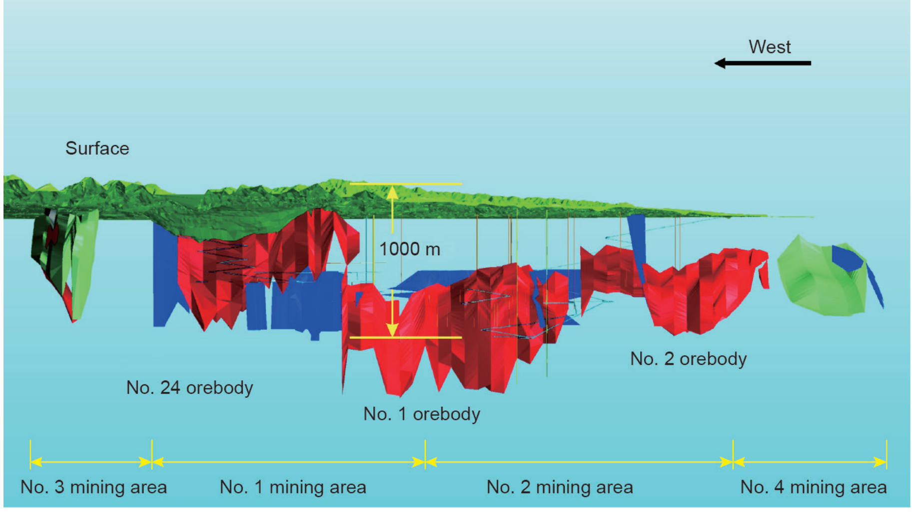

Fig. 1. A model of the Jinchuan nickel deposit created using SURPAC.

horizon shows an increasing trend, leaving deep stopes and their surrounding rock in a bad stress environment [4].

(2) The Jinchuan nickel deposit has a huge resource volume and a low average nickel grade of 0.96%; it contains many associated valuable elements that are worth extracting. However, the retaining resource is highly concentrated, with low grade ore accounting for a large proportion, making it difficult to take full advantage of the resource.

(3) The Jinchuan nickel deposit is big and deeply buried. Large-area pillar-free continuous mining and mechanized cemented undercut-and-fill mining were previously adopted, leaving behind an extra-large mining area of 570 000 m^2. Intensive large-area mining and blasting have resulted in a major challenge to stope stability. As deep mining continued and the scale of mining increased, the mining activity exerted an impact on more and more surrounding rock by changing its stress status and inherent properties. Furthermore, large-area mining in the multiple-echelon model made stress more active, causing rock stress to increase by several times—and even by as much as 10 times—around various excavating operations that were already under high ground pressure, thereby deteriorating the mining conditions.

3. Key technological problems for deep mining in the Jinchuan nickel mine

The Jinchuan nickel mine is a world-class, large, and refractory mine due to its complex geology, unique resource features, special engineering conditions, rock mechanics of broken expansion and rheology, high ground stress, and deep-buried and unstable orebodies. It has therefore drawn much attention from mining and rock mechanics professionals at home and abroad. A number of technological problems urgently need to be tackled to enable the effective exploitation of resources in this deep deposit [5].

(1) Control of broken expanded rock under high ground stress. Due to the high ground stress in the Jinchuan nickel mine, the surrounding rock of deep roadways shows obvious crack-expansion creep, and ground pressure activities happen frequently. When designing a deep mining layout, it is essential to determine the distribution law of the complex ground stress and how it happens, to scientifically categorize ore rock based on its stability, and to perform a quality assessment. The main theoretical basis of rock stability control is to understand the deformation and failure mechanism of the deep surrounding rock, and to clarify the impact mechanism of mining on rock failure. To ensure an efficient and safe mining operation, a dynamic monitoring system must be set up to monitor deformation across the mine and to develop a stope disaster prediction system.

(2) High-intensity mining with high productivity and recovery in thick and inclined orebodies. The orebodies in the Jinchuan nickel deposit are thick, inclined, and deep. The mine is characterized by fragmented ore rock, well-developed joints, and sophisticated stress. It is necessary to develop innovative and efficient mining methods, carry out pillar-free continuous large-area stoping in thick and inclined orebodies, realize continuous mining in deep orebodies, and balance the descent of multiple echelons. It is also necessary to maintain balanced mining and backfilling, increase mechanization and automation for a higher mining rate and lower dilution rate, and realize efficient mining at low cost.

(3) Continuous stoping in a large area. A cemented undercut-and-fill mining method has been adopted in the Jinchuan nickel mine. As mining proceeds in the deep mine, the world's biggest continuous backfilling block in a metal mine has already taken shape in Jinchuan; however, the lack of stability and deformation of the backfilling block have become a potential risk for a geological disaster deep in the mine. In addition, due to the intricate technology of high-density slurry cemented backfilling for deep mining, a number of problems occur, such as the difficult transport of high-density slurry, poor system stability, the complicated layout of backfilling pipelines, and severe wear on backfilling drill holes and pipelines. Efficient deep mining at Jinchuan also carries some key technical challenges: to optimize the composition of high-density backfilling slurry, to make the backfilling system stable and reliable, and to make the strength of the backfill compatible with the continuous mining of thick orebodies.

(4) Comprehensive utilization of mineral resources. The Jinchuan nickel deposit features a low average grade, high level of magnesium oxide, and serious rock alteration, along with many species of valuable elements. To develop lean ore in the No. 3 and No. 4 mining areas, it is essential to operate low-cost mining with higher overall recovery; innovate mining and mineral processing technology; improve the technical and economic index for extracting nickel, cobalt, copper, and associated elements; and make full use of the tailings and smelting slag in an economical and environmentally friendly way in order to promote a circular economy.

(5) Prevention of geological disasters in deep mining. It is generally thought that rock movement at the surface is not serious in metal mines where backfilling mining methods are used, and that a massive geological disaster cannot be induced. However, at Jinchuan, rock movement, deformation, and failure have taken place at the ground surface despite the adoption of high-density cemented backfilling. As the mining at Jinchuan extends further in depth and scale, prevalent rock movement, deformation, and building failure at the surface have occurred, posing a major threat to mine stability and shaft security. The mining depth within Jinchuan is over 1000 m, and the total mining area is over 570 000 m^2. Deformation results from a global positioning system (GPS) monitor show that the surface rock movement roughly centers on the major underground mining area, the deformation rate of the surface rock movement is accelerating slightly, and tension cracks develop at the surface. The Line 14 ventilation shaft, which is located at the rim of the subsidence basin of the No. 2 mining area, has experienced vertical subsidence of 1070 mm, horizontal movement of 455 mm, and three-dimensional (3D) movement of 1185 mm since it was rebuilt 13 years ago, in 2005, after having collapsed. Monitoring data show that extensive surface rock movement has posed a major threat to the underground mining and surface facilities. It has therefore become an important challenge to monitor deformation in the surrounding rock and backfill, study and establish the relationship between underground mining intensity and surface rock deformation, and set up a scientific prediction system for mine disaster and stability failure.

4. Key research directions and phased results for the exploitation of deep resources

4.1. Theory of and technology for broken, expanded, and rheological rock under high stress

4.1.1. The distribution law of ground stress in the Jinchuan nickel mine

Much attention has been paid to the investigation of the ground stress law at the Jinchuan nickel mine. Many research institutes have been engaged in measuring and monitoring stress in multiple phases, echelons, locations, and methods, and have obtained stress data at various locations and depths. A stress distribution regression function was worked out via statistical analysis, providing a primary understanding of the stress distribution law at the Jinchuan nickel mine. Fig. 2 shows the stress prediction and regression results.

Analysis on stress deep in the mine yielded the following results: The maximum and minimum horizontal principal stress varied to the third power with depth, while the vertical stress increased linearly with depth; there was a large gap between the maximum and minimum horizontal principal stress; and the direction of the maximum deep principal stress deflected and appeared to be increasing in its angle to the horizon, indicating higher shear stress at deeper levels and a worsening stability of the deep ore rock.

4.1.2. The mechanism of deformation and failure in the deep surrounding rock

Rock stability in the Jinchuan nickel mine depends mainly on ground stress environment, engineering geological conditions, rock mechanics, and mining impact. By means of rock mechanical tests over the years, it was found that the dominant deformation mechanism of the stressed jointed rock mass included unloading spring-back, dilatancy, crash creep, and water-absorbing expansion of the surrounding rock, with the characteristics of large, rapid, and long-lasting deformation, pressure from all directions, and obvious shrinkage deformation (as shown in Fig. 3 and Fig. 4). Deformation of the surrounding rock depends on mine-induced stress, and the deformation curve increases in stages with time, without a convergent trend. In general, the deformation rate fades out in a fluctuant way, but never reaches zero. The critical value for rock rheology was defined as 3 MPa by analyzing the rheological characteristic of the surrounding rock in the Jinchuan nickel mine. When the stress exceeded 4.35 MPa, the rheology of the ore rock accelerated. Stress-and-strain tests of the rock mass showed that the accumulated plastic deformation increased dramatically as the cyclic loading increased. When the stress was 7.16 MPa, the residual deformation accounted for two thirds of the total deformation.

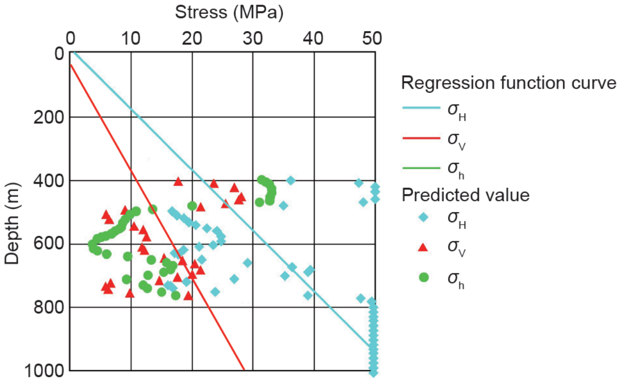

Fig. 2. The maximum and minimum horizontal principal stresses (σ_H, σ_h) and the vertical principal stress (σ_V) vary with depth.

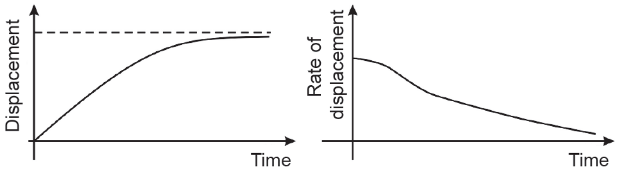

Fig. 3. Permanent engineering deformation–time and rate–time curves in non-dynamic pressure.

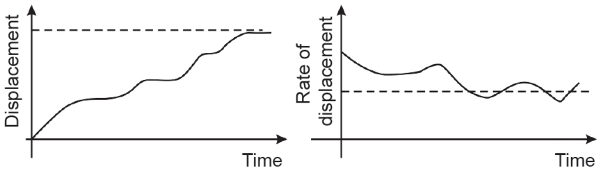

Fig. 4. Engineering deformation–time and rate–time curves in dynamic pressure roadways.

4.1.3. Deformation monitoring and a disaster-prediction and pre-warning system

Based on the surface GPS network (Fig. 5) and distributed optical fiber sensing technology, a stereo dynamic deformation monitoring system has been built across the Jinchuan nickel mine, and a disaster-prediction and pre-warning system has been developed.

Distributed optical fiber sensing technology was adopted at the Jinchuan nickel mine for deformation monitoring of the surrounding rock of the stopes and backfill. Next, an equivalent intelligent numerical model was set up according to the monitoring data. The model was set up with the equivalent mechanical parameters of the stope-surrounding rock in the Jinchuan nickel mine as follows: first, 3D orthogonal numerical tests and a genetic programming algorithm were used in order to establish the relationship between surface rock movement and the rock mass parameters; next, the sum of the square of the difference between the monitored and calculated value was looked at; and finally, the model was optimized by minimizing the sum.

$$M\,\mathrm{in}\,F(x)=\sum_{i=1}^{n}\left[f_i(x)-w_i\right]^2 \tag{1}$$

where $F(x)$ is a pattern-recognition optimization function, $f_i(x)$ is the calculated value of movement in the model in relation to point i, and w_i is the measured value of movement relating to point i. Equivalent rock mass parameters were obtained by solving the equation for the current mining stage (correspondent monitoring deformation), and a model verification and reliability assessment were then done (Fig. 6). Finally, a stope stability analysis and a rock movement prediction were carried out. A system was developed to manage the data for deformation monitoring, rock stability assessment, and

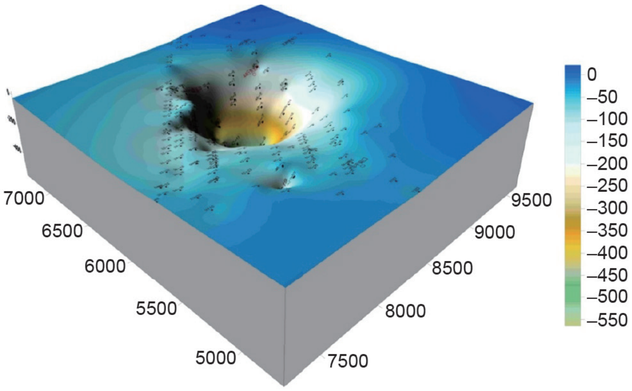

Fig. 5. A 3D graph of surface subsidence measured by GPS.

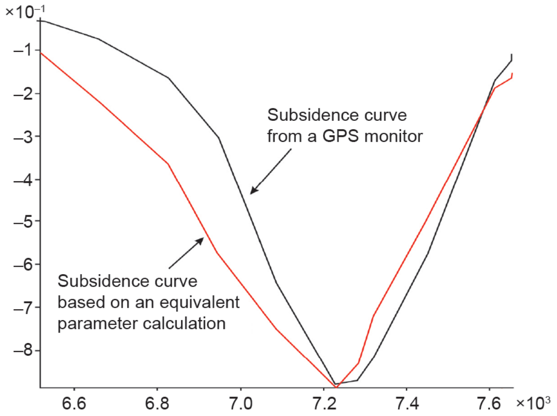

Fig. 6. A comparison of displacements from an equivalent parameter calculation and a GPS monitor.

disaster prediction and pre-warning, thereby providing support for the mining design and safe production.

4.1.4. Support technique for surrounding rock in deep roadways

Unimpeded and stable tunnels are important for safe and efficient mining in the deep Jinchuan nickel mine, and tunnel support is a fundamental requirement and key technique for deep mining. Theoretical calculations, numerical modeling, and onsite test work were systematically carried out for support technology, design methods, support material, operating techniques, and effect appraisal. This was done via comprehensive studies on the deformation mechanism, failure features, and de-stability model of the deep surrounding rock, and new breakthroughs were achieved in deep tunnel support.

We studied the deformation characteristics and de-stability model of the stressful and fragmented rock in the Jinchuan nickel mine, and developed an effective technology for controlling ground pressure activity and roadway deformation:

(1) A joint control technique for the deep repair of tunnel grouting and support loading. The surrounding rock in the repairing tunnels was groutable using cement slurry. The cement slurry concentration and reasonable grouting parameters were defined as follows: In general, a water-to-cement ratio of 1:1 was used in grouting the surrounding rock, with a grouting pressure of 2–3 MPa, one or two wall back grouting holes for every meter of tunnel, 1 m of row distance between grouting holes in the surrounding rock, 2 m deep holes, and a grouting cemented volume accounting for 1%–1.5% of the volume of the reinforced rock. Engineering practice showed that backfilling behind the support and grouting layer can pass the stress from the surrounding rock evenly onto the support structure, preventing a concentration of stress on the structure. Furthermore, an elastic backfilling layer can release a certain amount of deformation pressure, thereby preventing major deformation in the surrounding rock.

(2) A flexible support technique using grid steel arch bolting and shotcreting. Support resistance is necessary shortly after roadway excavation in weak rock in order to protect the backfill from passive compression. Grid steel arch bolting with shotcreting mesh is flexible and soft before it becomes rigid and resistant; it can close surrounding rock in a timely fashion and adjust and maximize the self-bearing ability of the surrounding rock, so it is suitable for surrounding rock with the characteristics of quick pressure movement, large convergence deformation, and strong rheology. Grid steel arch bolting with shotcreting mesh is therefore the dominant method of support in deep tunnels at Jinchuan. The grid steel arch bolting and shotcreting mesh process is as follows: First, the blasting parameters are optimized for smooth blasting, and it is ensured that the tunnel is excavated in line with its design as much as possible; next, the space of the grid steel arches is defined to be 800–1200 mm, the grid steel arches are erected, and the metal mesh and wet shotcreting are installed; finally, the grid steel arches far away from the tunnel face are thickened by shotcreting once again. As a result of this process, the repairing rate of the tunnels decreased from 35% to 20%.

4.2. A new technique of large-area continuous mining in honeycomb structural drives

4.2.1. Research on the technique of pillar-free large-area continuous stoping of thick orebodies

As the mining depth of the Jinchuan nickel mine is extended, lensoid thick orebodies gradually result in larger mining area. If interval pillars are left between panels, stress will concentrate on the pillars over time, with a peak stress of up to 447.94 MPa, according to numerical simulation analysis. This puts the pillars in high stress plastic areas and causes severe damage, which in turn makes it difficult to recover the pillars in the two-step mining method.

Given the stress distribution characteristics of deep thick orebodies and the ground control technology, the technique of pillar-free large-area continuous stoping was developed, which is quite different from the conventional two-step mining method (Fig. 7). The

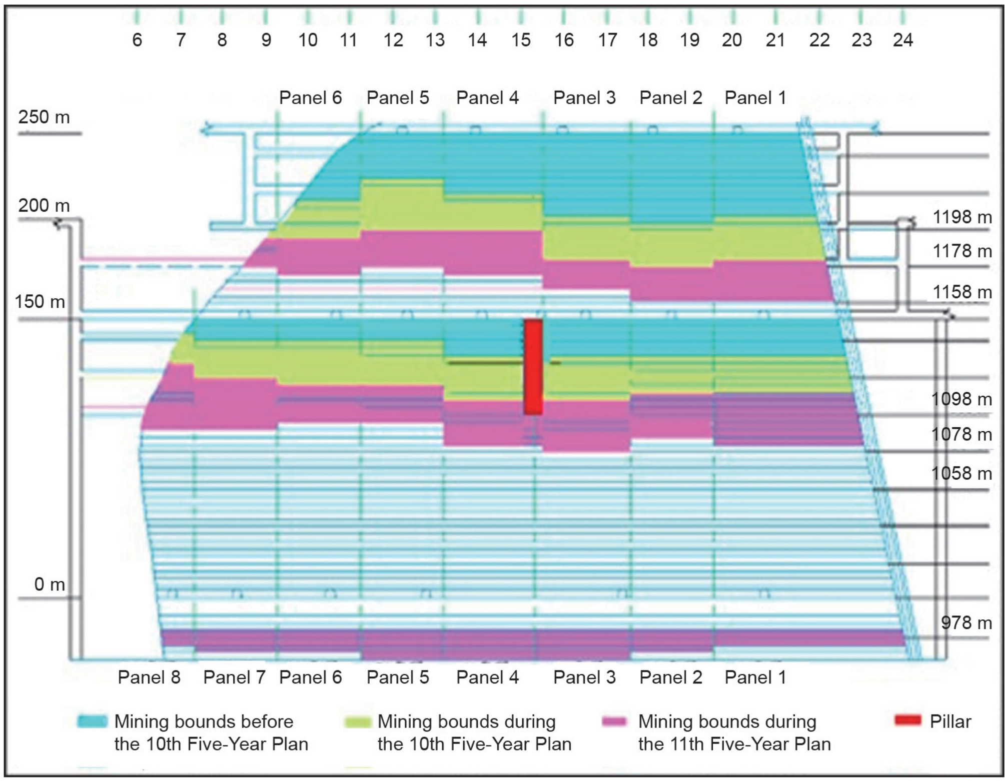

Fig. 7. The pillar-free large-area continuous mining method.

echelons were 100–150 m high, and the sublevels and layers were 20 m and 4 m high, respectively. The echelons and sublevels were connected by declines. The mining panels were divided along the orebody strike. No panel pillars were left. Mining was done in drives within the panels, with drives arranged in a line and blocked by the ore rock. The drives were backfilled one by one as soon as mining was finished. The hanging wall and surrounding rock were supported by backfilling and to-be-mined orebodies, thus realizing the continuous stoping of orebodies and achieving higher mining efficiency in the panels.

4.2.2. An efficient mining method with large-section hexagonal drives in honeycomb structures

Stope drives were arranged in a honeycomb structure based on the bionics principle. Scientific calculation showed that a honeycomb structure allowed a non-space layout among equilateral hexagons, and that a hexagonal prism could bear a maximum load with maximum capacity and minimum peripheral area, thereby presenting good structural stability.

According to the bionics principle, we tried arranging hexagonal drives in a honeycomb structure, placing both the drive section and the backfill section into a honeycomb structure, and realizing the most compact layout among the equilateral hexagons. Stress concentration was effectively reduced as a result, and full use was made of the support ability of the surrounding rock, thus producing good rock stability. However, the production capacity of the stopes was soon constrained by the structural parameters, the design parameters of the hexagonal drives, and the blasting technique. Based on a calculation using the 3D finite element model (3D-σ), a large-section hexagonal drive in the honeycomb structure mining method (Fig. 8) was later innovated by analyzing the stability of the backfill from the stress distribution, deformation rate, and plastic zone distribution. In addition, the structural parameters of the hexagonal large sections were optimized as follows: a 3.5 m wide bottom, 7 m wide waist, 6 m high section, and 31.5 m^2 section area. This represented a 40% increase of the original dimensions, so the mining efficiency and production capacity of the stopes were increased. The stress conditions around the stopes were remarkably improved, with the maximum principal stress decreasing from 93.48 MPa to 47.19 MPa, according to numerical simulation calculation, and with the stress concentration factor being 50% lower than when using square drives. Roof and sidewall failures in the drives were slashed dramatically, and stope maintenance cost was cut by 30%–50%.

4.2.3. Large-diameter empty hole spiral-cutting blasting

The geological characteristics of fragmented ore rock and developed joint fissures pose a major challenge to drilling and blasting in the Jinchuan nickel mine, holding us back from raising mining capacity subtantially. In response, we studied the forced state and throwing law of rock in empty hole blasting, and determined the mechanism of spiral-cutting blasting. We established a spiral-cutting hole-arranging principle based on the relationship between the free face width and the optimal resistance line. In addition, we determined the increasing order of the distance from charging hole to empty hole, and developed a large-diameter empty hole spiral-cutting blasting technique. The distance from an empty hole to the charging holes could be 1–1.8 times, 2–3.5 times, and 4–5.5 times the empty hole diameter. An asymmetric hole arrangement and millisecond detonation were helpful in the cutting formation. The blasting footage of each cycle was increased by 12%, and the blasting efficiency was over 90%, with the section profile of the drives under good control. This resulted in a workable process and in favorable technical conditions for tunnel support, mining, and backfilling operation.

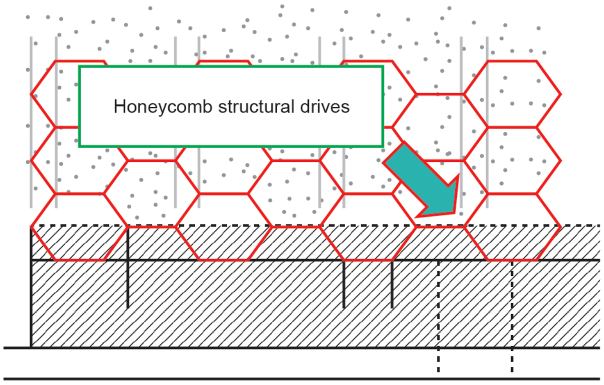

Fig. 8. The large-section hexagonal drive mining method.

4.2.4. Optimization of stope arrangement in thick orebodies

A panel is the basic mining unit at the Jinchuan nickel mine. The stoping design in the panels was originally one of single vein-crossing drifts, which carried the disadvantages of poor safety, long stoping-backfilling cycles, significant resistance to ventilation, and low equipment efficiency. The design was later improved to become double vein-crossing cyclic slice drifts (Fig. 9). The area to be mined was divided into blocks for independent or combined stoping for much higher efficiency. The use of double vein-crossing cyclic slice drifts improved the equipment efficiency, accelerated the slice switch, shortened the exposure time of the slice drifts and goaf, and cut the cost of the secondary support for the main and auxiliary vein-crossing drifts. Due to the double drifts technique, the running efficiency of the trackless equipment in the panels increased from 88% to 96%, the productivity in the panels increased by 20%, and the effective airflow rate increased by over 30%. In order to resolve the problems of low mining efficiency in individual stopes, a slow descending rate of upper stopes, and poor coordination among the stopes, a new technique was developed that comprised mutual mining in upper and lower stopes. Slice drifts were cut and mined in advance to ensure a reasonable descending rate of stopes and higher productivity, and balanced mining was realized as a result.

4.3. High-density slurry pipeline transport backfilling with mine solid waste as the coarse aggregate

4.3.1. Matching backfilling strength with the continuous mining of thick orebodies

The Jinchuan nickel mine mainly adopts an undercut-and-fill mining method, which results in large and thick backfills over the stopes. The quality and stability of the backfills have a strong impact

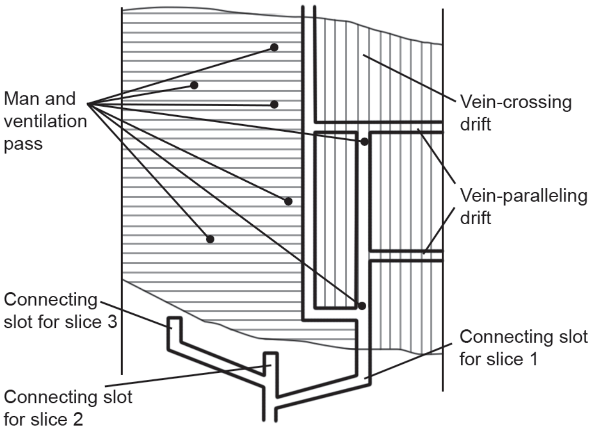

Fig. 9. Cutting and mining in double vein-crossing cyclic slice drifts.

on the safe stoping of the orebodies beneath them. Through extensive mining practice and testing, a high-density backfill slurry suitable for pipeline transport was prepared. This was done by using rod mill sand and gravel sand from Jinchuan as the aggregate of the high-density gravity system; optimizing backfill aggregates, cementing agents, and additives; and striking a good balance between backfilling strength and the continuous mining of thick orebodies.

The geometrical and physical properties of the thick backfill were obtained from the profile of the under-cemented goaf side (Fig. 10). The structure and strength of the thick backfill were revealed using a digital borehole camera, ultrasonic hole probing, and *in situ* backfill strength testing. After a considerable amount of time spent on consolidation and compacting, the backfill bodies joined closely without cavities and cracks, and the uniaxial compressive strength of the backfilling was as high as 7.8–11.9 MPa, thus meeting safety and production requirements.

4.3.2. The development of a high-flowing slurry backfill technique with mine solid waste as the coarse aggregate

Based on the stacking and interstitial effects of the aggregate, we studied various stacking compactness models and an optimal gradation equation for several types of aggregate. This work yielded a good method of grading the compatibility of aggregates. A gradation index method was used to analyze rod-milling sand gradation and slurry density in order to unveil the reason behind poor backfill quality despite a high consumption of cement. Taking into account the ratio of aggregate, cement, and moisture, a new cemented backfilling strength model equation was set up to obtain the best results in cost saving, backfilling strength, and transport density:

$$R = \alpha \Phi^{\beta} \left(\frac{W}{C}\right)^{\lambda} \left(\frac{C}{A}\right)^{\eta} \tag{2}$$

where Φ is the stacking compactness of the aggregate; $\frac{W}{C}$ is the ratio of moisture to cement; $\frac{C}{A}$ is the ratio of cement to sand; and α, β, λ, and η are test constants. Moreover, high flowing conditions were suggested for the high-density backfilling slurry: a slurry slump of over 220 mm, and a slump flow of over 450 mm. Medium and fine particles were used to load the coarse aggregate in the slurry, with the fine particles fully filling the spaces in the coarse aggregate. In the goaf, the slurry was almost self-leveling. In addition, a new technology of high-flowing slurry was developed that used mine solid waste as the coarse aggregate.

4.3.3. Research on high-density slurry flowing characteristics and the full pipe flow feeding mechanism

The critical fluidized density is referred to as the slurry density when the backfilling slurry density gradient that is vertical to the pipeline section is zero. The mathematical model for critical density is

$$M_Z = \left[1 - 16d_s / \left(16d_s\gamma_k - 3C_s\tau_0\right)\right]\left[\gamma_k / \left(\gamma_k - \gamma_0\right)\right] \tag{3}$$

where M_Z is the weight concentration of the slurry, d_s is the average particle size, γ_k is the dry weight of the compact backfill material in kg·m^{-3}, γ_0 is the specific gravity of water, C_s is the shape factor of the particles, and τ_0 is the initial shear stress of the slurry. Eq. (3) was used to determine the relationship between the critical fluidized density and particle size of solids, the initial shear stress of the slurry, and the compact specific density of the solids and transport carrier. It was determined that both a certain density and a certain proportion of fine particles were necessary for the preparation of slurry at the critical fluidized density. Test results showed that the slurry concentration was at the critical value with an optimal ratio when the ratio of tailings to rod-milling sand was 3:7 and the slurry density was 77%–79%. The flow pattern of the slurry had a Herschel-Bulkley fluid characteristic, and the coefficient of kinetic viscosity, η, was equal to 1–2.5 Pa·S. Based on a slurry system curve in a horizontal pipe and on the pump curve of a vertical pipe, we unveiled the working theory for a full pipe flow feeding system with variable-diameter pipes. In order to disperse the residual static head produced by the vertical pipes, the diameters of the vertical or horizontal pipes were reduced in an attempt to increase the friction resistance in the section where the slurry flowed, and to meet the technical requirements of the backfilling operation.

4.3.4. Research on a failure model of backfill drill holes in deep shafts and their repair

The backfilling pipeline system in the Jinchuan nickel mine is closely related to the mining operation. Most of the pipelines are located in complex rocks and dynamic excavating roadways, and failure of the backfill drill holes was the dominant cause of defaults in the backfilling system, which mainly occurred in the form of blocking, wear-induced leakage, and breaking. The settling and blocking mechanism in the backfill drill holes was discovered by studying the hydrostatic settlement speed of the solids in the backfill slurry, the hindered settlement law of non-spherical particles, and the settling blocking conditions of the slurry aggregate. Water hammer physical models were established for the pressure wave from the slurry and the vacuum bridge of the slurry. The breaking mechanism of the pipelines in the backfill drill holes was also determined. In addition, an impact wear physical model was set up for the vertical backfill holes by analyzing the momentum and energy of the backfill slurry. We developed a method to determine where a drill hole was broken, a method of permanent repair for drill holes (Fig. 11), and a method for the non-coupling installation of pipelines in backfill holes. Back-

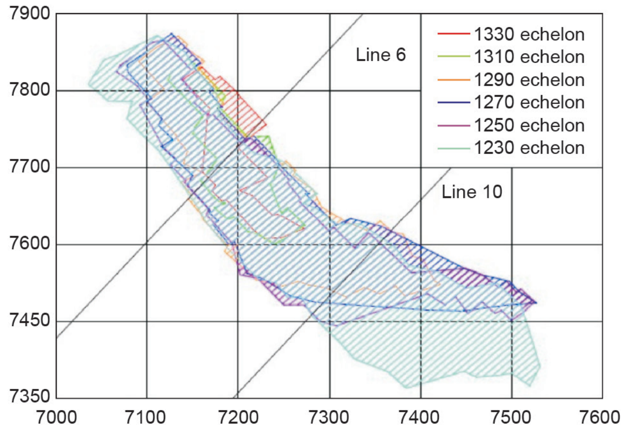

Fig. 10. Goaf-side shapes at echelons.

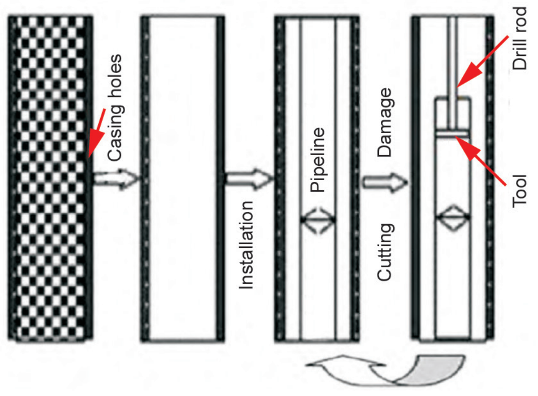

Fig. 11. The principle for repairing broken drill holes.

fill holes became permanently repairable via the regular cutting and replacing of broken pipelines. Broken drill holes may be refurbished into permanent ones by taking out damaged casing and making a non-coupling installation of backfill pipeline; in this way, efficient backfilling was secured.

5. Conclusions

The exploitation of the Jinchuan nickel deposit faces a series of major scientific challenges, including high ground stress, a complex geological structure, a difficult mining environment, and complicated rock mechanics. To achieve efficient development and comprehensive utilization of the resources in this deep mine, researchers at Jinchuan have participated in joint research, ceaselessly absorbed and studied advanced technology at home and abroad, learned from experts, constantly innovated mining engineering theory, and improved on existing technology.

The mining conditions and rock deformation mechanism found at the Jinchuan nickel mine are characterized by high stress and a huge deposit size. A theory and technology were developed for ground control with stressed and fragmented rocks, thus laying a foundation for efficient and safe mining under these conditions.

New technology was invented for large-area continuous mining using honeycomb structural drives in this deep mine, thereby realizing continuous stoping and descending of orebodies. The mechanization and mining capacity were boosted, increasing the mining capacity and the profit margin.

Technology for the pipeline transport of high-density slurry was developed using mine solid waste as a coarse aggregate. A metal mine was built using state-of-the-art backfilling techniques and parameters; this mine has the highest backfilling capacity in the world. In fact, the overall backfilling technology at Jinchuan is at a world-leading level.

A technology package was established for safe and continuous deep mining in the enormous and complex Jinchuan nickel mine, thereby achieving a new technical breakthrough in deep mining. This package is applied not only in Jinchuan, but also in a number of domestic mines, such as the Kalatongke nickel mine in the Xinjiang Uygur Autonomous Region, the Huize lead-zinc mine in Yunnan Province, and the Banmiaozi gold mine in Jilin Province.

As the mining operation in the Jinchuan nickel mine is evolving toward greater depth, higher intelligence, and lower waste, it is of far-reaching scientific significance for the efficient exploitation and comprehensive utilization of deep resources, and for the sustainable development of the Jinchuan nickel mine, to develop safe, efficient, and low-cost mining methods for lean ore resources in deep mines; to recycle tailings and smelting slag; to develop large-flow backfill slurry with a large particle size in the deep Jinchuan nickel mine; to study the relationship between the law of stress variations at mine depth and the response of rock mechanics; and to develop new techniques for deep tunnel support that are suitable for the Jinchuan nickel mine.

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