Monitoring and analysis of ground subsidence and backfill stress distribution in Jinchuan Mine, China

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Backfilling is widely used in mining operations. Deformation of a large volume of backfill leads to rock movement and ground subsidence. This study analysed ground subsidence and backfill deformation, combined with ground subsidence monitoring and numerical simulation. The results showed that the ground subsidence trough was located at the centre of the hanging wall of the ore body. The maximum vertical displacement exceeded 2000 mm. Underground excavation and filling led to stress redistribution. The shear stress concentrated at the backfill boundary and contact zone of the backfill and surrounding rock. The shear stress distribution changed with the shape of the backfill. The corner of the backfill boundary was the key position of shear stress concentration. The Mohr's circle showed the envelope line where cohesion of 500 kPa could meet the strength requirement in the shallow part of the backfill; in the deep part, the cohesion required was 1500 kPa. The deep part of the backfill therefore failed more easily than the shallow part.

Keywords: Backfill deformation, ground subsidence, mining, stress redistribution.

BACKFILLING mining plays an important role in mining operations. It can improve the stability of the underground rock mass. Even so, some environmental problems of mining are not completely avoided, such as overlying rock mass movement, surrounding rock mass deformation and surface subsidence. In China, the backfill mining technique has been adopted in over 40% of non-ferrous metal mines with underground working and nearly 40% of gold mines[1]. Some studies on backfill deformation and ground subsidence have been carried out in recent years. Haslinda *et al.*[2] studied the shear strength characteristics of mudstone backfill. The back analysis was used in field data processing with some empirical methods like profile and influence functions. Woo *et al.*[3] developed a comprehensive database of ground subsidence caused by mining to seek empirical relations between overlying rock mass movements and mining depth[3]. Mohammadali *et al.*[4] predicted mining-induced ground subsidence in Canada. Salamon[5] derived an analytical solution for stresses and displacements of the surface due to mining[5]. Stress distribution influences backfill deformation. The effective and total stresses of vertical backfilled stope were determined by an analytical method that showed nonlinear distribution[6]. Brady and Brown[7] provided a comprehensive discussion on the methods used to determine mining-induced ground subsidence[7]. Some methods have been developed to study the ground subsidence, such as observational and monitoring methods, graphical technique, profile and influence functions, empirical approach, numerical simulation and physical simulation[8–11]. Some researchers have studied characteristics of the rock and ground movement caused by mining and reactive faults[12,13]. These studies provide some basis for the present article.

Jingchuan mine, located in Jinchang city, Gansu Province, is the largest nickel production base in China. The major ore deposit is about 65,000 m long, 200 m wide, and over 1000 m deep. The rock strata of mine fields consist of meta-hyper-metamorphic rocks of the lower Proterozoic strata and Quaternary strata. These rocks are composed of schist, marble, migmatite, and gneiss, and the Quaternary strata thickness is about 25–280 m from the surface. In the field, some well-developed faults of different sizes intersect each other; faults are divided into three groups. Figure 1 shows the three main groups of faults locating in the mine area strata. Faults F1 and F16 belong to the first group, are oriented northwest ward and mainly characterized by compression shear. The second group consists of compression shear oblique faults oriented east-west ward (EW) including F8 and F23. Fault F17, belonging the third group, is oriented northeast ward (NE) and characterized by the tension-shear transversal fault. Besides these, some smaller strike faults are distributed in the mining area. The mechanical properties of rock mass in the mining area are influenced by these weak structural discontinues.

Considering the metamorphic strata of the mine area and its tectonic setting, the nickel mine adopted a mechanized mining method using backfill. The size of each mining panel is about 100 m wide and perpendicular to the strike of the ore body and backfill. The void caused by mining is backfilled immediately; therefore the filling work is part of the mining work. The mining method is underhand and in some horizontal drifting slices of 4 m height. Nearly 10 drifts are arranged in each delamination layer. The void is filled immediately after stope excavation; then the adjacent stope excavation begins. The backfill material is cement paste with tail and some additive. The backfill replaces the ore-body without pillars; so the upper layer backfill serves as the artificial roof of the next mining layer. The backfill is a kind of sand–cement grout and the sand–cement ratio is 78%. The raw material

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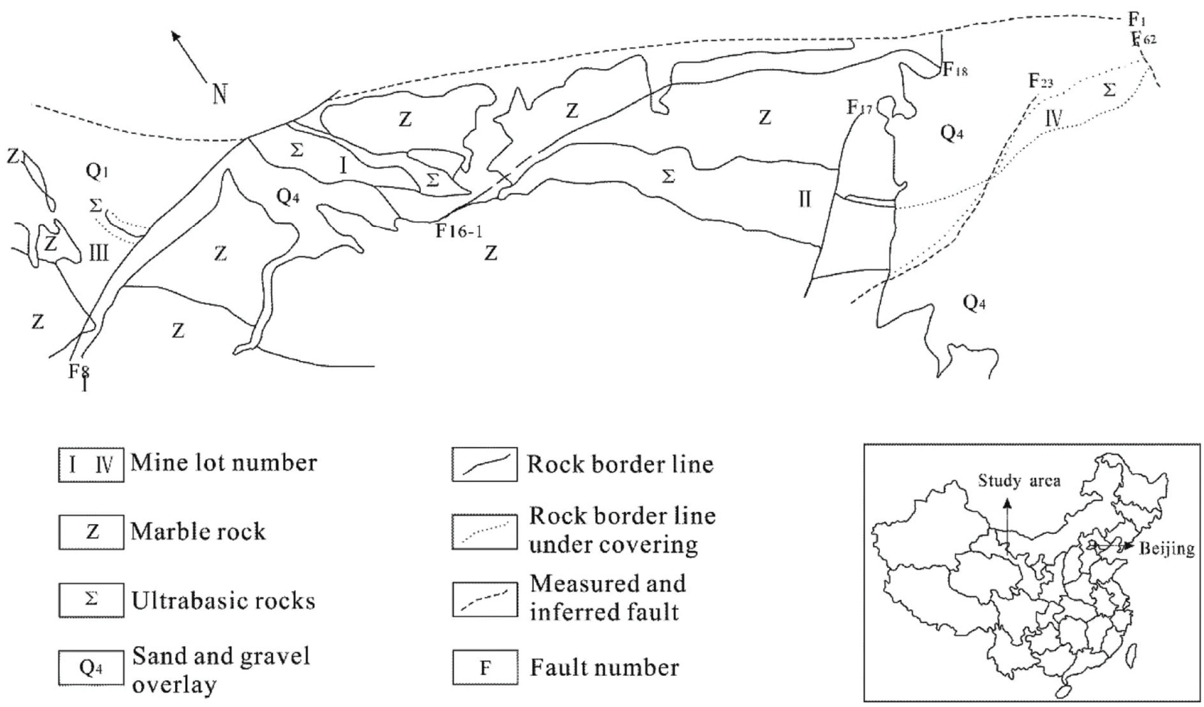

Figure 1. Geologic map of Jinchuan mine, China.

used is sand (3 mm grain size) and ordinary Portland cement; the cement–sand ratio is 1 : 6. The Young's modulus of backfill is about 3000 MPa, whereas the compressive strength of backfill required is about 5 MPa (ref. 14).

Zone no. 2 is the primary zone of Jinchuan Mine area because of its output. In the study area, the ground subsidence is obvious. At the beginning of the present study, the work was on zone no. 2. The obvious ground subsidence occurred after focus mining with backfill for over 10 years. Fissure, one type of the ground movement, was first observed in 1999. Some engineering structures had failed because of rock mass movement, such as mine shafts and tunnels. In 2005, one of the most important engineering structures, viz. 14# ventilation failed due to rock movement. The fissures parallel to the ore-body strike, and distribute around the backfill.

Several methods are used to monitor and study ground subsidence and rock mass movement. Both traditional and modern techniques are used, such as geodetic measurements and synthetic aperture radar. In traditional mine surveying, horizontal and vertical displacement measurement use the level instrument. However, there are limitations in using these methods in real engineering projects. Generally, the geological environments of metallic deposits are complex, like hilly and mountainous topography. Thus, intervisibility conditions may limit the horizontal displacement measurements. About the leveling surveying, the low precision and long measuring time are disadvantages that exist in the long-time monitoring work. For example, the steel ruler and level gauge are difficult to apply in steep mountainous area for topographic reason. The method of real-time synchronous measurement cannot used in the extensive rolling topographies for long period of horizontal and vertical displacement measurement[12].

The global positioning system (GPS) monitoring that can be adapted to almost all regions, has been increasingly applied to surveying work. To investigate ground surface movement at Jinchuan Mine, a GPS monitoring network was established in 2001. The monitoring network in zone no. 2 consists of a reference with seven benchmarks. The datum points was away from the subsidence area and all points were set on the bed rock. The reference net that composed of datum points is basis of the monitoring work. Monitoring tests are carried out semi-annually. The monitoring net has 101 measuring points and these points are laid out along the exploratory lines.

The backfill is divided into two parts along its thickness. The first part was formed prior to the monitoring work and has a thickness of 84 m from the 1334 m level to the 1250 m sub-level. Stope excavation of the 1250 m level was complete in 2001, the year in which monitoring work started. This part of the backfill had already formed before monitoring and early-stage data monitoring indicated that this backfill was subjected to deformation and mining influence. The second part of the backfill was formed after monitoring started. It extends from the

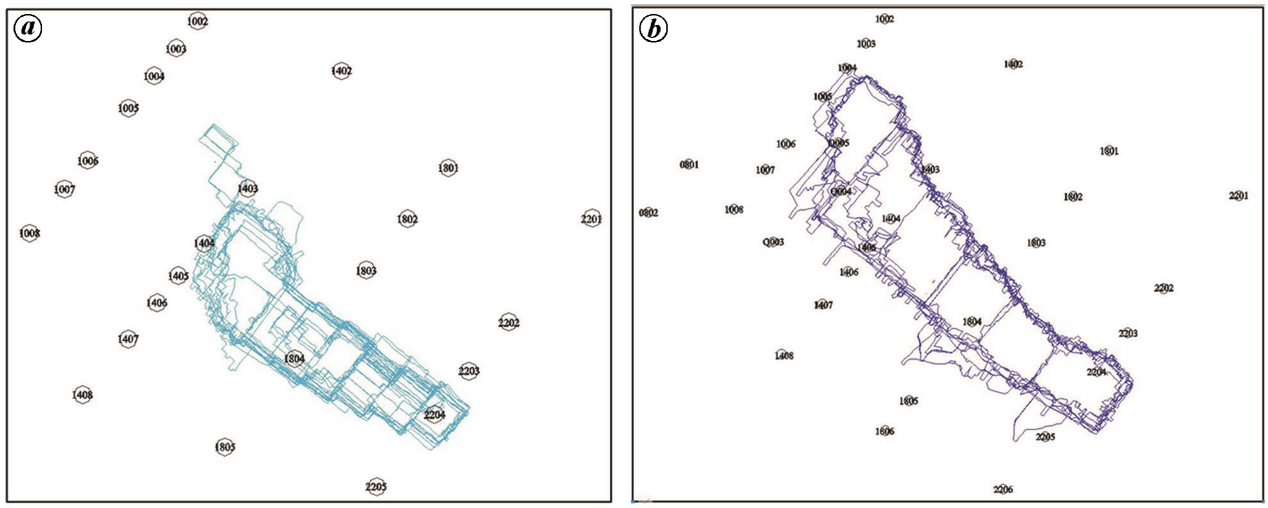

Figure 2. Monitoring point above the backfill. ***a***, Monitoring point above the backfill of 1334–1250 m; ***b***, Monitoring point above the backfill of 1250–1150 m.

1250 m sub-level to the 1150 m sub-level and is 100 m thick. Figure 2 *a* and *b* shows the distribution of surface monitoring points above the backfill.

Through continuous monitoring, vertical displacement results showed characteristics of ground movement. The cumulative displacements of monitoring points were calculated based on some data-processing steps, including baseline processing, coordinate conversion, constraint network adjustment and precision assessment. The data-processing results demonstrated that all the monitoring points had moved due to mining excavation and backfill deformation. A subsidence bowl had developed and it showed a gradual increase in area.

After nearly 10 years of cumulative displacement, the subsidence points focused on the exploratory line nos 10, 14 and 18, and the cumulative vertical displacements exceeded 2000 mm (Figure 3 *a*). The ground subsidence centre is located in the hanging side of the ore body. And the vertical displacement of the hanging side is larger than the footwall side (Figure 3 *b*). The maximum displacement increased as the mining deepened. In the ground subsidence area, almost all the displacement vectors point toward the backfill. Displacements on the hanging side are also larger than those of the footwall.

The major cause for ground subsidence is backfill deformation. The mining process includes two steps: excavation and filling. In Jinchuan Mine, the size of each stope is 4 m × 5 m. Several stopes are excavated at the same time in different panels and at different levels. A stope excavation takes 7 days and then filling of the stope also takes almost the same duration. The stope void is temporary. Characteristics of this type of void are its dispersed location and short duration. The ground subsidence is long-term movement, the vertical displacement is almost 2000 mm in 20 years. The stope void is temporary and dispersed, but backfill deformation lasts many years and is concentrated at the centre. The temporary void has less influence on ground subsidence compared to backfill deformation in mining operations.

As shown in Figure 3 *a* and *b*, monitoring points 1404, 1804 and 2204 are located on top of the backfill. The first part of the backfill is located between the exploratory line nos 14 and 22, and the second part is located between lines 10 and 22. The width of the backfill under line no. 22 is smaller than that under line nos 14 and 18. The vertical displacements of points 1404 and 1804 are larger than point 2204 (Figure 3 *c*). This displacement change indicates that backfill deformation at the centre is larger than that on the sides. Study of backfill deformation characteristics is therefore necessary to examine ground subsidence and rock movement.

The finite element software automatic dynamic incremental nonlinear analysis (ADINA) was developed in 1986 for linear and nonlinear finite element analysis of rock, solids and structures, heat transfer and electromagnetics. It was used for simulating backfill deformation. A three-dimensional (3D) numerical model was employed to study the characteristics of ground subsidence and backfill deformation, whereas a two-dimensional (2D) numerical model was used to study backfill deformation and stress distribution influenced by mining excavation. The numerical simulations mainly studied interactions between the backfill and surrounding rocks.

The size of the 3D model was 1700 m × 750 m × 500 m. The boundary of the backfill had a step-profile, according to practical mining engineering. The size of 2D model was 200 × 520 m^3. Each level was 50 m in depth, and each panel was 100 m along the ore-body strike direction. The area of each stope was 4 m × 4 m. The total number of steps was 500, including those of mining and

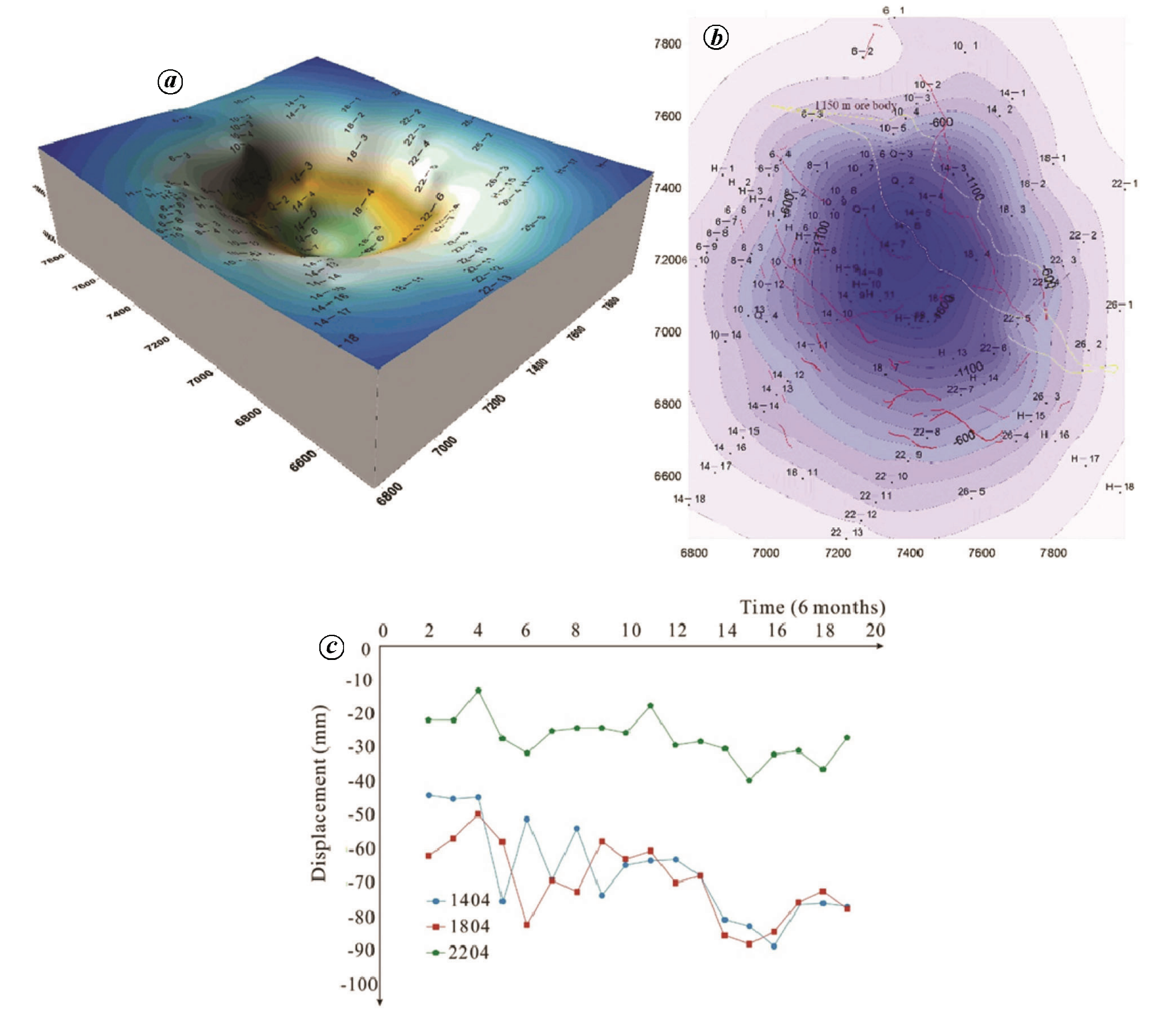

Figure 3. Ground subsidence of Jinchuan Mine. ***a***, Ground subsidence in 3-dimension; ***b***, Ground subsidence in 2-dimension; ***c***, Vertical displacements of monitoring points on the backfill.

Table 1. Model parameter settings

Parameters	Settings
Mesh type	Rule-based with 4 nodes
Element type	Plane strain
Solver	Gaussian elimination solver
Analysis assumptions	Small displacement and small strain
Convergence criterion	Convergence according to displacement norm

filling. Table 1 shows the parameters used to solve the model.

The size of backfill was nearly 1300 m × 250 m × 200 m with a 60° dip, which was surrounded by rocks. The boundary of the backfill was set as an irregular step-profile.

In the 3D model, the ground displacements had the same characteristics as the monitoring data. The displacements on the top of the middle part of backfill were larger than those on the top of backfill sides. The vertical displacement of the hanging wall was larger than that of the footwall, and the horizontal displacement was oriented to the backfill (Figure 4). The model was therefore able to provide guiding results to some degree. In the mining area, ground subsidence and rock mass movement have continued for nearly 20 years, and no sudden failures have occurred. The excavation and filling takes nearly 15 days, but backfill deformation takes a long time. In addition, the voids that are excavated are scattered in different parts of the ore-body. Excavation is therefore not the major reason for rock mass movement and ground subsidence; it is caused by backfill deformation.

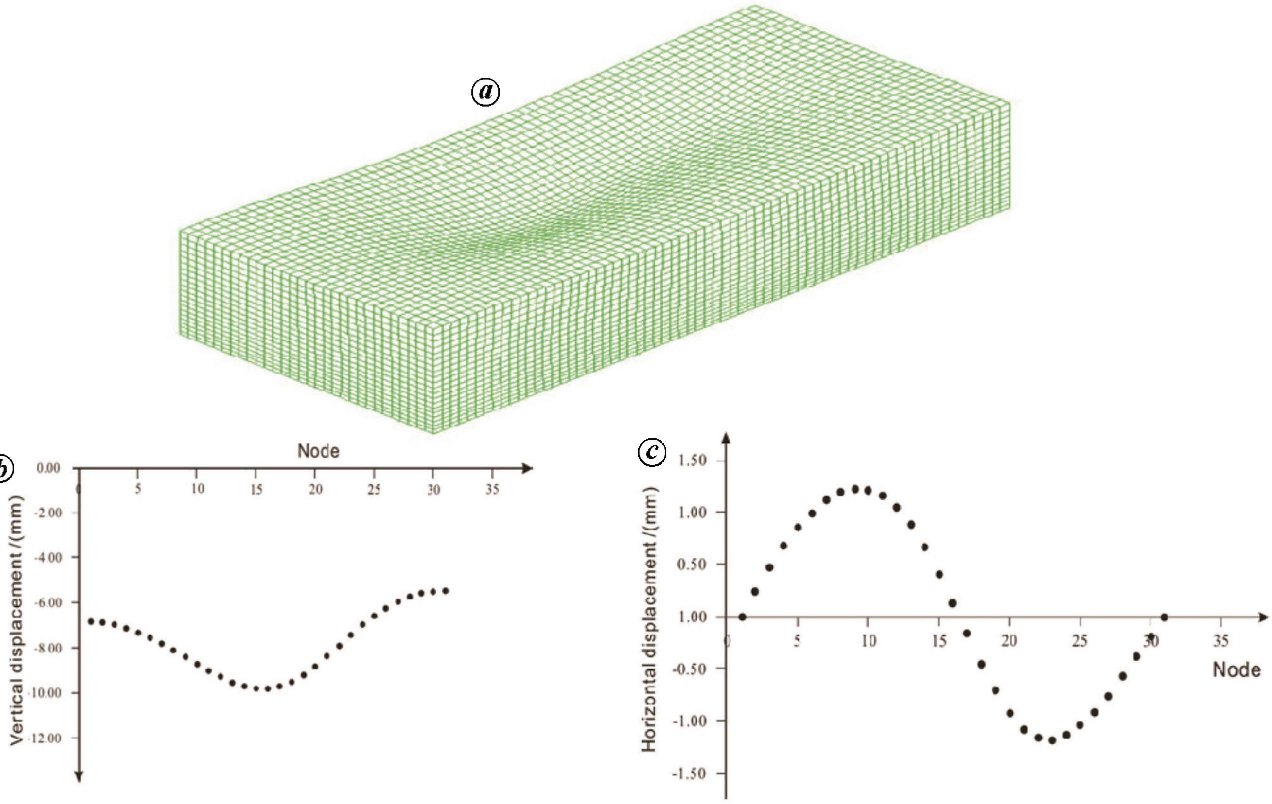

Figure 4. Displacements direction of ore body tendency. ***a***, The mesh map and the shape of backfill in 3D simulation mode; ***b***, Vertical displacement; ***c***, Horizontal displacement.

After the ore-body is replaced by backfill, the strength difference between backfill and its surrounding rocks leads to a decrease in the strength of the contact zone. The contact zone is a weak location. The load on the backfill is transferred to the surrounding rocks. The stability of the backfill is mainly related to its shear stress, surrounding rocks and contact zone. Therefore, it is necessary to analyse changes in shear stress distribution during mining and filling.

Shear stress could lead to backfill being subjected to shear deformation that causes local failure. Figure 5 *a* shows the overall shear stress distribution. The shear deformation is caused by backfill deformation and surrounding rock movement. The backfill boundary is the transitional section of the backfill, which has low strength compared with the high strength of the surrounding rocks. The backfill and surrounding rocks have large differences in material properties, strength, and deformation characteristics. Shear stress concentrates at the boundary of the backfill. The shape and depth are the major influencing factors for shear stress distribution (Figure 5 *b*). The shear stress increases with depth of mining, and is concentrated on the boundary corner of the backfill (Figure 5 *c* and *d*). Therefore, the boundary of the backfill is the key location for the stability and subsidence study.

In the mining process, backfill is passively supported by compression of the surrounding rocks. The degree of deformation of the rock mass determines the stress magnitude. At the beginning of mining, the backfill is shallow and the stresses and stress differences are both low. So the surrounding rocks have less deformation and backfill is under pressure as a block that has no failure. The stress difference increases in the deep part of the backfill and it is more easily deformed.

The 2D model simulated excavation using the mining sequence of every other stope that was used in the Jinchuan Mine. The total number of steps was 257, the mined void was filled by cement paste, and then the next access drift was excavated. The mining panels were about 100 m wide and excavated at the same time as the same mining sequence (Figure 6 *a*). This model focused on mining processes that have an influence on backfill stress and deformation.

After the first excavation step and the filling step, the stress redistributed in the form of effective stress. The stress distribution illustrated that the excavation and filling operation occurred as local disturbances. Stress redistribution concentrated near the excavation area and the far-field stress was unperturbed. This is a reasonable expectation because immediately after filling, the filled region simply has stresses due to self-weight.

As shown by the 3D model, the backfill boundary is the key component affecting the surrounding rocks. In addition, the inflection points of the backfill boundary

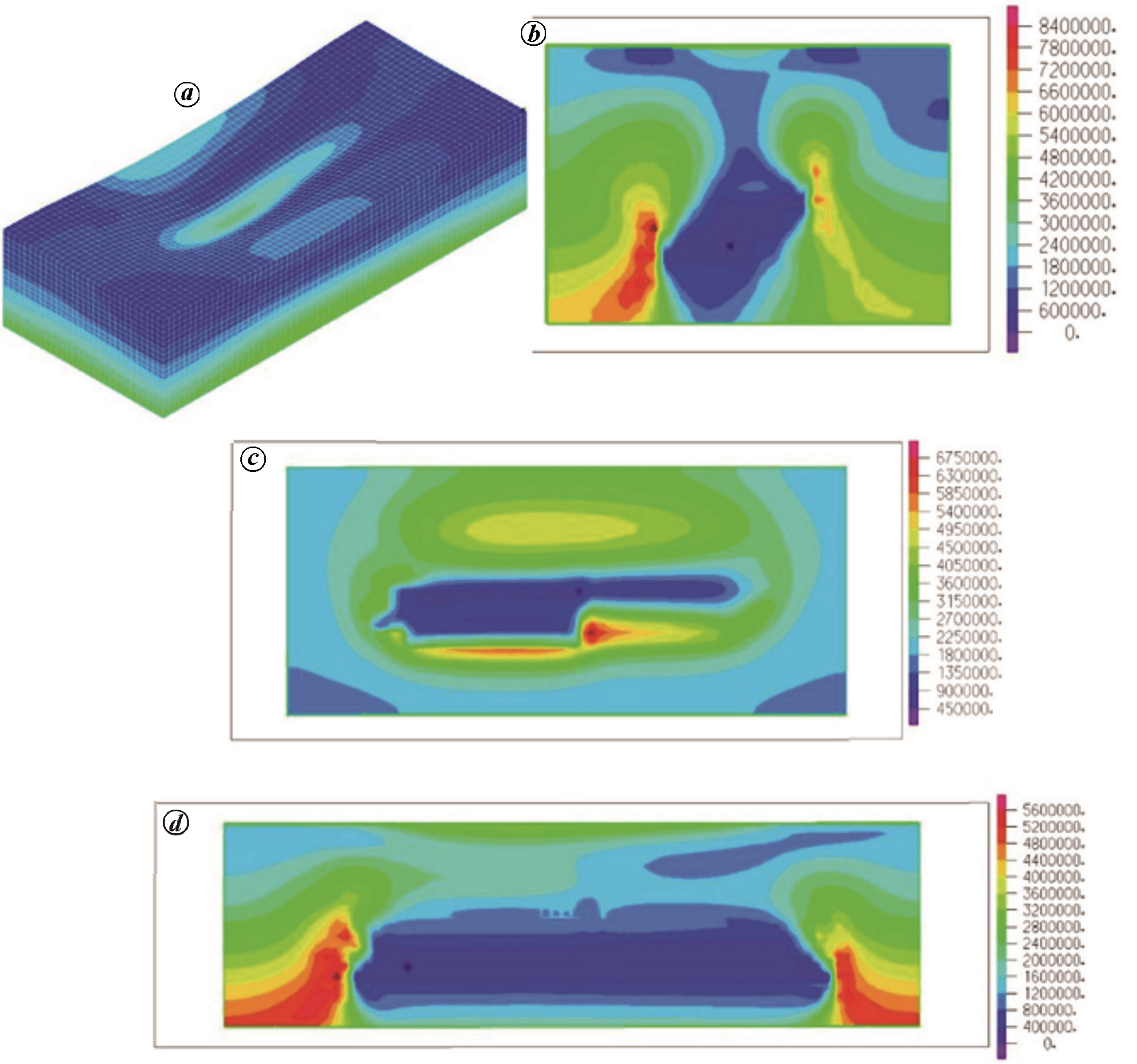

Figure 5. The shear stress distribution of model. ***a***, Overall distribution of shear stress; ***b***, The shear stress in direction of ore body tendency; ***c***, The shear stress in direction of ore body deep; ***d***, The shear stress in direction of ore body strike.

deform easily because of stress concentration. Two corner points of the model were chosen to analyse the stress situation (Figure 6 *a*). Point 1929 is located in the shallow part of the backfill and point 1624 is in the deep part. The envelope lines (the red lines in Figure 6 *b* and *c*) demonstrate different cohesions of the backfill. According to the maximum and minimum principal stresses, the Mohr's circles of shallow and deep backfill are different. According to statistical data for mines in China, backfill cohesions range from 320 to 1800 kPa. Point 1929 in shallow backfill was excavated in step 4 and backfilled in step 5. The next mining layers were excavated in steps 6 to 21. The No. 72 element which the point 1929 was located was excavated in step 18 and backfill in step 19. When this element was utilized as an artificial roof, the Mohr's circle of element nodes moved to the ordinate origin.

Figure 6 shows that the maximum and minimum principal stresses of the backfill change according to a regular pattern. When the filling completed $\sigma 1$ and $\sigma 3$ increased caused by adjacent mining voids. The stress difference also increased, as indicated by the radii of the Mohr's circles. When the next layer was mined, the principal stresses of the upper backfill, which is the artificial roof, suddenly decreased and then increased. As shown in Figure 6 *b* and *c*, in the shallow backfill, the envelope line

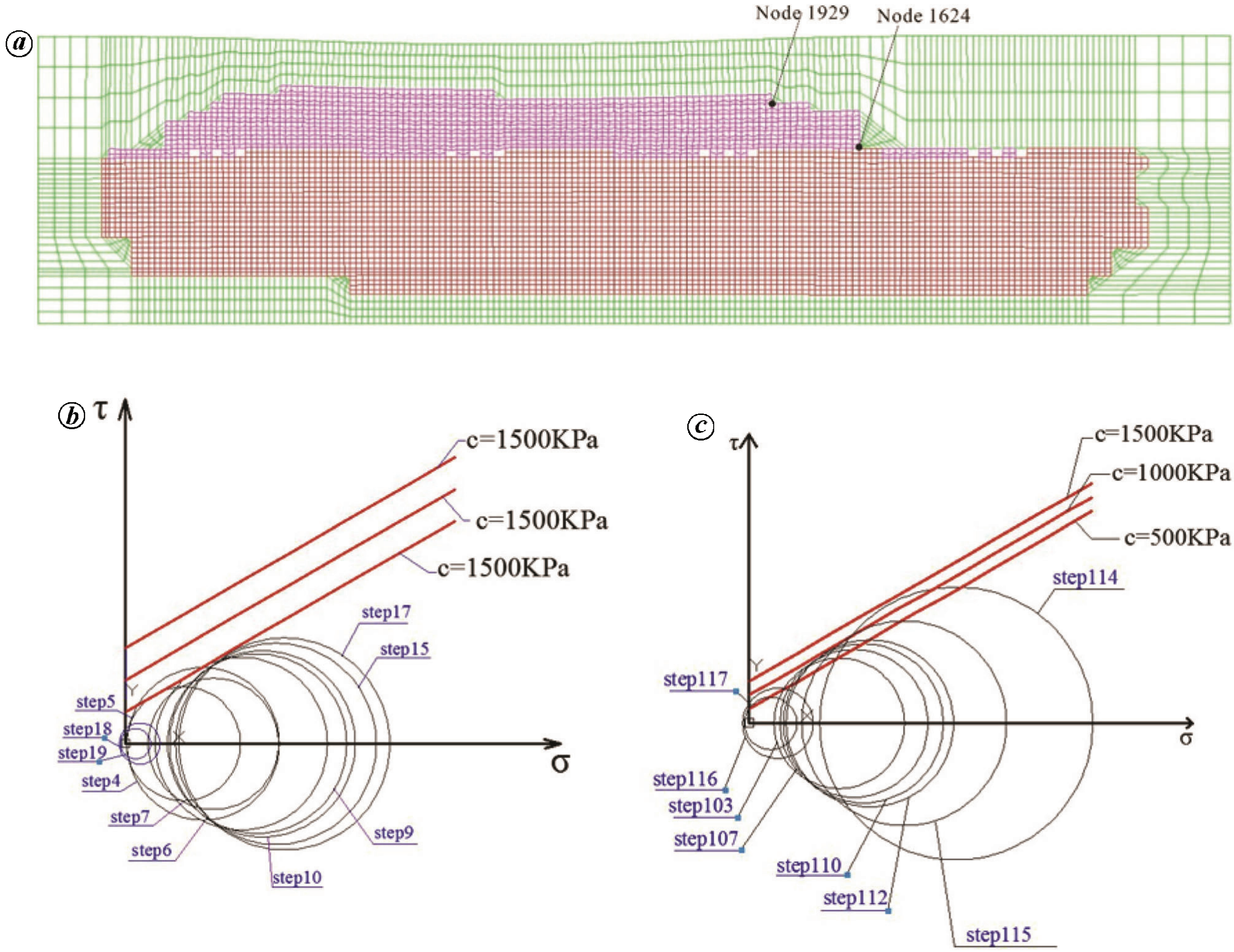

Figure 6. The Mohr's circle of special nodes of different excavation steps of 2-D numerical model. ***a***, The mesh of 2D numerical model; ***b***, The Mohr's circle of point 1929; ***c***, The Mohr's circle of point 1624.

for cohesion of 500 kPa could almost meet the strength requirement, but in the deep backfill, the cohesion needed to increase to 1500 kPa. The deep backfill is therefore easily deformed and prone to failure.

Mining operations have caused obvious ground subsidence and rock movement. The major reason is backfill deformation. Since the 21st century, the maximum value of vertical displacement has already exceeded 2000 mm. The centre of the subsidence area is located at the hanging side of the ore-body and the backfill. The overlying rock mass movement and ground subsidence have close relationship with backfill deformation. Numerical model analysis of backfill shows that the shear stress is concentrated on the backfill boundary, contact zone of backfill and surrounding rocks, and the boundary corner of the backfill. Therefore, the contact zone and boundary corner are key areas to ensure local stability of the backfill. The Mohr's circle of the corner moves toward the right of the axis and its radius increases during mining of a given level. When the next level is excavated, the Mohr's circle returns to the initial state. The envelope line for cohesion of 500 kPa meets the required strength in shallow backfill, but the required cohesion for the deep backfill is 1500 kPa. Therefore, the deep part of the backfill can be deformed more easily than the shallow part, leading to ground subsidence caused by rock movement. Monitoring work is necessary to ensure safety during mining operations.

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