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Ore Loss Mechanisms in Diamond Layout Sublevel Open Stopping for Moderately Dipping Medium-Thick Orebodies

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Abstract:

The diamond layout sublevel open stopping (DLSOS) method enables efficient extraction of moderately dipping medium-thick orebodies through gravity-driven ore flow, while ore loss persists during lower stope extraction due to geometric and frictional constraints. This study elucidates these loss mechanisms via coupled physical experiments and Particle Flow Code (PFC) simulations, focusing on three governing parameters: footwall side-hole angle, surface friction coefficient, and ore-drawing crosscut spacing. Granular flow exhibits preferential hanging-wall mobility with marked footwall restriction, yielding three residual forms: surface residue, end-of-crosscut residue, and inter-crosscut ridge residue. The footwall surface residue increases as the side-hole angle decreases. Physical experiments (6 m spacing) demonstrate that peak recovery depends on both angle and friction: 83.61% at 40° under ore-fragment friction ($\mu = 0.95$) versus 88.59% under fine-sandpaper friction ($\mu = 0.45$). Numerical simulations confirm monotonic recovery increase with angle, validating the trend but omitting inter-crosscut ridge effects present in physical experiments. Extending spacing to 7.5 m reduces recovery to 80.2% at 40° under ore-fragment friction, with 6 m spacing consistently superior across all angles. These findings elucidate three distinct ore-loss mechanisms in DLSOS lower stopes and establish quantitative guidelines for angle-friction-spacing optimization.

Keywords: Ore loss mechanism; Diamond layout sublevel open stopping; Side-hole angle; Surface friction coefficient; Ore-drawing crosscut spacing

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1 Introduction

Moderately dipping medium-thick orebodies host substantial global reserves, including 70% of phosphate, 30% of gold, 18% of iron, and 5–9% of non-ferrous metals^[1, 2]. Conventional extraction methods, primarily room-and-pillar and drift-and-fill methods^[3], are constrained by fundamental inefficiencies. Room-and-pillar operations cannot exploit gravity flow due to shallow dips, forcing reliance on auxiliary equipment that elevates costs and depresses efficiency. Moreover, mandatory rock pillars reduce recoverable reserves while risking splitting failures that endanger personnel. Fractured hanging walls exacerbate these stability deficits, accelerating waste rock intrusion and dilution. Drift-and-fill operations compound these inefficiencies through intricate scheduling and prohibitive backfill costs; safety-driven span restrictions further limit production capacity^[4]. Prior research sought to mitigate these deficiencies through improved ground support and span optimization. Maybee and Hoek^[5, 6], for instance, developed reinforced roof systems to extend stable spans. These empirical approaches lacked theoretical grounding and thus yielded only marginal improvements. To circumvent unstable in-situ pillars and enhance recovery, researchers subsequently engineered artificial support systems for ground pressure control^[7, 8]. Li et al. developed pre-stressed expandable pillars for the overhand drift-and-fill mining method to maintain stope roof stability^[9], replacing in-situ rock pillars and thereby reducing ore loss. However, artificial support systems are usually site-specific and require additional design, installation, and economic considerations under complex geological conditions. Collectively, conventional methods remain constrained by inefficiency and hazards, while incremental improvements have failed to fundamentally transform extraction of these challenging orebodies. To circumvent these inherent limitations, Xu et al.^[10] proposed the diamond layout sublevel open stoping (DLSOS) system. This method bifurcates the stope into upper and lower panels, extracting the lower panel first to establish a stable working base. Upward fan blast holes drilled from dedicated drifts eliminate worker exposure beneath unsupported roofs, while gravity-driven ore flow coupled with trackless haulage resolves the transport inefficiencies associated with conventional methods. However, first-step extraction inevitably incurs ore loss from stope morphology and operational factors—specifically footwall side-hole angle, surface friction coefficient, and ore-drawing crosscut spacing. These loss mechanisms remain poorly understood, hindering DLSOS adoption despite its operational advantages.

Ore recovery research employs four complementary methodologies: theoretical modeling, field trials, physical experiments, and numerical simulation. Theoretical advances began with Malakhov's ellipsoidal draw theory^[11], providing the first mathematical description of gravitational flow in fragmented ore. Random medium theory^[12, 13] subsequently refined early dilution prediction, establishing foundations for precision caving design. The Bergmark-Roos model^[14, 15] emerged as a classical framework for granular flow through loose media, with Melo^[16, 17]

extending these approaches to derive two- and three-dimensional draw-body morphologies. These frameworks remain confined to simplified geometries, whereas complex field conditions demand experimental validation beyond purely mathematical treatment. Consequently, field trials have proliferated to ground theory in actual mining environments. Brunton et al.^[18] exemplify this approach at Ridgeway Gold Mine, embedding steel markers within blast rings and recovering them magnetically to map extraction zones in sublevel caving operations. Their analysis identified blast design as a critical recovery determinant, informing SLC optimization. The replication of such trials is limited by prohibitive time and labor costs, which constrains their broader application.

Physical experiments excel in ore-loss investigation by enabling precise, repeatable control of stope geometry and boundary conditions, direct visualization of granular flow to identify residue forms and flow regimes, and rapid, cost-effective acquisition of results. Tao et al. proposed an improved diversion drawing technique for longitudinal sublevel caving in inclined medium-thick orebodies. By constructing a physical model to simulate the drawing process, they recorded the ore recovery rate and mixing rate of waste rock. The results demonstrated that this technique can effectively control ore loss and dilution, verifying its effectiveness^[19]. Halim adopted physical experiment method to determine the drawn-out body and loosen body under multiple hopper ore drawing conditions, and elucidated the mechanisms of granular flow and the mixing process of ore and waste rock^[20]. Numerical simulations complement these experiments by offering flexible, cost-effective parameterization of ore-loss mechanisms. Among available methods are Cell Splitting^[21], Stochastic Medium Simulation method^[22-25], and Particle Flow Code (PFC)^[26-28]. Among these, the Stochastic Medium Simulation method captures the inherent uncertainties of rock mass fragmentation and grade distribution more realistically but at higher computational and data costs. The Cell Splitting Method remains in the research stage, with its simulation accuracy yet to be validated. As a discrete element method, PFC uniquely incorporates heterogeneity and stochasticity while enabling observation of both macroscopic (velocity, displacement) and microscopic (force chains, porosity) parameters, making it particularly suitable for granular flow-dominated problems.

This study integrates physical experiments with PFC2D simulations to elucidate ore-loss mechanisms during DLSOS lower-stope extraction, focusing on three governing parameters: footwall side-hole angle, surface friction coefficient, and ore-drawing crosscut spacing. Experiments establish quantitative relationships between these factors and specific residue forms, while simulations dissect microscale granular flow through force chains and velocity fields. Together, these approaches yield a mechanistic foundation for lower-stope optimization.

2 Engineering background

This research targets a Chinese gold mine hosting a 30°-dipping, 10–15 m thick orebody with fractured hanging walls. Longstanding drift-and-fill operations (Fig. 1a) suffer from restricted stope dimensions (3.5 m × 3.5 m) and low advance rates, crippling single stope productivity. Compensatory multi-stope operations introduce logistical complexity, while triangular hanging-wall losses remain unavoidable. To overcome these limitations, the DLSOS mining system^[10] was developed and successfully applied in the field. As shown in Fig. 1b, the orebody is divided into sublevels from bottom to top, and each sublevel comprises two diamond-shaped stoping blocks accessed via crosscuts from the haulage drift, with slot raises marking block boundaries. Extraction proceeds upward: fan blast holes drilled from dedicated drifts, blasted ore is transported by load-haul-dump (LHD) to sublevel ore pass, and the lower stope is then backfilled to stabilize the base for upper-stope mining. Relative to drift-and-fill operations, this system enhances productivity and minimizes wall-rock exposure through centralized drilling and rapid backfilling. Conducting both drilling and drawing within drifts improves operator safety, while effective lower-stope backfilling secures foundations for subsequent upper extraction.

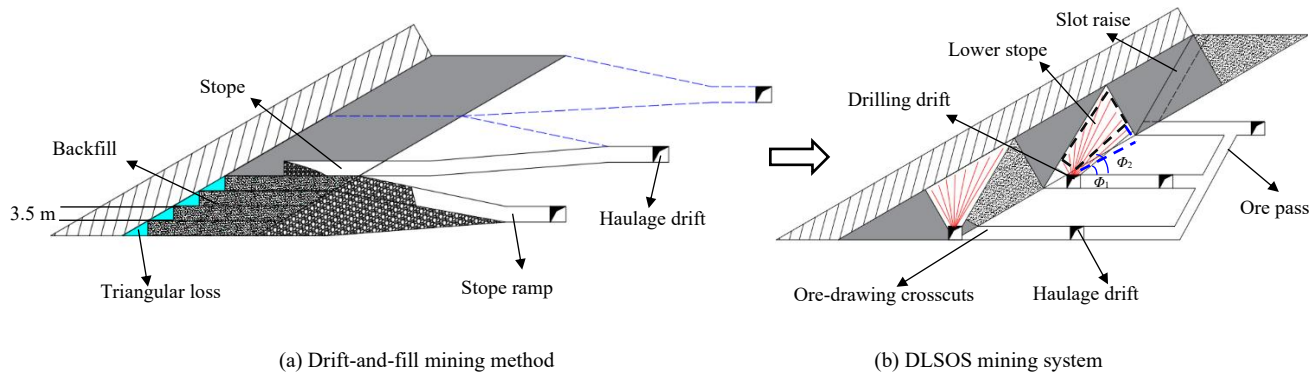


Fig. 1 Comparison between the drift-and-fill method and the DLSOS mining system^[10, 29, 30]

In the lower stope extraction process, inherent ore loss exists due to frictional effects and the constraints imposed by stope geometry. Three residue forms dominate: inter-crosscut ridge residue, footwall surface residue, and end-of-crosscut residue. The ore-drawing structure employs a flat-bottom draw layout. Restricted by safety requirements, the LHD is unable to enter the drilling drifts during ore extraction, resulting in ridge residues between adjacent ore-drawing crosscuts and triangular residues at the ends of the ore-drawing crosscut. The amount of ridge residue is closely dependent on the spacing of the ore-drawing crosscuts. Footwall surface residue hinges on the side-hole angle and surface friction: angle mainly governs both extractable volume and residual retention. As shown in Fig. 1b, a side-hole angle of Φ_1 gives higher ore extraction quantity but leaves more residual ore along the footwall surface, whereas increasing the angle to Φ_2 reduces both ore extraction and residue quantity. These three forms collectively degrade DLSOS recovery. This study validates and quantifies these relationships through integrated

physical experiments and numerical simulations.

3 Experimental verification

3.1 Physical experiments

3.1.1 Similarity conditions

Physical modeling was conducted to quantify factor-specific effects on ore recovery. To replicate caved-rock flow behavior, the following simplifying assumptions govern the similarity criteria: (1) Gravitational flow of caved ore comprises slow-moving, non-cohesive coarse fragments. (2) The granular mass is heterogeneous yet isotropic. (3) Flow occurs in a 3D environment free of weak boundaries. (4) Rock breakage (primary and secondary) is excluded. Based on these assumptions, the following similarity criteria govern the physical model: (a) Geometric similitude: block and drawpoint dimensions, particle size distribution, and particle shape. (b) Unity of gravitational and bulk density scales: $\lambda_p = \lambda_g = 1$. (c) Time-scale relation: $\lambda_t = \lambda_l^{1/2}$. (d) Stress-scale relation: $\lambda_o = \lambda_r = \lambda_l = 1$. (e) Residual friction angle equivalence: $\lambda_{or} = 1$. (f) Wall friction angle congruence with internal friction: $O_w = O$, where λ denotes the scale factor for variable^[20, 31]. The similarity ratio was set to 1:50 to ensure experimental fidelity.

3.1.2 Physical model

As shown in Fig. 2a, the physical model comprises a floor-mounted lower stope with ore-drawing crosscuts and basal drilling drifts. Components were assembled via screws and grooves. Overall dimensions are 40 cm in height (H), 60 cm in width (W), and 60 cm in length (L). The iron base provides structural rigidity, while transparent acrylic walls enable direct flow visualization. To replicate lower-stope flow behavior, three parameters are adjustable: (1) Footwall side-hole angle (30° – 55°), controlled via stopper. (2) Ore-drawing crosscut spacings, scaled from field values (6 m/7.5 m) to model dimensions (12 cm/15 cm), yielding five and four crosscuts, respectively. (3) Footwall friction coefficient, modulated via fine sandpaper ($\mu \approx 0.45$) or ore fragments ($\mu \approx 0.95$) from inclined-plane tests, as shown in Fig. 2b. The friction coefficient derives from inclined-plane tests, and was determined as:

$$\mu = \tan \theta \quad (1)$$

where μ denotes the friction coefficient and θ the inclined-plane angle at incipient sliding. Measured values are $\mu = 0.45$ (fine sandpaper) and $\mu = 0.95$ (ore fragments).

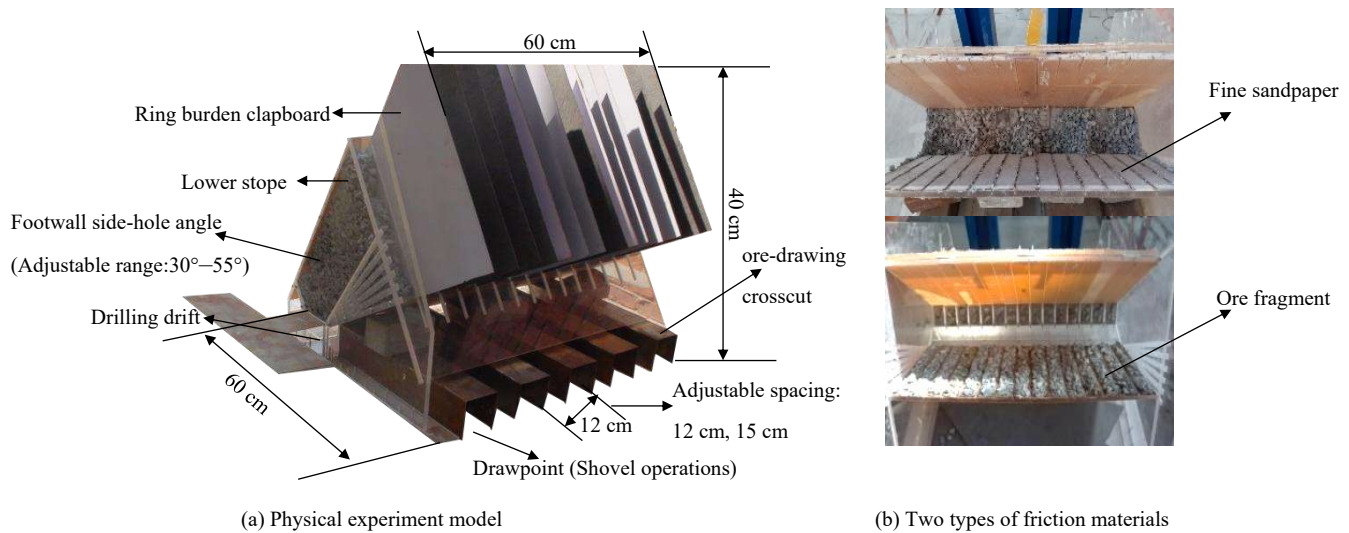


Fig. 2 Experimental design: model configuration and friction conditions

3.1.3 Similarity material

Field measurements established the in-situ fragmentation distribution. Blasted rock images (Fig. 3a) were imported into AutoCAD as OLE objects; fragment perimeters were digitized via closed polylines to generate polygonal geometries. Size data extracted from CAD drawings yielded the blasted-ore distribution. Applying the 1:50 similarity ratio produced the target experimental gradation (Fig. 3b). Field ore was subsequently crushed, sieved, recombined, and homogenized to replicate in-situ blasting conditions.

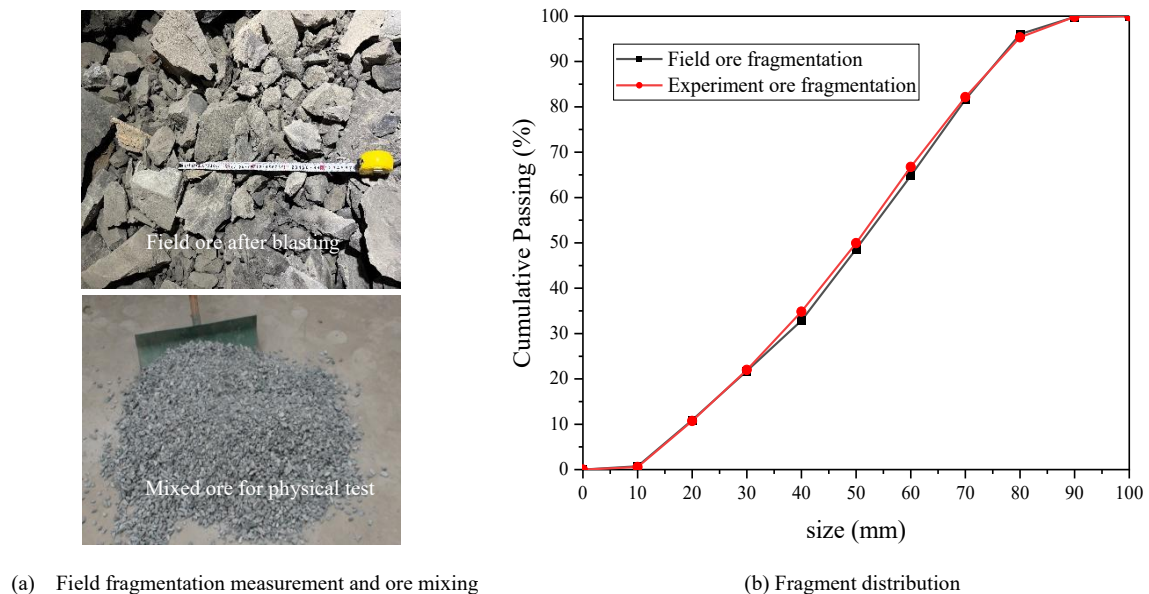


Fig. 3 Experimental ore preparation and fragmentation statistics

3.2 Numerical simulation

3.2.1 Numerical model

A 2D model was constructed along the orebody strike section at full mine scale. Caved ore comprises PFC2D circular

particles, with walls constraining granular flow. As shown in Fig. 4, model dimensions are 20 m (L) $\times$ 22 m (H); crosscut and drift sections measure 3.5 m $\times$ 3.3 m. Footwall friction coefficients and side-hole angles (φ), defined as the angle between footwall and ore-drawing crosscut, are specified directly within the PFC2D environment, matching experimental ranges.

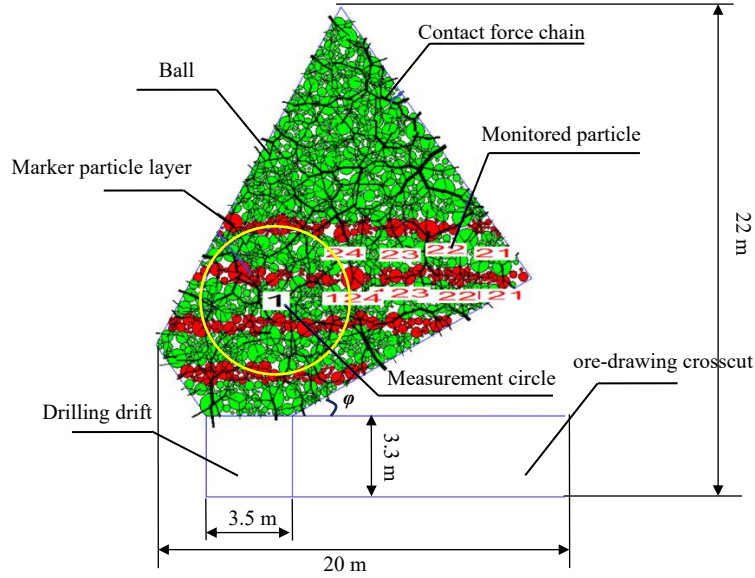


Fig. 4 Numerical model and simulation parameter determination

Numerical parameters comprise geometric properties and contact constitutive relations. Conventional trial-and-error calibration of PFC2D micromechanical parameters^[32, 33] proves time-consuming, labor-intensive, and statistically blind—especially for multiparameter optimization^[34, 35]. To circumvent these limitations, Li et al.^[36] developed a laboratory-response calibration method: geometric properties (model dimensions, particle radii, porosity, density) derive from material characterization, while contact parameters (stiffness ratios, friction coefficients) are back-calibrated against experimental responses.

Geometric parameters match field scale: $R_{\max} = 22.04$ cm, $R_{\min} = 2.803$ cm, porosity $n = 0.15$, and particle density $\rho = 2700$ kg/m³. Contact parameters comprise particle-particle and particle-wall stiffness ratios (K_n/K_s) and interparticle friction coefficients (μ), back-calibrated via physical experiments. Contact modulus E_c and stiffness ratio K_n/K_s are calibrated iteratively against Poisson's ratio ν and elastic modulus E , whereas μ is determined via bottomless cylinder tests coupled with numerical simulation. All parameter values are summarized in Table 1. System parameters comprise gravitational acceleration and three computational controls: time step, differential density factor, and mechanical damping. Time step and density factor are auto-calculated adaptively; mechanical damping values are listed in Table 1.

Table 1 Numerical simulation of microscopic parameters

Parameters	$R_{\max}$ (cm)	$R_{\min}$ (cm)	ρ (kg/m ³)	K_n (N/m)	K_s (N/m)	μ	g (m/s ²)	Mechanical damping
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value	ball	22.04	2.80	2700	1e7	1e7	1.75	9.8	6.5
	wall	---	---	---	1e9	1e9	2.0	---	---

3.3 Experimental design and implementation

Both physical and numerical experiments comprise loading, drawing, and data acquisition phases. For physical trials, pre-crushed ore was homogenized, volumetrically and gravimetrically characterized, then charged into the model. Post-blast particle flow was replicated by sequential removal of ring-burden clapboards. Numerically, porosity for each size fraction was calculated from field fragmentation data to initialize particulate assemblies using specified radii ranges. Micromechanical parameters were assigned, and the extrusion-repulsion method expanded particle radii to achieve equilibrium. In the physical trials, ore was extracted manually at the drawpoints using a small shovel to approximate the sequential mucking process of LHD operation, whereas numerically this was effected by particle deletion. Each mucking cycle was followed by system equilibration until exhaustion. To elucidate flow kinematics, the numerical model incorporated marker layers, tracked particles, and measurement circles (Fig. 4). Trajectories recorded in X and Y directions were combined with marker-layer deformation to resolve granular motion patterns.

Experiments independently varied three controlling parameters: footwall side-hole angle (30° – 55°), surface friction coefficient, and ore-drawing crosscut spacing. Both physical and numerical investigations spanned the full angular range. Friction coefficients were adjusted via material substitution in physical trials and prescribed directly in simulations. Crosscut spacing was modulated by varying crosscut count in the physical model. PFC2D simulations excluded spacing effects. Single-parameter variation was conducted under *ceteris paribus* conditions. For each condition, ore loaded, drawn, and residual were quantified to calculate recovery rates. Experimental schemes are detailed in Table 2: 24 physical configurations ($6 \text{ angles} \times 2 \text{ frictions} \times 2 \text{ spacings}$) and numerical simulations spanning 30° – 55° with four friction levels ($f = 2.0, 1.8, 1.2, 0$).

Table 2 Experiment schemes

parameter	Physical experiment	Numerical simulation
Footwall side-hole angle		$30^{\circ}/35^{\circ}/40^{\circ}/45^{\circ}/50^{\circ}/55^{\circ}$
Ore-drawing crosscut spacing	6 m and 7.5 m	Not considered
Footwall friction coefficient	0.45 and 0.95	0/1.2/1.8/2.0

4 Results and analysis

4.1 Ore-loss mechanism

Post-experiment observations revealed three residue forms in the lower stope: footwall surface, end-of-crosscut, and inter-crosscut residues (Fig. 5a). Residue magnitudes varied with structural parameters. Numerical simulations (Fig. 5b) reproduced footwall and end-of-crosscut residues but inherently excluded inter-crosscut ridge effects due to their 2D

nature. Numerical simulations resolved two distinct draw stages. Stage one comprises free fall of blasted ore into drifts and crosscuts, followed by stabilization. During descent, interparticle compression manifests through force-chain destruction and regeneration. As shown in Fig. 5b, contact force chains indicate that the granular mass develops preferentially along the hanging wall, while footwall-bound particles sustain persistent compression. At equilibrium, force chains self-organize within the granular mass: loose upper structures overlies compacted lower zones. This stratification reflects preferential flow along hanging-wall boundaries, whereas footwall contact severely restricts particle mobility, corresponding to observed footwall surface residue (Fig. 5a). Stage two emulates LHD drawing via particle deletion in drilling drifts. The loosened mass develops preferentially along hanging-wall boundaries, whereas footwall particles remain compressed, corresponding to the observed footwall surface residues (Fig. 5b). Crosscut-end ore similarly maintains compacted states, corresponding to triangular end residues (Fig. 5b). Fig. 5c tracks monitoring particle displacements in X and Y throughout drawing. Trajectories reveal initial migration toward drilling drifts, redirection above drift midpoints, and eventual extraction—whereas particles 21 and 121 (footwall-proximal) remain as surface residue. Marker layers indicate that active flow zones concentrate above drilling drifts, while footwall particles inhabit inactive zones (Fig. 5c). These observations corroborate force-chain findings: granular flow preferentially follows hanging-wall boundaries with minimal footwall mobility.

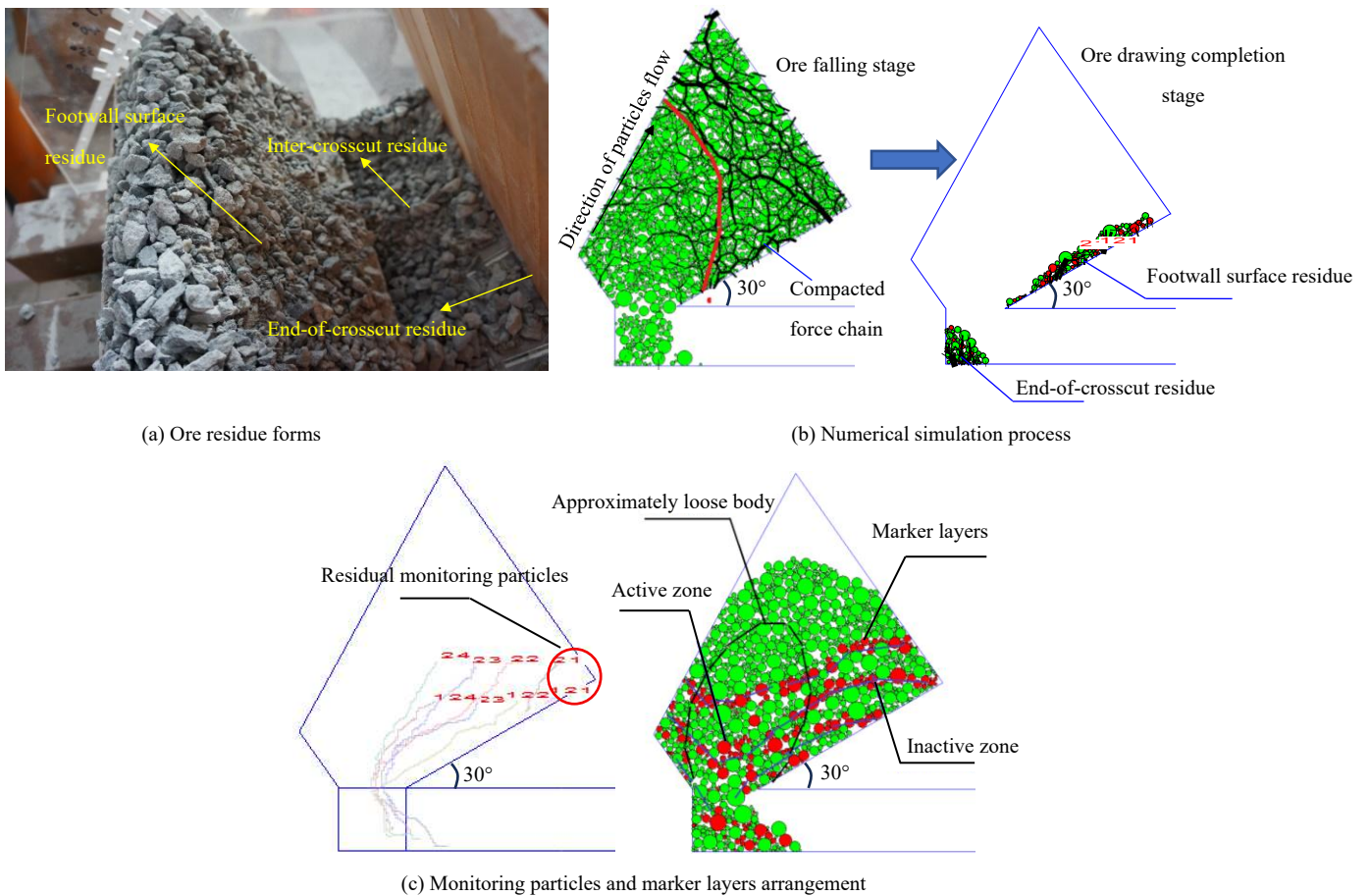


Fig. 5 Experimental results and mechanism

4.2 Effects of influencing factors

4.2.1 Footwall side-hole angle

For 6 m spacing and ore-fragment friction ($\mu = 0.95$), Fig. 7 illustrates angle-dependent recovery. Physical experiments show that filling ore decreases with angle, whereas recovery quantity peaks at 40° (32.4 kg)—mirrored by recovery rate maxima of 83.61%. At shallow angles (Fig. 6a), pronounced footwall protrusion dominates loss; steeper angles reduce this geometric residue but diminish extractable volume. Steeper angles attenuate protrusion geometry, reducing footwall residues. Yet further angle increase constrains recovery via diminished loading volume. Residual ore declines monotonically, stabilizing beyond 50° (5.35 kg) as inter-crosscut and end-of-crosscut residues (Fig. 6b).

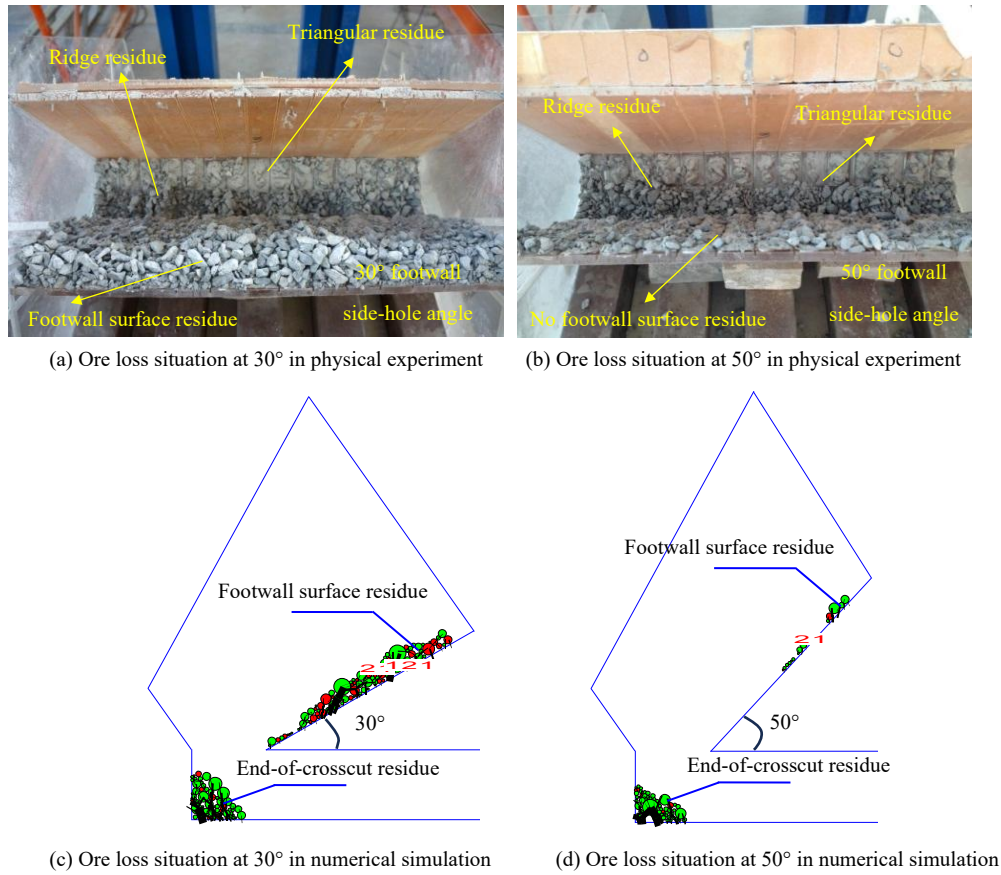
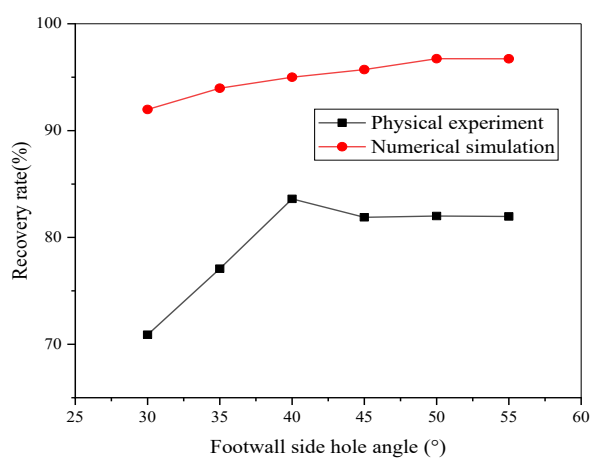


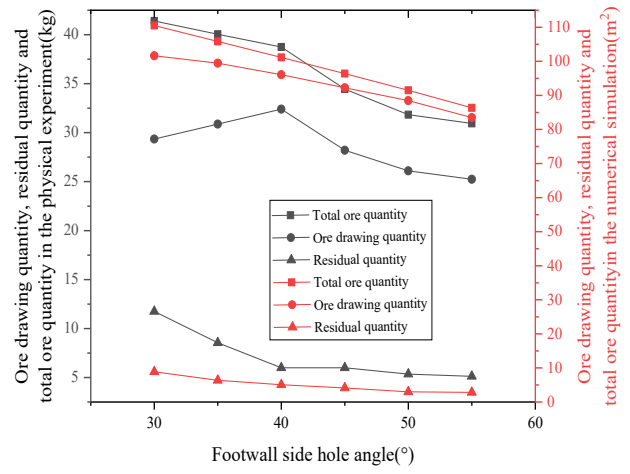
Fig. 6 Residual ore at side-hole angle of 30° and 50°

Numerical simulations (Fig. 6c, d) reveal monotonic footwall residue reduction with increasing angle. At 30° , force chains among footwall particles exhibit compacted configurations (Fig. 6c), indicating poor flowability that explains surface residue—consistent with physical observations. At 50° , footwall residue approaches zero (Fig. 6d), matching experimental results. Unlike physical experiments, numerical recovery rates increase monotonically with angle and consistently exceed experimental values (Fig. 7a). This discrepancy can be attributed to the following reasons: In the physical experiments, recovery is governed by a relative balance between the reduction in footwall surface residue and the decrease in effective drawable ore volume. Increasing the side-hole angle reduces footwall geometric protrusion

and improves recovery at small to moderate angles; however, once the footwall surface residue is nearly eliminated, further angle increase provides limited additional reduction in total residue, while the relatively stable triangular and inter-crosscut ridge residues occupy a larger proportion of the reduced ore volume, leading to a post-peak decrease in recovery. In contrast, the numerical model excludes the inter-crosscut ridge residue and the idealized particle shape and boundary conditions enhance particle mobility, allowing footwall surface residue to continue decreasing over a wider angle range. Consequently, the positive effect of reducing footwall surface residue remains dominant throughout the simulated angle range, and no post-peak decline is observed in the numerical results. In actual field production, the selection of the footwall side-hole angle should comprehensively consider both the blasting volume and ore loss to determine the optimal angle.



(a) Recovery rate in physical experiment and numerical simulation



(b) Ore recovery situation in physical experiment and numerical simulation

Fig. 7 Ore recovery under different footwall side-hole angles

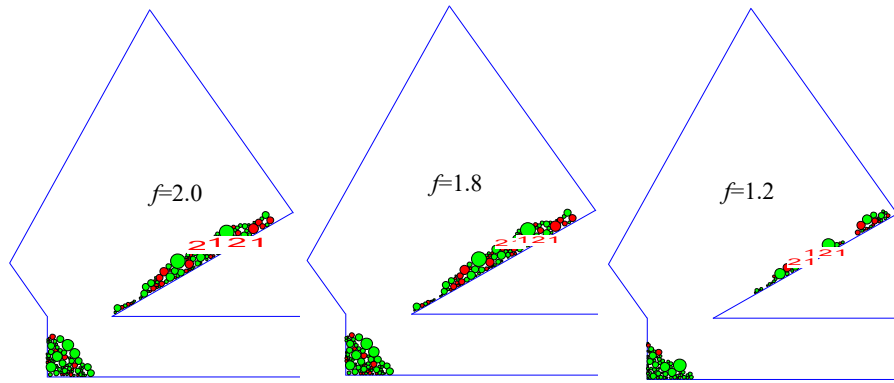
4.2.2 Friction coefficients

Blasting generates irregular footwall surfaces whose roughness directly governs recovery. To isolate friction effects, physical experiments at 6 m spacing evaluated recovery across angles for two friction coefficients. As shown in Fig. 8a and Fig. 8b, under identical footwall side-hole angles, fine-sandpaper friction yielded consistently less footwall residue than ore-fragment friction. Fig. 8c reveals numerical residue-friction relationships at fixed angles: surface residue decreases with diminishing friction, mirroring physical experimental trends. Elevated friction intensifies force-chain compaction in footwall residues, constraining particle mobility. Reduced friction weakens these chains and diminishes surface retention. When f increases from 1.8 to 2.0, the residue remains nearly unchanged (Fig. 8c), indicating that the influence of friction on recovery becomes negligible beyond a threshold. The coefficient significantly influences ore recovery only within lower ranges.



(a) Ore residuals at different side-hole angles
under ore fragment friction

(b) Ore residuals at different side-hole angles
under fine-sandpaper friction



(c) Residue situation under different friction coefficients in numerical simulation

Fig. 8 Residual ore distributions under different friction conditions

Fig. 9a reveals identical trends across friction conditions: recovery quantity peaks then declines with increasing angle, while residue decreases and stabilizes. The maximum recovery reached 36.25 kg at a side-hole angle of 35° , at which no footwall surface residue was observed (Fig. 9a). Under the ore-fragment friction condition ($\mu = 0.95$), the maximum recovery was 32.4 kg at 40° , whereas the footwall surface residue was eliminated only when the angle increased to 50° . Both friction conditions yield recovery rates that initially increase then decrease, peaking at 40° —83.61% for ore-fragment friction and 88.59% for fine-sandpaper friction. Superior recovery metrics under lower-friction conditions indicate that surface roughness reduction enhances recovery. Field implementation should employ smooth blasting or footwall pre-wetting to mitigate friction effects.

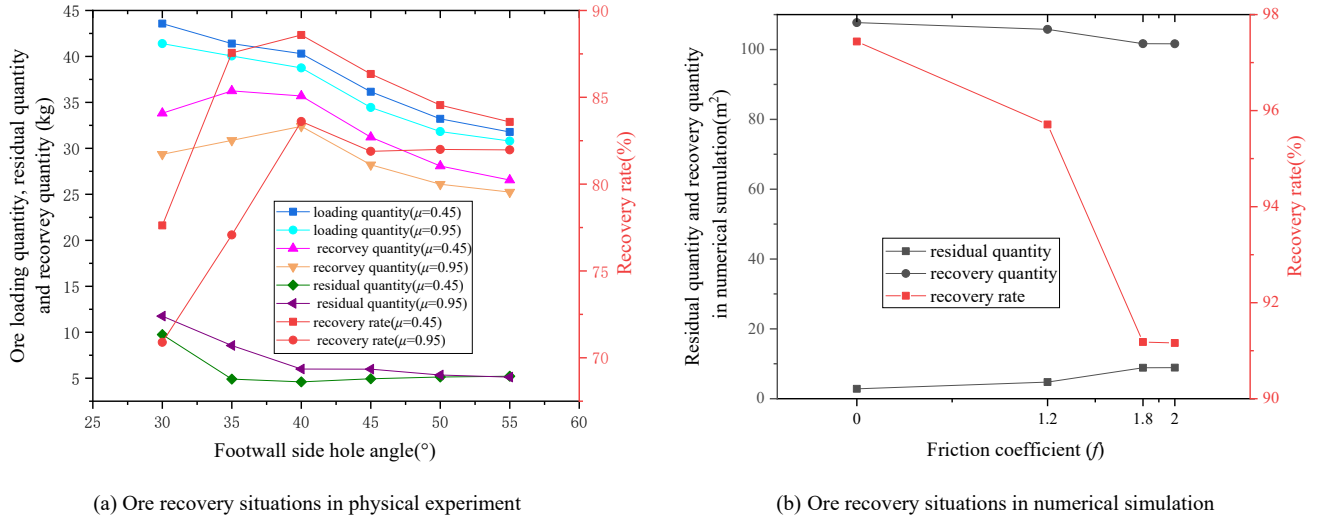
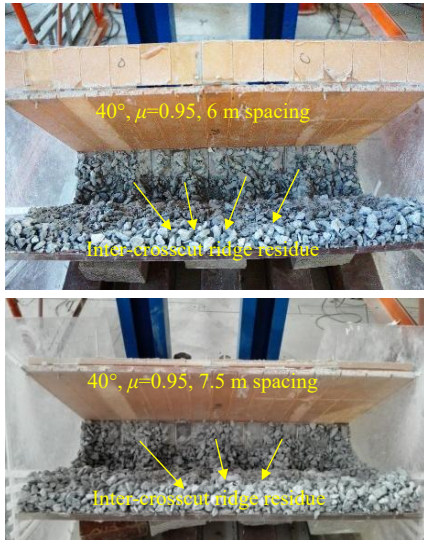


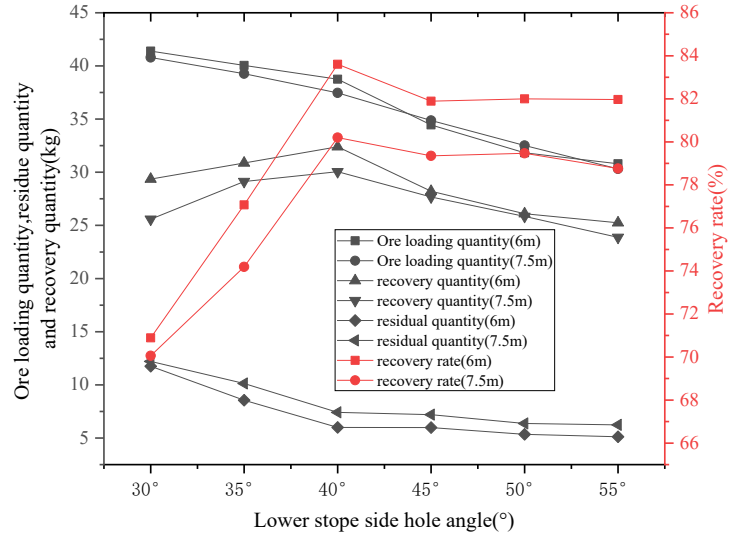
Fig. 9 Ore recovery under different footwall friction coefficients

4.2.3 Ore-drawing crosscut spacing

Ore-drawing crosscut spacing critically governs recovery, and quantifying this relationship informs structural parameter optimization. Physical experiments employed five and four crosscuts to represent 6 m and 7.5 m spacings, respectively. For both configurations, recovery varied with angle. Fig. 10a illustrates residue patterns at 40° under ore-fragment friction, while Fig. 10b reveals that recovery mass for both spacings peaks at 40°. 6 m spacing consistently outperforms 7.5 m spacing in recovery. Residual ore decreases with angle, stabilizing beyond 50° where footwall residue vanishes—averaging 5.5 kg (6 m) versus 6.4 kg (7.5 m). Recovery rates follow a similar trend for both crosscut spacings, with the maximum recovery occurring at a side-hole angle of 40°. The peak recovery rate reaches 83.61% for the 6 m spacing and 80.2% for the 7.5 m spacing, reflecting the same angle–volume trade-off discussed in Section 4.2.1. Although narrower spacing reduces inter-crosscut ridge residue, it also increases development costs and therefore requires economic optimization. Alternatively, remote-controlled LHDs could eliminate both triangular and ridge residues, providing a technological solution to the spacing trade-off.



(a) Ore residuals under different ore-drawing crosscut spacings



(b) Ore recovery situation in physical experiment

Fig. 10 Ore recovery under different ore-drawing crosscut spacings

4.3 Discussion

Comparative analysis of the physical experimental and numerical simulation curves reveals a systematic bias. The numerical simulation consistently predicts higher recovery rates than the physical experiments, and this discrepancy mainly arises from model simplification. As shown in Fig. 11a, in the numerical model, circular particles do not reproduce the interlocking behavior of irregular natural ore fragments, which enhances granular flowability and facilitates particle migration into the drilling drifts, thereby leading to an overestimation of recovery. In addition, although friction coefficients can be assigned numerically, the actual irregularity and roughness of the footwall surface generated by blasting cannot be fully reproduced, which further improves the modeled mobility of footwall particles and reduces the predicted amount of retained ore, as shown in Fig. 11b. Moreover, the numerical model does not account for the effect of ore-drawing crosscut spacing and therefore cannot capture inter-crosscut ridge residue, resulting in an underestimation of total residual ore. Therefore, the evaluation of ore loss should be based on a combined analysis of numerical simulation and physical experimental results. The actual footwall surface roughness in the field lies between the two conditions tested (fine sandpaper, $\mu \approx 0.45$; and ore fragments, $\mu \approx 0.95$). Consequently, the optimal footwall side-hole angle for field application is likely to fall within the range of 40–45°, balancing recovery and geometric residue elimination.

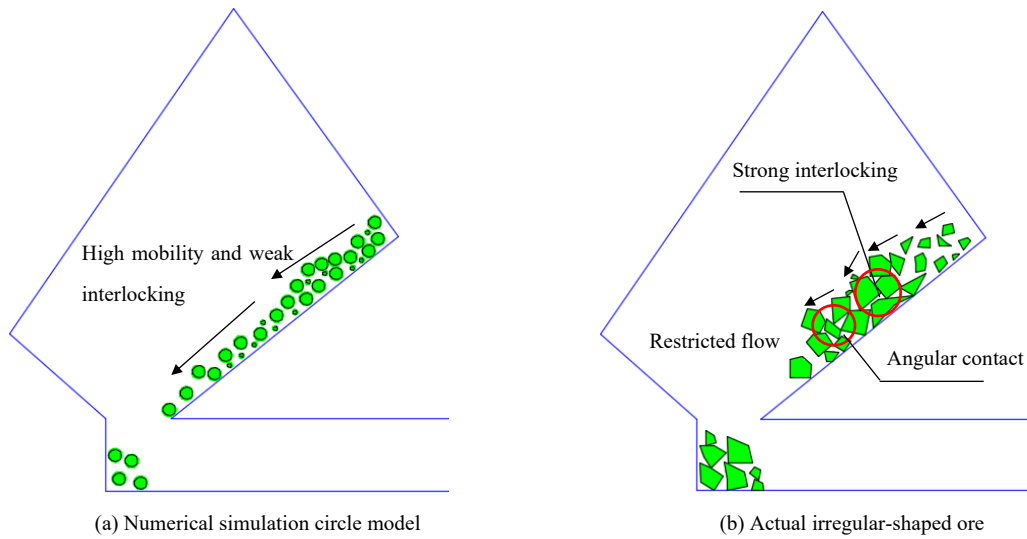


Fig. 11 Flow behavior of circular and irregular ore particles

5 On-site scan comparison

Field industrial trials were conducted at a Chinese gold mine, where 3D scanning technology was employed to capture the void shape and volume^[37, 38]. The footwall side-hole angle was set at 50° . The scanned void shape confirmed that the field conditions aligned with the physical experiment results: at 50° , the residual ore on the footwall surface was nearly zero, and the main residue forms were ridge residue and triangular residue, which is consistent with the physical experiment. The theoretical ore loss rate in the field was determined by mapping the physical experimental results obtained under field-matched structural conditions. Specifically, the quantities of inter-crosscut ridge residue, footwall surface residue, and end-of-crosscut triangular residue were quantified in the similar-material physical model and normalized by the initial ore mass of the draw unit. This residual ratio was then mapped onto the corresponding field stope geometry, yielding a theoretical ore loss ratio of 33.95% without considering over-break and under-break. The over-break section consisted of ore from the upper stope and was therefore not classified as dilution. The final ore loss rate, derived from the scanned void model, was 38.2%. The theoretical ore loss rate reflects the inherent loss controlled by the ore-drawing structure and geometric conditions, whereas the final ore loss rate also accounts for field-related effects, such as blasting-induced geometric deviations, complex granular flow behavior, and operational variability during ore drawing. As a result, the final ore loss rate is typically higher than the theoretical value.

6 Conclusions

This paper investigates ore loss during the ore drawing process in the lower stope of the DLSOS mining system. Experimental research on the ore loss process during medium-length hole blasting in moderately dipping, medium-thick fractured orebodies was conducted through physical experiments, numerical modeling. The main

conclusions are as follows:

(1) Ore residue in the lower stope of the DLSOS system is not controlled by a single factor, but results from the combined effects of the footwall side-hole angle, footwall friction coefficient, and ore-drawing crosscut spacing. The first two factors govern footwall surface residue by restricting ore flow along the footwall boundary, whereas the ore-drawing crosscut spacing controls the scale of inter-crosscut ridge residue by changing the size of the inaccessible zone between adjacent ore-drawing crosscuts.

(2) The footwall side-hole angle primarily affects footwall surface residue. As the angle increases, the recovery rate first rises and then falls. The maximum ore recovery rate of 83.61% is achieved at 40°, while footwall residue is completely eliminated at 50°.

(3) The footwall surface friction coefficient also primarily influences footwall surface residue. Rougher surfaces lead to lower recovery rates. Under fine-sandpaper friction, footwall residue vanishes at 35° (maximum recovery: 36.25 kg), whereas ore-fragment friction requires 50° to achieve zero residue (maximum: 32.4 kg). Both conditions exhibit peak recovery rates at 40°: 88.59% for sandpaper and 83.61% for ore fragments. For field practice, an angle of 40–45° is recommended given typical footwall roughness.

(4) At 6 m crosscut spacing with a 50° side-hole angle (zero footwall residue), the combined ridge and triangular residue totals 5.5 kg. This increases to 6.4 kg when the spacing is widened to 7.5 m. The three factors studied have only a minor influence on triangular residue, whereas ridge residue depends solely on ore-drawing crosscut spacing.

(5) Field industrial trials and void scanning confirmed the three residual forms observed in the physical experiments. The back-calculated theoretical ore loss rate in the field was 33.95%, whereas the final measured ore loss rate reached 38.2%.

The integration of physical experiments and numerical simulations elucidates the mechanisms of ore residue formation in the lower stope of the DLSOS mining system. These findings provide quantitative guidance for optimizing footwall side-hole angle, footwall surface friction conditions, and ore-drawing crosscut spacing, thereby improving ore recovery and supporting more efficient application of the DLSOS method in moderately dipping, medium-thick fractured orebodies.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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