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Review

Stope Structural Parameters Design towards Green and Deep Mining: A Review

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Abstract: A reliable design of stopes is critical to ensure both safety and efficiency in mining operations. The evolving mining methods and technologies as well as increasing mining depth dictate the need to continually improve stope designs. This paper presents a comprehensive review in order to compare and consolidate various stope design methods. This review covers various aspects of stope design, including design principles, factors to consider, and the diverse range of design methods available. The results led to the classification of various methods encompassing engineering analogies, fundamentals, numerical simulations, and industrial tests. Of particular significance, the review furnishes detailed insights into the research conducted on each method, as well as each method's practical performance in engineering applications. Furthermore, the review highlights the inherent limitations in current design methods and suggests potential avenues for future research. Finally, by comprehensively considering the functional roles and advantages of each design method, it overcomes the limitations of relying solely on a single method for stope structural parameter design, and a general process is proposed.

Keywords: underground mining; green and deep mining; mining method; stope parameters; design principles; design methods; design process

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1. Introduction

Underground stope design involves determining the geometric shape and size of underground stopes, which play a crucial role in safe production and have economic benefits [1–3]. Designing the stope structural parameters entails tackling a complex optimization problem involving numerous decision variables [4,5], which include the occurrence of the ore body, geological structures [1,6,7], rock mass quality [8,9], mining-induced ground pressure [10–12], the ore loss rate, the dilution rate [13,14], and the required production capacity of the mine, among others [15,16]. The interdependencies among these variables are challenging to express using precise mathematical or mechanical formulations, and the correlation between each decision variable is often weak. Consequently, achieving a sound design of stope structural parameters remains an enormous challenge.

Furthermore, the rational design of stope structural parameters is facing increasing demands due to the evolving mining methods and processes. As the requirements for ecological environment protection increase amid the gradual depletion of shallow resources, green and deep mining are inevitable in mining development [17–19]. Worldwide, there are more than 116 metal mines with a mining depth exceeding 1000 m, with the majority in South Africa, Canada, the United States, Australia, Russia, China, and other countries [20–22]. At the same time, the backfill mining method is increasingly used [23,24]. The technical conditions of deep mining are more complex, and the probability of mining disasters caused by high stress increases [20,22]. The filling mining method needs to ensure the stability of the surrounding rock in the goaf before the filling of the stope is completed. Therefore, designing appropriate stope structural parameters is crucial to ensure the safety of mining personnel and equipment during mining activities.

Extensive research has been conducted by scholars on various methods for stope parameter design. These investigations have progressed from empirical approaches to more sophisticated methods, including engineering analogies [25,26], theoretical analyses [27–29], numerical simulations [30–33], and industrial tests [34,35]. Substantial innovative outcomes have been achieved through these endeavors. However, given the diversity and complexity of considerations in stope structural parameter design, each method has its own limitations. Thus, it is imperative to collate and summarize the existing methods for designing stope structural parameters. Under this context, the primary objective of this paper is to provide a comprehensive review of the current research status pertaining to stope structural parameter design methods worldwide. This review aims to elucidate the progress made thus far in this field, evaluate the strengths and weaknesses of existing design methods, and identify future research directions in stope parameter design. On this basis, a general process for designing stope structural parameters is proposed.

2. Design Contents, Principles, and Considerations

2.1. Stope Design Contents

The design of stope structural parameters is contingent upon the specific mining method adopted by the mining operation, and the content and considerations involved in designing these parameters differ among various mining methods.

At present, underground metal mining methods can be categorized into three distinct groups based on their approach to managing and controlling ground pressure: the caving method, open stope method, and filling method [36–38]. In the context of deep and green mining, a discernible shift is taking place in the selection of mining methods for underground metal mines, gradually transitioning from the conventional caving method towards the adoption of the open stope method and filling method [39,40]. The evolution process and design content of mining methods towards green and deep mining are illustrated in Figure 1.

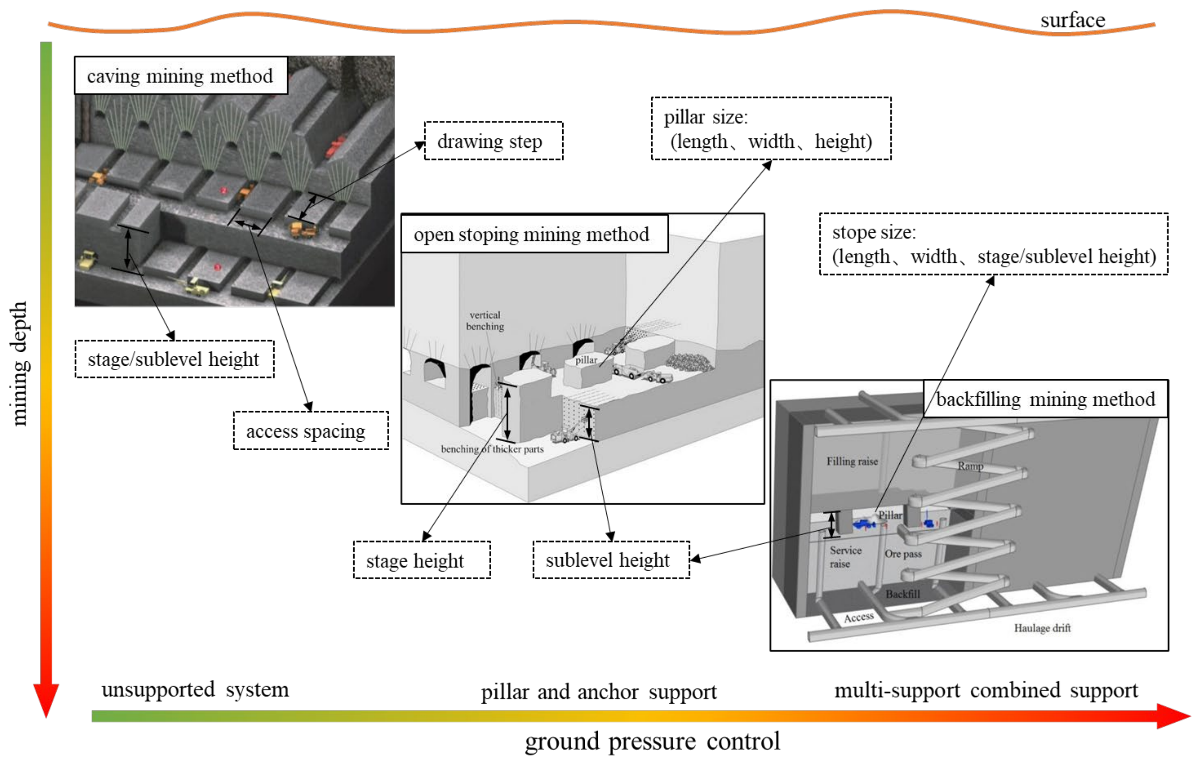


Figure 1. Evolution process and design content of mining methods towards green and deep mining.

In the process of ore extraction, the caving mining method manages ground pressure by controlling and inducing the free collapse or subsidence of surrounding rock. It does not create a goaf during ore recovery. Therefore, stope parameter design in the caving mining method mainly includes three key parameters: stage height, access spacing, and drawing step [41,42]. The open stope and filling methods require reserving pillars and sometimes adopting support measures to control ground pressure in order to maintain the stability of the goaf. Therefore, the content of stope parameter design for the open stope and filling methods is the same, including the dimensions of pillars and stope sizes [43,44].

2.2. Stope Design Principles and Considerations

Stope structural parameters have a great impact on the safe and efficient production of mines, as shown in Figure 2. A geometrically large stope can lead to the failure and/or collapse of surrounding rocks, impeding normal and safe operations. In the meantime, the collapse mixes waste rocks with ores, increasing the cost of ore upgrading and increasing unplanned dilution, thereby increasing the cost of beneficiation [45,46]. On the contrary, geometrically conservative stope parameters can lead to large mining and cutting quantities and a low ratio of ore recovery, increasing production costs and reducing economic benefits. In addition, a small stope will possibly restrict the utilization of large mining equipment, reducing production efficiency [47,48].

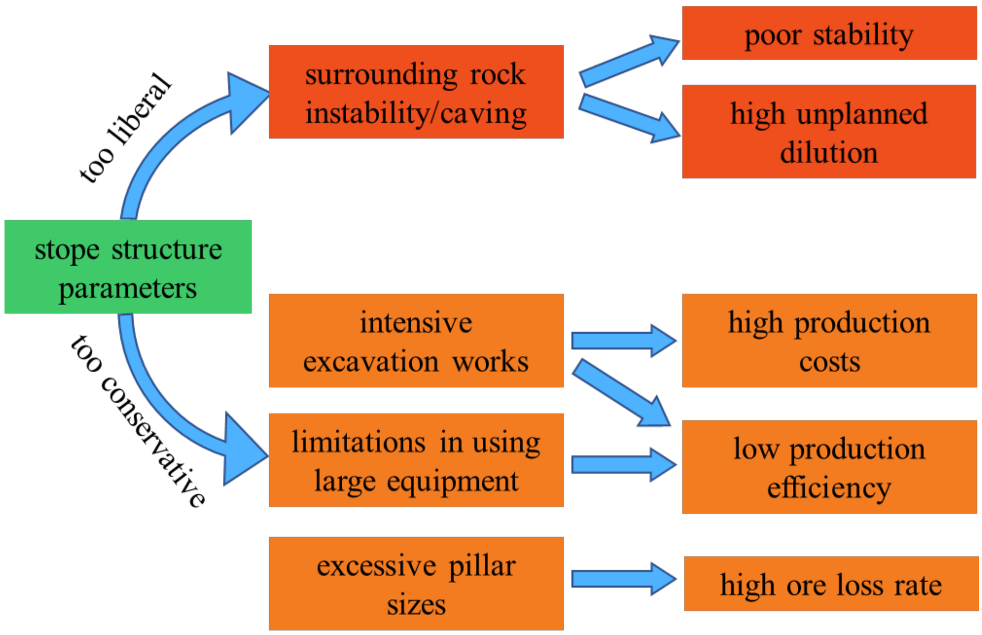


Figure 2. The impact of stope structural parameters on mine production.

In the context of deep and green mining design, mining safety, mining efficiency, and minimized environmental impact are three fundamental goals. Given that these three goals may contradict each other to a certain extent, a robust and coherent design methodology should be established and employed to achieve an optimal set of stope structural parameters. The design should balance the relationship between safe production and economic benefits. In some circumstances, a design that maximizes the stope structural parameters while ensuring compliance with safety and ore recovery rate standards may be desired.

The design of stope structural parameters is an optimization problem involving multiple factors, which can be divided into subjective and objective factors, as shown in Figure 3.

Figure 3. Factors to be considered in the design of stope structural parameters.

The multiple factors involved introduce significant challenges to the stope design. One of the primary complexities is their relative significance in differing environments. For instance, with mining extending deeper, the in situ stress has gradually evolved into the predominant factor of mining stability and thus necessitates substantial attention during the design phase [49,50]. Furthermore, to align with the modern goals of sustainable and eco-friendly development, these factors of environmental preservation, energy efficiency, emission reduction, long-term sustainability, and economic indicators must be thoroughly integrated into the design process [15,51–53].

3. Engineering Analogy Method

The engineering analogy method draws on both successful and failed experiences of mines in various conditions. It involves a classification of mining geo-conditions to select the appropriate parameters for a specific mine site condition. Furthermore, its design scope extends beyond stope structural parameters and encompasses mining method selection and mine support parameter design. A comprehensive analysis of factors such as ore body deposition, ore-rock properties, the production capacity scale, and equipment performance is essential in using the engineering analogy method. It is worth noting that consideration should be given to not only the pre-existing mining conditions but also the available construction technology levels and organizational management capabilities.

In order to reduce the subjectivity of engineering analogies, empirical charts have been developed [54,55]. Empirical charts are developed by domestic and foreign scholars based on mining production practices, aiming to capture the response characteristics of rock masses under various mining conditions and establish a specialized database. Through data collection, analysis, and summarization, empirical charts are constructed.

With the widespread adoption of rock mass quality classification systems, mining engineers can quantitatively assess mining conditions and establish a connection between the stability of underground structures and factors such as the geometric shape of the mining site and rock mass characteristics. To a certain extent, due to the widespread use of rock mass quality classification systems and the formation of a standard system, the database has been expanded, which further increases the reliability of the empirical chart method in guiding engineering design. Moreover, owing to the intricate nature of rock mass instability and failure mechanisms, the empirical chart method serves as a valuable tool for engineers in expeditiously analyzing and predicting phenomena, thereby offering guidance and support for mining design. Consequently, this method finds extensive utilization among both domestic and foreign engineers. Several common experience charts are listed in Table 1.

Table 1. Different types of experience charts used for stope structural parameters design.

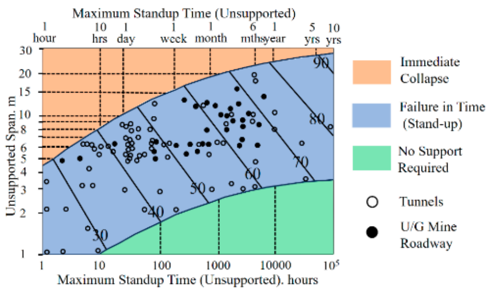
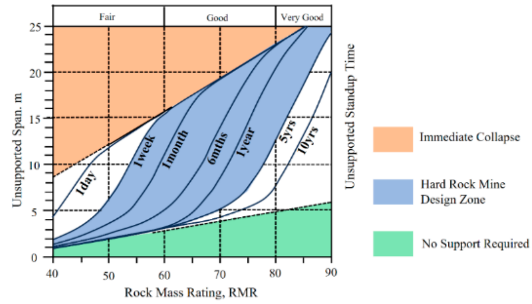
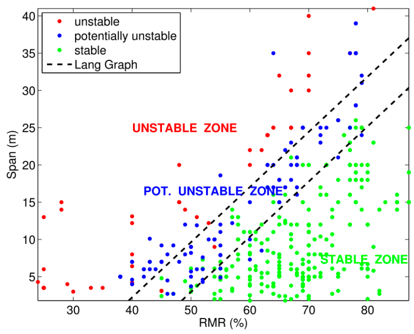
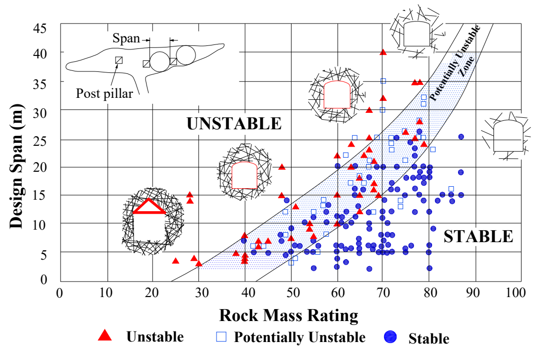
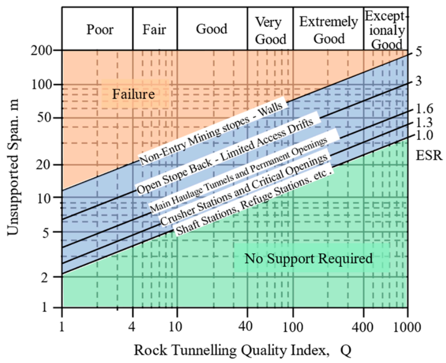
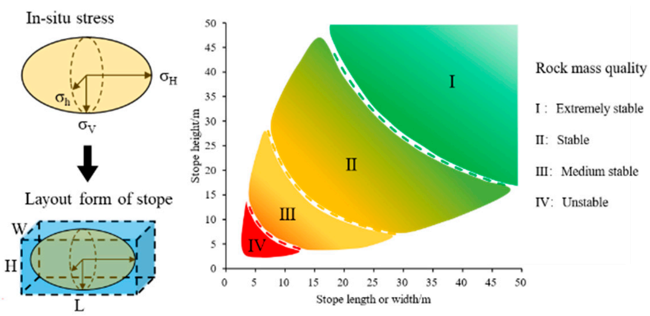
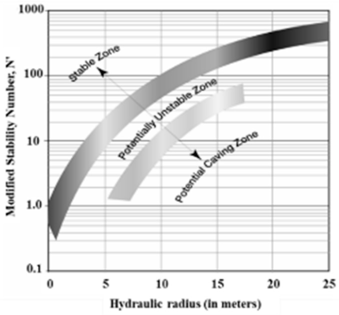
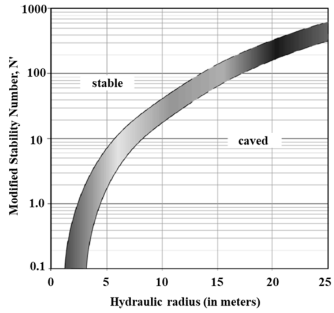
RMR Critical Span Chart (rock mass quality)	 Bieniawski (1993) [56]	 Hutchinson and Diederichs (1996) [57]
	 Lang (1994) [58]	 Wang et al. (2002) [59]
Q Critical Span Chart (rock mass quality)	 	
Maximum Allowable Exposure Area Chart (rock mass quality + in situ stress)	 	

Table 1. *Cont.*

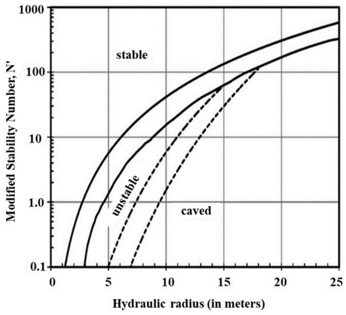
Stability Chart (rock mass quality + mining-induced stress + joint attitude + gravity influence)



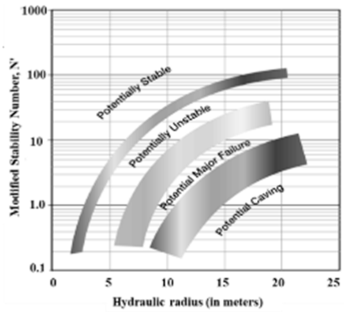
Mathews et al. (1980) [60]



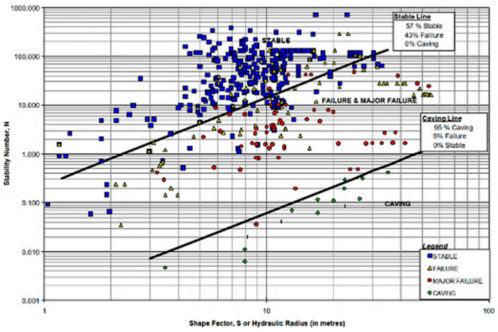
Potvin (1988) [61]

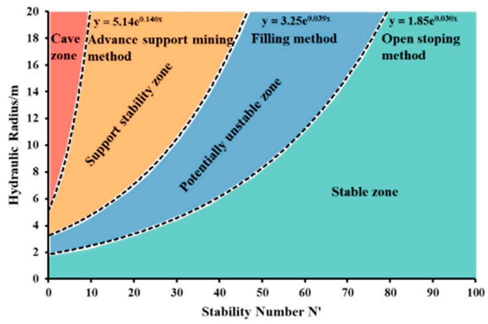


Nickson et al.(1992) [62]



Stewart et al. (1995) [63]


Mawdesley (2001) [64]



Zhao et al. (2022) [65]

Building upon the Rock Mass Rating (RMR) system [66–68], in 1993 Bieniawski created a graphical representation of the relationship between unsupported span and time for different rock mass qualities. His chart correlates unsupported span, self-stabilization time, and the RMR score with a focus on evaluating the stability and the duration of stability of engineering projects [56,69,70]. Subsequently, Hutchinson and Diederichs made improvements to this chart by emphasizing span design [57]. However, it is important to note that most of the data underlying these two charts are derived from tunnel projects. As tunnelling and mining conditions can differ largely, the applicability of this chart should be carefully considered when using it to design structural parameters for mining operations.

In 1994, Lang from the University of British Columbia developed the RMR Critical Span Chart based on 172 sets of observations at the Detour Lake mine [58]. This chart consists of three zones: stable, potentially unstable, and unstable. In 2002, Wang et al. expanded the database to include 292 sets of observation data, resulting in an updated chart [59]. The RMR Critical Span Chart presents as a convenient and efficient tool for specifically estimating the maximum span that can maintain the stability of underground engineering based on the RMR rock mass classification score. It has been widely applied in several mines in North America and has been widely accepted and adopted by the mining industry [69].

The Q Critical Span Chart was developed by Barton and his team during the period from 1974 to 1994 [71]. It is based on the statistical analysis of multiple engineering cases and illustrates the relationship between the rock mass classification Q system and the unsupported span limits for various excavation types. To calibrate the system, the initial 200+ cases were classified, and the system has been successfully applied in the construction of over 2000 tunnels and underground projects.

The Maximum Allowable Exposure Area Chart was developed by Zhao et al. based on data from the mining design manual [72]. To use the chart, the first step is to determine the form of the stope layout based on the characteristics of ground stress. The structural parameters of the stope should be proportional to the magnitude of ground stress, and the longitudinal direction of the stope should align with the maximum horizontal principal stress. Subsequently, the maximum allowable exposure area of the stope can be determined by determining the rock mass quality class using either the RMR, Q, or BQ methods [73–75]. It is important to note that this chart includes only four rock mass levels and does not encompass extremely unstable rock mass areas, such as Class V rock mass. Class V rock mass is not permitted to have an exposed area without support. Thus, when excavating tunnels or developing mining areas within this class of rock, advance support must be provided for maintenance to avoid potential roof caving and slope fragmentation.

The Stability Chart, originally formulated by Mathews et al. in 1980 using data from 26 mining cases, has undergone progressive refinement and enhancement over the years [60]. The advantage of stable charts lies in their creative proposal of the stability coefficient N′.

The stability number N′ is calculated as follows:

$$N^{'} = Q^{'} \times A \times B \times C$$

where Q′ is the index of rock mass quality, which is the modified Q system classification method; A incorporates the effects of mining stress; B is the joint occurrence adjustment coefficient; and C is the gravity adjustment coefficient.

The stability coefficient N calculation considers factors such as rock mass quality, mining stress, joint occurrence, and gravity, making the Stability Chart more suitable for complex and variable working conditions. Especially in deep mining, the rock mass is mainly subjected to stress-controlled failure, and incorporating mining stress into the design of the mining site highlights its superiority. Consequently, many scholars have further studied and improved the Stability Chart. Several variant charts like Potvin (1988), Nickson et al. (2001), etc., have been developed [61–65,76,77]. The Stability Chart is widely employed and valued in the mining industry for guiding the design of underground excavations in deep hard-rock metal mines.

The process of designing stope structural parameters using the empirical chart method is simple and efficient, as shown in Figure 4, providing a visual representation of this method.

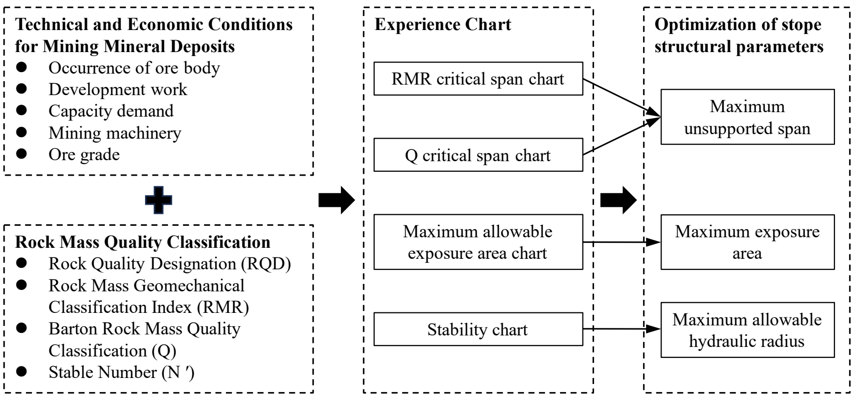


Figure 4. Design process of stope structural parameters based on empirical charts.

4. Theoretical Analysis Method

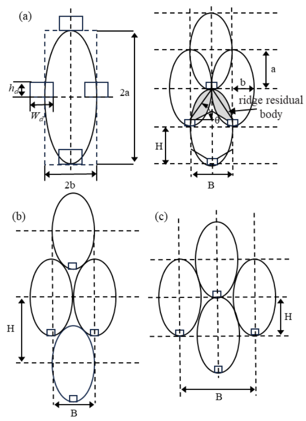
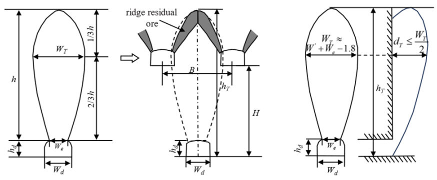
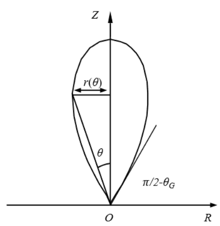
4.1. Theory of Stope Structural Parameters for Caving Mining Method

Due to its unique ground pressure control method, the design of the parameters of the caving mining method aims to maximize ore recovery while minimizing waste rock mixing. Therefore, the theoretical analysis method focuses on analyzing the morphology of the drawn-out ore body by assuming the fragmented ore body as a continuous medium or a random medium [78–80].

4.1.1. Continuous Medium Ore-Drawing Theory

The continuous medium theory assumes that the ore and rock mass are continuously and uniformly distributed, with the same physical and mechanical properties, and external forces are only affected by gravity. Various theories have been developed, including the ellipsoidal ore-drawing theory, quasi-ellipsoidal ore-drawing theory, and Bergmark–Roos-equation-based ore-drawing theory, as shown in Table 2 [25,81–86].

Table 2. Design of stope structural parameters based on continuous medium ore-drawing theory.

Basic Theory		Calculating Sketch	Formula
Typical ellipsoid drawing theory [79,82,87]	traditional structure (a)		$H = 2a - h_d - \frac{B}{2}\tan\theta$ $B = 2b$ $L = \frac{B - W_d}{4}$ $\frac{b}{a} = \sqrt{1-\varepsilon^2}$
	high-sublevel structure (b)		$\frac{H}{B} = \frac{\sqrt{3}}{2} \times \frac{a}{b}$ $\frac{b}{a} = \sqrt{1-\varepsilon^2}$
	large access spacing structures (c)		$\frac{H}{B} = \frac{\sqrt{3}}{6} \times \frac{a}{b}$ $\frac{b}{a} = \sqrt{1-\varepsilon^2}$
Atypical ellipsoid drawing theory [79,88]			$W_T \approx W' + W_e - 1.8$ $d_T \leq \frac{W_T}{2}$ $B > \frac{W_T}{0.65}(h_T > 18m)$ $B < \frac{W_T}{0.60}(h_T \leq 18m)$ $L \leq \frac{d_T}{2}$ $B < H$
Bergmark–Roos-equation-based drawing theory [83]			$r(\theta) = \frac{H(\cos\theta - \cos\theta_G)\sin\theta}{1-\cos\theta_G}$ $\theta_{\max} = \arccos\left(\frac{\cos\theta_G + \sqrt{\cos^2\theta_G + 8}}{4}\right)$ $\theta_G = 45° - \varphi/2$

The traditional ellipsoidal ore-drawing theory, initially proposed by the Soviet scholar PM Malakhov in 1958, provides an approximation of the ore body shape as an ellipsoid to study the movement patterns of collapsed ore and rock.

Early observations from industrial experiments indicate that the long axis size of the ore-drawing body is typically 2.5 to 3.0 times the short axis size. Therefore, it is recommended that the height of a single mining unit in the non-pillar sublevel caving method should be 2.5 to 3.0 times the width. Furthermore, due to the characteristics of ore recovery in sublevel caving, the traditional ellipsoid theory suggests that the drawing ellipsoids must intersect to ensure sufficient ore recovery.

The traditional ellipsoidal ore-drawing theory is based on the morphology of individual ore bodies without considering the arrangement relationship between multiple ore bodies in actual mining scenarios. When multiple ore bodies are spatially arranged, the overlapping of these ore bodies becomes significant, deviating from the fundamental principle that ore bodies should be tangent to each other. To address this issue and maintain tangency between adjacent drawn-out ore bodies, two optimal structural modes were developed. One mode is characterized by a high-sublevel structure, while the other exhibits a large access spacing structure. This theory posits that the optimization of the parameters of the stope revolves around the optimization of the spatial arrangement of release bodies, with the highest density being deemed optimal.

The atypical ellipsoid drawing theory was proposed by the American mining scholar KVAPIL [25,88]. The theory argued that the drawn-out ore body in sublevel caving does not conform to a standard ellipsoid shape but rather a "shell" ellipsoid. Based on this assumption, the design of the structural parameters focuses on maximizing the inclusion of residual ore within the upper sublevel ridge, thereby ensuring the highest possible recovery. When applying this theory to designing the structural parameters of the stope, the dimensions and shape of the proposed access and the sublevel height should be determined initially. Subsequently, the height of the drawn-out ore body can be estimated based on the sublevel height, typically being around 2/3 of the drawn-out ore body height. With this information, the access spacing and the drawing step can be calculated using the appropriate theoretical equations. The theoretical width of the drawn-out ore body W' and the effective mining width W_e can be determined from Figure 5.

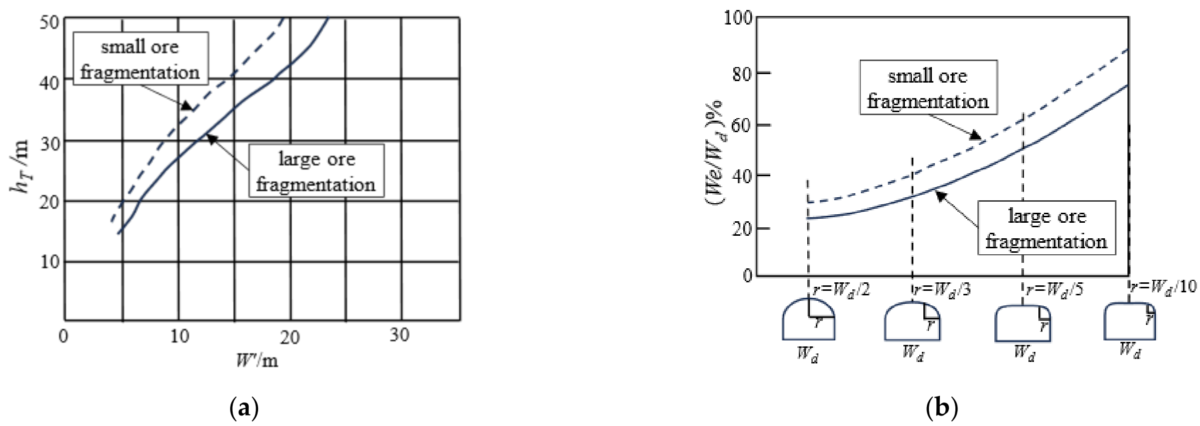


Figure 5. Schematic diagram of the method for determining the theoretical width of the ore body and the effective mining width: (**a**) relationship between h_T and W'; (**b**) relationship between W_e and route size and shape.

The Bergmark–Roos theory assumes that the trajectory of ore movement transpires as a linear motion with a null initial velocity and a consistent acceleration. Throughout the motion process, each particle exclusively encounters the gravitational influence of its own mass and the frictional impact of proximate particles. By leveraging Newton's triad of laws as fundamental benchmarks, this theory systematically derives the trajectory equation of the liberated body through comprehensive calculations. The stope structural parameters are designed according to the area, volume, and maximum width of the drawn-out ore body combined with the layout form.

4.1.2. Random Medium Ore-Drawing Theory

The random medium ore-drawing theory considers collapsed ore and rock as ideal loose materials characterized by uniform specifications, independent existence, and no deformation [29,79]. It assumes negligible cohesion or friction between spherical particles.

Under the influence of gravity, the particles are released, and their movement follows a probability distribution function. As the loose body moves, the particles tend to shift from less probable positions to more probable directions.

The theory of random medium ore drawing was initially introduced by the Polish expert JLITWNISIZYN in the 1950s [79,89–92]. Subsequently, the theory was expanded and developed, as shown in Table 3.

Table 3. Key nodes in the development of random medium ore-drawing theory.

Years and Experts	Main Contributions	Equation
1950s JLITWNISIZYN [91]	Proposed using probability methods to investigate the movement patterns of loose bodies, formulated a random medium model.	$\frac{\partial W(z,x)}{\partial z} = \frac{\partial a}{\partial z} \times W(z,x) - B(z)\left[\frac{\partial^2 W(z,x)}{\partial x_1{}^2} + \frac{\partial^2 W(z,x)}{\partial x_2{}^2}\right]$
1962 Yongjia Wang [89]	Introduced a medium constant representing the loose nature of ore (β), and the general probability density equation for medium motion was derived. The theoretical system of the random medium for ore drawing was established for the first time.	$\varphi_z(x) = \frac{1}{2\sqrt{\beta\pi z}} \exp(-\frac{x^2}{4\beta z})$
1972 B-B Kurikov [92]	Extended the analysis from the two-dimensional plane problem to the three-dimensional space problem and provided the corresponding differential equations.	$p(x,z) = \sqrt{\frac{2b}{\pi bz}} \exp(-\frac{2bx^2}{a^2 kz})$ $\frac{\partial p(u,w)}{\partial w} = B\frac{\partial^2 p(u,w)}{\partial u^2}$ $\frac{\partial p(u,v,w)}{\partial w} = B\left[\frac{\partial^2 p(u,v,w)}{\partial u^2} + \frac{\partial^2 p(u,v,w)}{\partial v^2}\right]$
1992 Fengyu Ren [29,79]	Integrated the random medium method with the actual physical process of gravity flow and introduced two parameters, α and β, which effectively reflected the flow characteristics of grain flow based on the movement of particles under experimental boundary conditions.	$p(x,z) = \frac{1}{\sqrt{\pi\beta z^\alpha}} \exp(-\frac{x^2}{\beta z^\alpha})$ $p(x,y,z) = \frac{1}{\sqrt{\pi\beta z^\alpha}} \exp(-\frac{x^2+y^2}{\beta z^\alpha})$ $p(r,z) = \frac{1}{\sqrt{\pi\beta z^\alpha}} \exp(-\frac{r^2}{\beta z^\alpha})$

Before applying this theory to calculate the reasonable access spacing, it is essential to determine the appropriate height of the stage. Additionally, to accurately measure the flow parameters of ore particles in the vertical direction of the pass, experimental studies of ore discharge at the end of the leak can be conducted. Ren Fengyu proposed a formula to determine the reasonable access spacing [79]:

$$B = 6\sqrt{\frac{1}{2}\beta H^\alpha} + \mu w_d$$

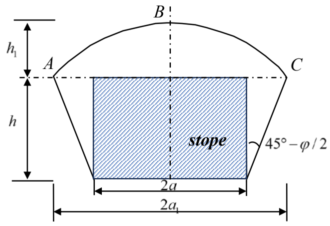
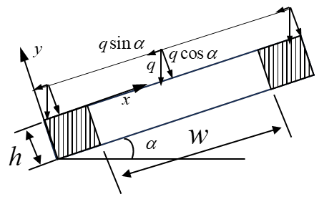
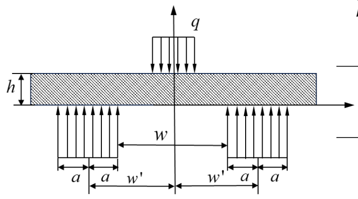
where α and β represent the flow parameters of the loose body in the direction of the vertical route, and μ is related to the exposed width of the waste rock funnel on the top plate of the access road. For the non-dilution ore-drawing method, μ is approximately equal to 0. For the low-dilution ore-drawing method, μ is approximately in the range of 0.1 to 0.6. And for the cut-off grade ore-drawing method, μ is approximately equal to 0.75.

4.2. Theory of Stope Structural Parameters for Open Stope Mining Method and Fill Mining Method

The open stope and backfill mining methods need to ensure the stability of the stope during the ore extraction process. Therefore, the design methods involve establishing a mechanical analysis model to study the relationship between pillar, stope size, and stope stability [93–97]. The basic mechanical theories used in this type of analysis includegranular mechanics and structural mechanics, as shown in Table 4.

The theories established based on granular mechanics include the loose coefficient theory and the Proctor arch theory. The former posits that in the event of a collapse in the excavation area, safety can be ensured as long as the thickness of the upper pillar exceeds the height necessary to fill the void with the collapsed rock. PU's arch theory, also known as the fracture arch theory, holds that upon the creation of the goaf, the roof develops into a parabolic arch belt, responsible for bearing the weight of the overlying rock mass. In principle, the parameters of the stope and pillar designed by the loose coefficient theory are more conservative than those of the Poisson arch theory.

Table 4. Theoretical analysis method for calculating structural parameters of stopes.

Theory		Calculating Sketch	Functions
Granular mechanics [93]	Theory of the loose coefficient		$h_1 = \frac{h}{1-k_p}$ [1]
	PU's equilibrium fracture arch theory		$h_1 = \frac{a_1}{f} = \frac{a+h\tan(45^\circ-\frac{\varphi}{2})}{f}$ [2]
Structural mechanics [95,96]	Thickness-to-span ratio		$\frac{h}{kw} \geq 0.5$ [3]
	Simply supported beams		$w = \left[\frac{4h\sigma_{tmax}}{3\gamma\cos\alpha} - \frac{h^2\tan^2\alpha}{9}\right]^{1/2}$ [4] $w = \left[\frac{4h\sigma_{tmax}}{3\gamma}\right]^{1/2}(\alpha = 0^\circ)$
	Beam theory		$h = 0.25w\frac{\gamma w+\sqrt{(\gamma w)^2+8wq\sigma_{tmax}}}{\sigma_t l}$ [5]
	K.B. Lu Pennie theory		$h = k\frac{0.25\rho w^2+\sqrt{(\rho w)^2+800\sigma_n g}}{98\sigma_n}$ [6]
	B И. Bogo Liubov theory		$h = k\frac{\rho w^2+\sqrt{\rho^2 w^2+16\sigma_n p_n}}{g\sigma_n}$ $p_n = \frac{rH_yK_n(K_c+K_{nep})}{K_p}$ [7]

[1] k_p is the rock loosening factor. [2] f is the rock firmness coefficient $f = R_C/100$; φ is the internal friction angle of the surrounding rock, (°). [3] k is the safety factor. [4] σ_{tmax} is ultimate tensile strength of rock mass; α is the dip angle of ore body, (°); γ is the unit weight of rock mass, (10^4 N/m^3). [5] q is additional equipment load, (KPa); l is the calculated width of the roof unit. [6] ρ is roof rock mass density, (t/m^3). σ_n= (7%~10%) $\sigma_c/(k_1\ k_2)$ is the strength limit of the roof; σ_c is uniaxial compressive strength (MPa); k_1 is the strength safety factor, k_1 = 7~10; k_2 is the structural weakening factor under bending conditions, k_2 =2~3; g is the pressure of the filling body on the roof, (MPa). [7] P_n is the dynamic load formed by the blasting rock mass; H_y is the trapezoidal height, r blasting index; K_c, K_{nep}, K_n, K_p are the reduction coefficient of ladder height, over-drilling coefficient, dynamic load coefficient, and rock-loosening coefficient during blasting, respectively.

Extensive research indicates that the roof layer of underground excavations primarily experiences tensile stresses. Accordingly, structural mechanics analyses mainly consider the possibility of rock mass failure due to maximum tensile stress exceeding the strength of the rock mass.

The theory concerning the ratio of thickness to span in simply supported beams posits that the roof of the stope can be regarded as a fully intact structure, and it does not consider rock mass strength compared to other theories. It relies on the ratio between the thickness of the top plate and the span of the stope as a fundamental parameter in assessing the stability of the stope roof. When the ratio is greater than or equal to 0.5, the roof of the stope is considered stable. The theory of simply supported beams regards the roof of a mining area as a simply supported beam with supports at both ends. Subsequently, the maximum allowable span of the stope structural parameters is determined based on the tensile strength characteristics of the rock mass and the thickness of the top pillar. Of course, the thickness of the top pillar can also be calculated based on the span of the stope.

The beam theory postulates that the stope roof can be modeled as a flat beam with fixed supports at both ends. The self-weight of the overlying rock mass, along with any additional loads, is considered as the applied load on the roof strata, and the tensile strength of the roof rock mass is the key stability criterion. K.B. Lu Pennie's analysis provided an additional method for estimating roof strength. B И. Bogo Liubov's analysis incorporated blasting dynamic loads into the design.

5. Numerical Simulation Method

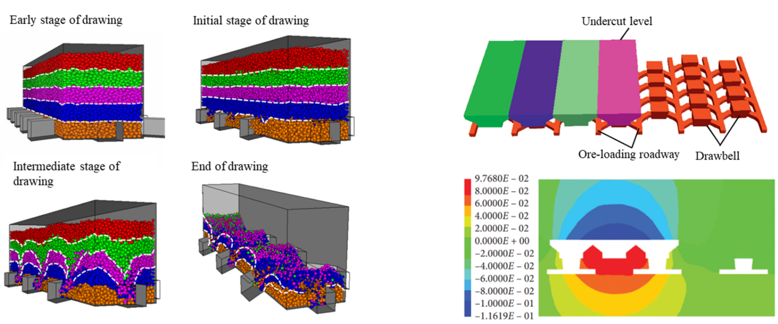
The advancement of computing technology has facilitated the development and widespread application of various geotechnical numerical simulation codes or software packages in engineering design. When utilizing numerical methods to design and optimize the structural parameters of mining sites, careful consideration must be given to selecting appropriate software based on the specific mining methods employed and the indicators under analysis during the design process. The commonly used types of numerical simulation software for mining engineering are shown in Table 5 [98–104].

Table 5. Numerical simulation software for mining engineering and its main applications.

Modeling Approach	Numerical Method	Numerical Code	Rock Mass Representation	Rock Mass Failure Realization	Main Applications
Continuum	FDM	FLAC2D/3D	Continuum medium	Deformation (displacement), stress, plastic yield, and safety factor	Analyze and evaluate the stope stability
	FEM	RS2/3 ANASY ABAQUS			
	BEM	Map3D			
Discontinuum	DEM	UDEC 3DEC	Assembly of deformable or rigid blocks	Blocks movements and/or blocks deformations	Stability analysis of rock mass controlled by structural planes
		PFC2D PFC3D	Assembly of rigid bonded particles	Bond breakage and particle movements	Simulating ore flow in caving mining method

The general process of utilizing numerical simulation methods for designing structural parameters in mining sites involves several key steps. Initially, the approximate parameter range is determined through theoretical analysis or experimental investigations. Subsequently, various parameter combinations are designed, and numerical software is employed to calculate whether the indicators of each combination meet the specific requirements of the mine. This iterative process facilitates the determination of appropriate mining site structural parameters.

For the design of structural parameters in caving methods, the primary focus lies in simulating the ore recovery efficiency [31,105–107]. In such cases, discrete element software like PFC2D or PFC3D proves essential. On the other hand, when designing mining methods with bottom structures, such as natural caving, the primary concern shifts to the stability of the bottom structure during simulations, as the bottom structure plays a vital role in ore collection [108,109]. For these scenarios, continuum modeling software such as FLAC3D is often employed to perform simulations. Figure 6 showcases some simulation results in this context [31,110].



(**a**) (**b**)

Figure 6. Numerical simulation results of optimization of mining parameters in caving method: (**a**) simulating the ore-drawing process using PFC3D software; (**b**) stability analysis of bottom structure using Flac3D3.10 Software [31,110].

For the design of stope structural parameters in the open stope and backfilling mining methods, the simulation of ore flow is often omitted, and the focus shifts towards the assessment of the stability of the surrounding rock mass [111,112]. The procedure involves the initial creation of a geometric model of the mining site, followed by the simulation of its excavation process. The impact of geological structures on the stability generally needs to be considered. A comprehensive comparative analysis of factors such as stress, displacement, and the distribution of plastic zones within the excavations is then conducted to analyze optimal parameters for the mining operation [113,114]. Some examples of such simulation results are shown in Figure 7 [115,116].

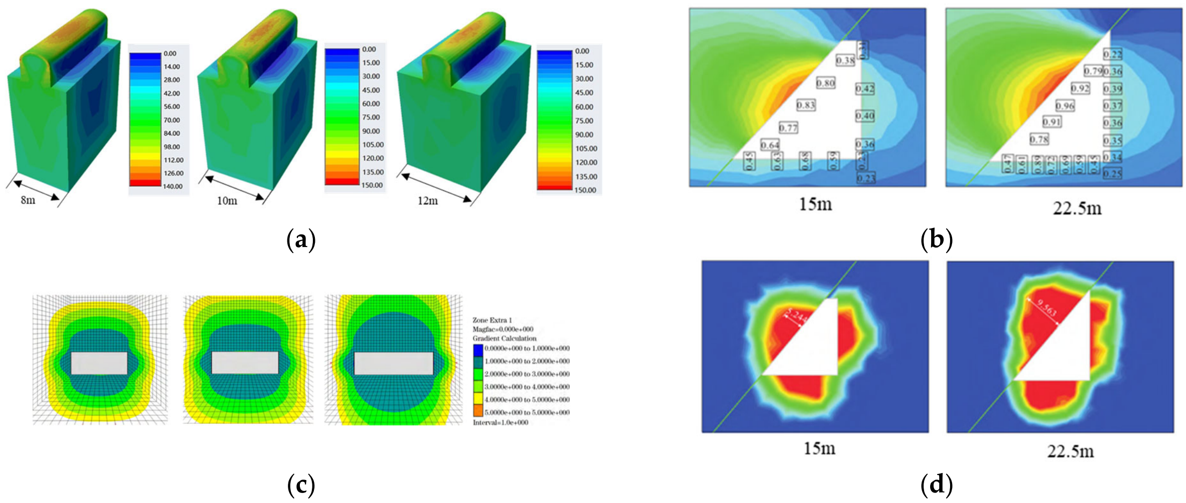


Figure 7. Numerical simulation results of optimization of stope structural parameters in open stope and filling methods: (**a**) variation in maximum principal stress in different span stopes (RS3); (**b**) distribution of displacement in different heights of stopes (RS2); (**c**) safety factor of different span stopes (FLAC3D); (**d**) distribution of plastic zone in different heights of stopes (RS2) [115,116].

6. Physical Modeling Test and On-Site Industrial Testing

6.1. Physical Modeling Test

The physical simulation test method involves creating a scaled-down physical model to mimic the ore-drawing process in the caving method [117–121]. Through this approach, the movement behavior of ore and rock during the ore-drawing process is observed, and the shapes of the released and residual bodies are depicted. Additionally, this method explores the mixing process of ore and rock, as well as principles governing ore and rock loss and dilution. By leveraging these insights, a drawing plan is formulated, and the structural parameters of the mining site are optimized, in conjunction with fundamental analyses.

The accuracy of physical model experiments largely depends on the similarity between the model experiments and the actual industrial sites [122]. When constructing a physical model, two essential principles must be satisfied: geometric similarity and mechanical similarity. At the same time, different proportions of physical experimental models also have different uses. Typically, for validation experiments a 1:100 scale model can be selected, as it strikes a balance between accuracy and feasibility. However, when conducting relatively large-scale experiments, a 1:50 or 1:25 scale model may be selected. Figure 8 showcases some examples of physical ore-drawing models commonly used in experimentation [123–126].

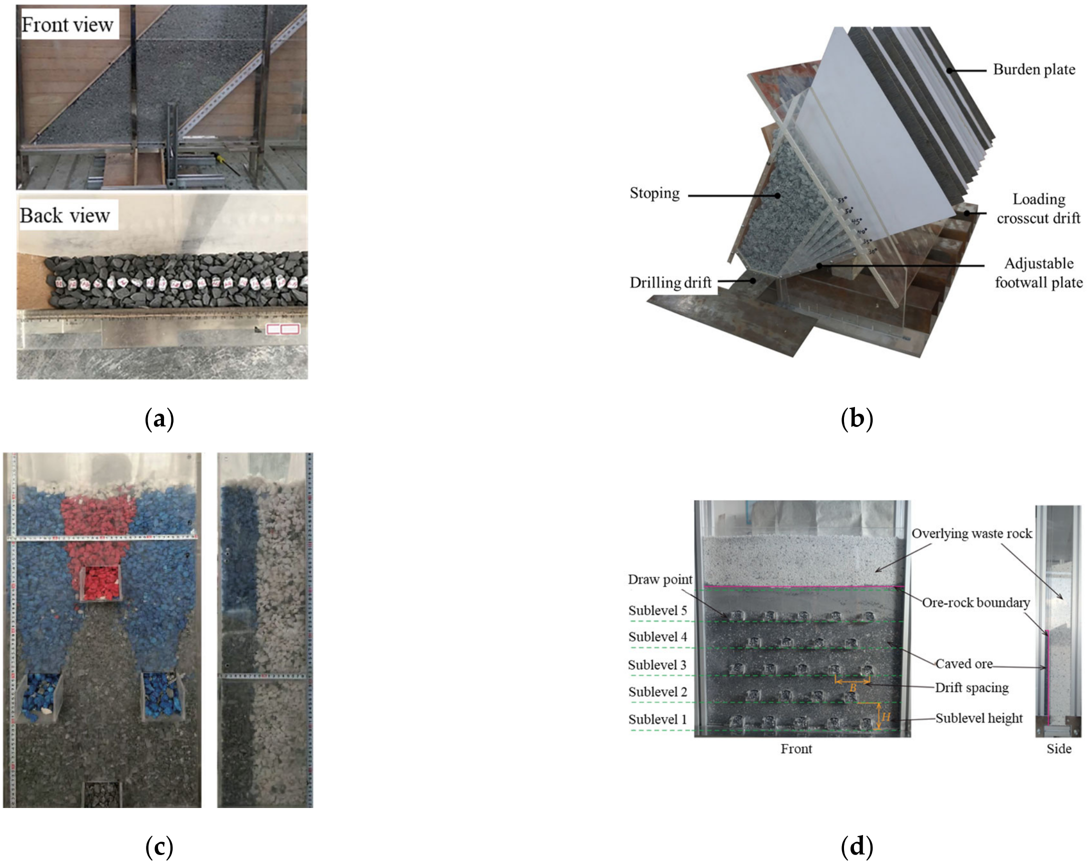


Figure 8. Scaled physical model of the draw experiments: (**a**) single-route model of the ore draw (1:25); (**b**) multi-compartment three-dimensional ore-drawing model (1:50); (**c**) single-compartment three-dimensional ore-drawing model (1:50); (**d**) multi-segmented three-dimensional ore-drawing model (1:100) [123–126].

Under a specific sublevel height, the static angle of ore drawing for fragmented ore can be determined through experimental measurements to facilitate the calculation of the corresponding access spacing [127,128]. The calculation diagram is shown in Figure 9.

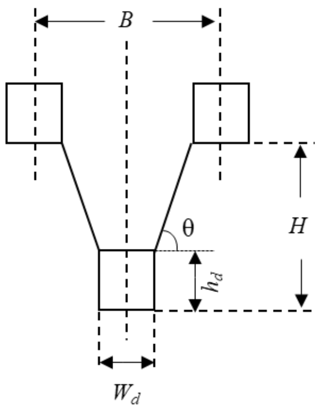


Figure 9. Schematic diagram of using static angle of ore drawing to calculate the access spacing.

The formula for calculating the access spacing is

$$B = 2\left(\frac{H - h_d}{\tan\theta} + w_d\right)$$

In situations where both the sublevel height and the access spacing are already determined, the drawing step derived from the ore-drawing experiment requires further transformation, and the calculation formula is presented as follows:

$$L = L'(1 - K)$$

where L is the drawing step of the on-site testing; L′ is the ore-drawing step obtained by the model; K is the density coefficient; and in the sublevel caving method, K = 20%.

6.2. On-Site Industrial Testing

The on-site industrial experimental design of stope structural parameters involves several key steps [129]. Firstly, representative experimental mining sites are carefully selected to ensure the validity and relevance of the experimental results. Subsequently, construction operations are carried out based on the predetermined stope parameters. During the mining process, various observation methods are employed to track the distribution of collapsed ore and to measure the shape of the released body. By comparing the shape of the released body with that of the collapsed ore body, valuable insights into the relationship between stope structural parameters and ore recovery effectiveness can be obtained.

Currently, the marker recovery method stands as the primary approach for determining the morphology of released bodies. This method entails drilling blast holes in the ore blocks of the targeted mining area and strategically placing landmark particles within them, following a predetermined plan. As the ore-drawing process commences, these markers are progressively recovered. Based on the sequential recovery order of landmark particles in the collapsed ore rock, the original position of the ore rock before mining, and the quantity of ore rock released, the shape of the ore body can be meticulously delineated. A schematic representation of this process is depicted in Figure 10 [130].

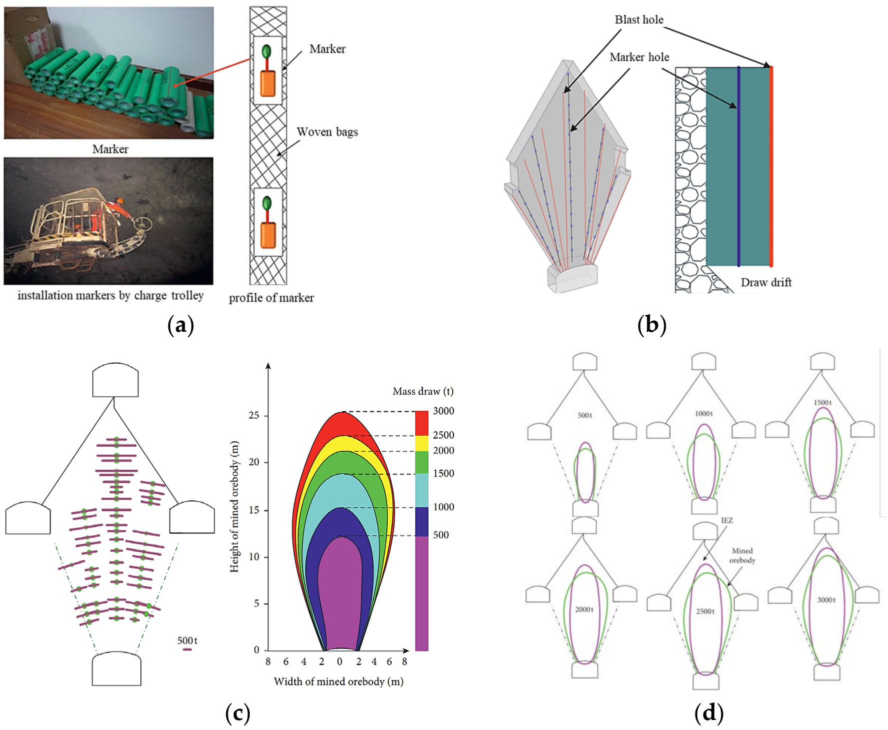


Figure 10. Determination of release body morphology by marker recovery method: (**a**) marker and on-site installation process; (**b**) the relationship between the position of markers and blast holes; (**c**) markers monitored in the test and their corresponding quality of drawing ore; (**d**) comparison of the mined orebody's shape and the IEZ's shape in the test [130].

Furthermore, on-site industrial tests for the open stope and backfill mining methods utilize techniques such as stress and displacement monitoring [49,131], microseismic analysis [132,133], and 3D laser scanning to assess the stability of the roof or the wall of the stope that is prone to damage [134]. These methods serve to validate the feasibility of the stope parameter designs, and several monitoring devices are illustrated in Figure 11 [135].

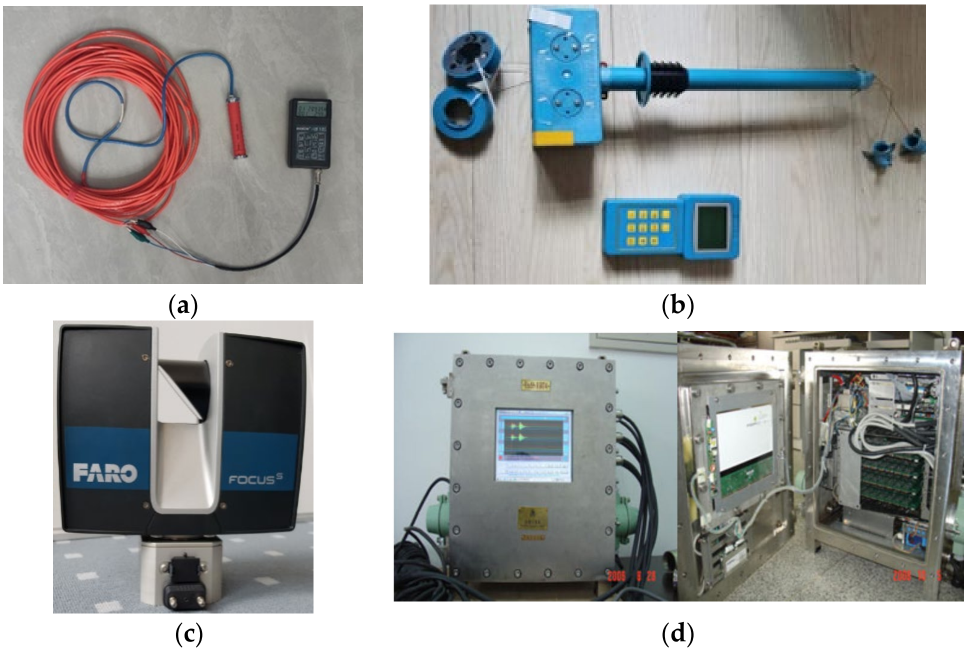


Figure 11. Monitoring devices: (**a**) vibrating wire strain gauge; (**b**) displacement sensor; (**c**) 3D laser scanning (FARO); (**d**) the underground explosion-proof microseismic monitor [135].

7. Discussion

7.1. Advantages of Various Methods

By reviewing different stope design methods, they can be divided into four categories: the engineering analysis method (experience chart), theoretical analysis method, numerical simulation method, and test method (physical modeling test and on-site industrial testing). The application of stope parameter design methods in different mining methods is shown in Table 6.

Table 6. Application of stope parameter design methods in different mining methods.

	Engineering Analogy Method	Theoretical Analysis Method	Numerical Simulation Method	Physical Modeling/On-Site Industrial Testing
Caving mining method	Engineering analogy	Ore-drawing theory	Ore flow/stability analysis	Physical modeling/on-site industrial testing
Open stope/filling mining method	Experience chart	Fracture arch theory Simply supported beams/plate beam	Stability analysis	On-site industrial testing

The evaluation of design methods for different mining parameters is shown in Table 7.

Among these methods, engineering analogy methods are widely used in different design scenarios due to their simplicity, efficiency, and low cost. Especially in the design of the open stope and backfilling mining methods, continual improvements were made to the engineering analogy method, and various empirical charts were developed. The utilization of these empirical charts helps mitigate design subjectivity to a certain extent. Furthermore, the empirical chart methodology comprehensively accounts for various factors, including rock mass quality, original rock stress, mining-induced stress, and joint occurrences, significantly enhancing the rationality of the design.

Table 7. Evaluation of different stope parameter design methods.

Method	Advantage	Limitations	Functional Positioning
Engineering analogy method	Simplicity, efficiency, and low cost. Experience charts reduce subjectivity in the design of stope parameters.	The specific conditions of different mines cannot be exactly identical, leading to subjectivity and uncertainty in the design parameters. The quality of the reference database directly affects the accuracy of the design.	Given a rough range of stope parameters, it is primarily utilized in the preliminary design phase.
Theoretical analysis method	In-depth insight into the interplay between stope structural parameters and rock mechanics behavior, offering robust theoretical underpinnings for engineering design.	Under complex geological and engineering conditions, this method might necessitate a series of assumptions and simplifications, affecting accuracy.	Preliminary design of stope structural parameters under specific working conditions.
Numerical simulation method	Visual, dynamic, and quantitative calculation. Using numerical models to simulate excavation and ore-drawing processes comprehensively and accurately evaluates the stability and performance of the mining site.	Its implementation demands significant computational resources and time, necessitating model calibration and validation for accuracy assurance.	Stope structural parameter optimization.
Physical modeling test	Visually observe the movement behavior of ore and rock during the ore-drawing process and depict the shapes of released and residual bodies.	Only applicable to caving mining methods. It is difficult to simulate under complex boundary conditions.	Optimize stope parameters in conjunction with the ore-drawing theory.
On-site industrial testing	The most direct and intuitive method for evaluating stope parameters.	The on-site testing method requires a large amount of human resources and material configuration and often requires a lot of time, thereby interfering with the normal mining progress of the mine.	Verify the rationality of the design of mining parameters. Calibration of numerical models.

In the realm of theoretical analysis methods, the ore-drawing theory serves as the foundational and indispensable theoretical basis for parameter design in caving method mining sites. Within this domain, the continuous medium ore-drawing theory stands as the earliest, most extensively researched, and broadly applied one. It delves deep into the kinematics of loose bodies under both infinite and simplified boundary conditions. In contrast, the random medium ore-drawing theory employs mathematical statistics to elucidate the motion characteristics of loose bodies, tightly aligning them with real-world scenarios. When addressing the challenges of ore extraction under varying boundary conditions, the random medium ore-drawing theory exhibits superior accuracy and fidelity compared to the continuous medium ore-drawing theory.

The research agenda within the theoretical analysis method for open stope mining and fill mining predominantly centers on the interplay between roof thickness, stope span, and stope stability. A theoretical analysis grounded in the principles of soil mechanics is leveraged to design a secure roof thickness predicated on factors like the loose coefficient, cohesion coefficient, and internal friction angle of the ore. This theoretical approach is typically applied to surface-level shallow tunnel projects and is exclusively suitable for rock fragmentation scenarios in hard-rock mines. Meanwhile, the structural-mechanics-based theoretical analysis method employs the maximum tensile strength index of the roof rock mass to compute the dimensions of pillars and stopes essential for maintaining mining area stability. These theoretical methodologies holistically consider factors such as the stability of upper pillars due to influences like backfill and mechanical equipment, as well as the impact of blasting vibrations. These theoretical analysis methods, rooted in solid mechanical principles, yield favorable results under specific operational conditions.

With the advancement of relevant algorithms and software, numerical simulation methods have gained increasing prominence and emerged as the predominant approach in mining design. A notable feature of these methods in caving mining is the use of discrete element software to simulate ore flow and investigate the influence of mining parameters on ore extraction outcomes. Additionally, the most widely employed numerical simulation approach involves analyzing mining area stability based on indicators like stress, displacement, and safety coefficients of the plastic zone. This analysis aims to optimize mining area and pillar parameters.

Experimental methods represent the most intuitive means of assessing the rationality of stope parameters. Physical model experiments play a pivotal role in shaping mining parameters for caving methods, frequently in conjunction with ore-drawing theories to optimize these parameters. On-site industrial testing represents the ultimate step in evaluating mining site parameters. Moreover, numerical models can be fine-tuned through the integration of stress and displacement monitoring data.

7.2. Future Trends of Mining and New Requirements of Stope Design

The advantages and applications of various mining parameter design methods have been discussed. Looking ahead, considering the current trajectory of the mining industry and the constraints associated with each mining parameter design approach, several future development trends are proposed.

The caving mining method offers high production efficiency and cost effectiveness. However, it leads to severe surface subsidence and significant environmental damage, especially as mining depth increases. In contrast, the open stope mining method and the fill mining method are capable of controlling surface subsidence, contributing to ecological and environmental protection. Nevertheless, these methods entail higher production costs compared to the caving method. In particular, the fill mining method involves additional costs associated with filling operations. Despite these cost implications, its exceptional ground pressure control capabilities have led to an increased utilization of this method in deep mining operations. In the context of deep, green mining, underground metal mine mining methods are gradually changing from the traditional caving method to the open stope mining method and filling method.

Empirical methods, such as engineering analogy and empirical chart techniques, should be seen as data-driven models from a mathematical perspective. Developing rich and standardized databases is a prerequisite for advancing these empirical methods. In the context of deep mining, where geological complexity and in situ stress conditions are more intricate, the design of stope structural parameters should be adaptable to surrounding rock conditions and stress levels. Thus, the expansion of databases should prioritize incorporating deep mining data, particularly focusing on the response characteristics of different rock qualities under varying stress conditions. Moreover, standardizing assessment criteria and quantitative methodologies is essential to facilitate data consistency in mining.

The future trend will emphasize extracting valuable insights from vast mining datasets through mathematical induction methods like artificial intelligence and machine learning, establishing connections between data for enhanced engineering design. In recent years, propelled by significant advances in computer technology, artificial intelligence methods such as neural networks, genetic algorithms, analytic hierarchy processes, and fuzzy evaluations have been rapidly integrated into stope parameter design. These methods, characterized by their adaptability and cognitive abilities, prove to be potent tools for capturing intricate interdependencies among factors affecting stope structural parameters. Through application, intelligent algorithms are deployed to systematically develop convincing evaluation system models or precise mathematical expressions. Theoretical analysis methods often involve simplified and abstracted computational models, tailored to specific working conditions. Challenges arise due to the inherent heterogeneity and anisotropy of rock masses. Future developments in this field will likely emphasize mechanistic research, exploring rock failure mechanisms and particle flow principles and enabling the assignment of appropriate weights to various factors considered in the design of stope structural parameters.

Numerical simulation methods are increasingly used in designing and optimizing stope structural parameters. Future trends include refining geological and mechanical models, enhancing the accuracy of mechanical parameter settings, and improving boundary conditions. Achieving multi-field coupled discrete material release numerical calculations and underground engineering rock stability analysis is also a research focal point. Furthermore, the integration of large-scale parallel computing and artificial intelligence techniques in numerical simulations will enhance efficiency and accuracy.

Industrial experiments will benefit from advanced sensing technologies and real-time monitoring capabilities, leading to more accurate and timely results. Experimental data will serve to validate and calibrate numerical simulation models and evaluate the performance of stope structural parameters under complex conditions.

In conclusion, the future of stope structural parameter design lies in an integrated approach, combining various methods and technologies. Empirical methods will evolve into data-driven intelligent design, theoretical analyses will delve deeper into fundamental research, numerical simulations will offer more accurate predictions, and industrial experiments will provide practical validation for numerical models. This amalgamation will drive innovation and advancement in stope structural parameter design by finely optimizing stope structural parameters.

Finally, based on the functional positioning of each design method, a general process for designing stope structural parameters is proposed, as shown in Figure 12. By leveraging the advantages of each design method and categorizing the applicable scenarios of each method, this design process aims at providing optimal design methodology towards achieving green and sustainable mining operations in increasing deep and complex mining conditions.

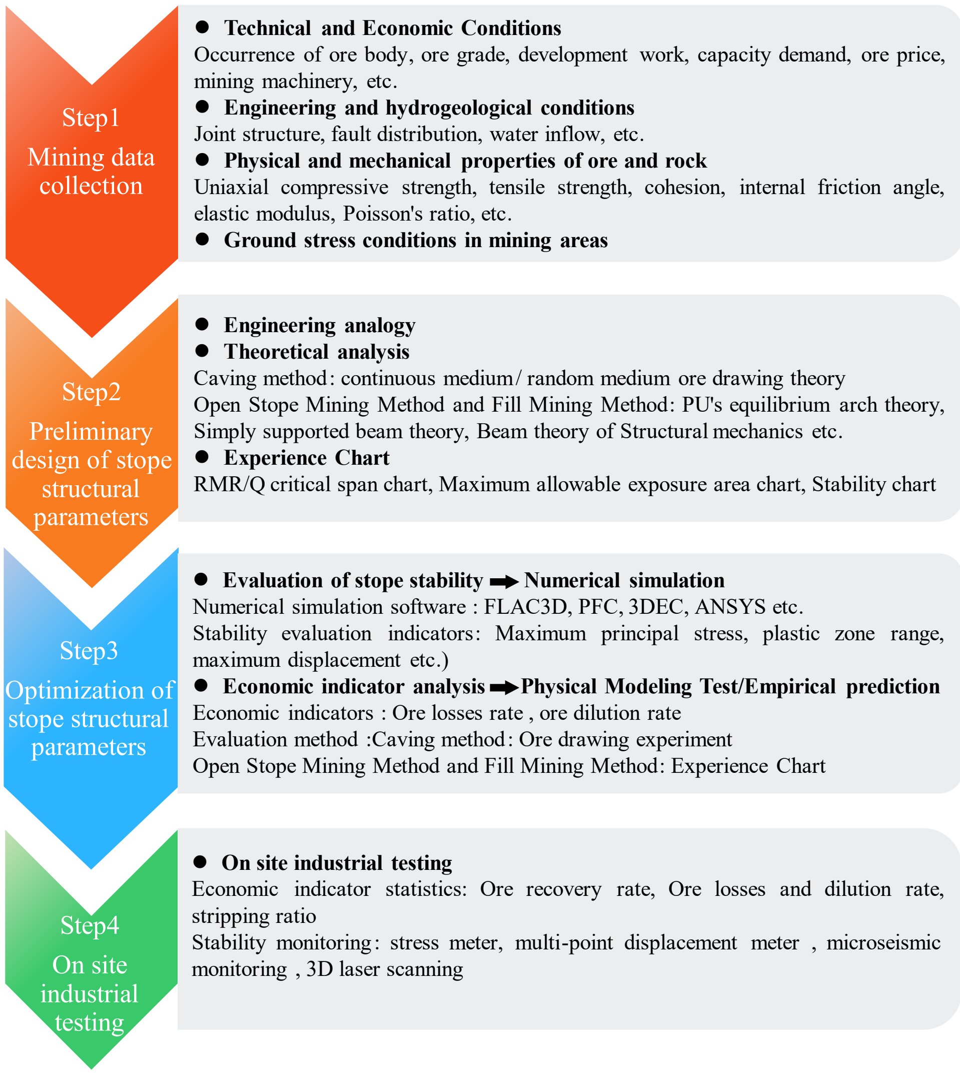


Figure 12. Design process of stope structural parameters.

8. Conclusions

The design of stope structural parameters directly impacts the safe production and economic efficiency of mining enterprises. This paper summarizes the existing methods for designing stope structural parameters under different mining methods. Considering the evolving trends in the mining industry, this paper further proposed new research needs to continually improve the design of mining stopes. The main conclusions drawn are as follows.

Amidst the backdrop of deep mining and green mining initiatives, there has been a gradual transition in mining methods from caving methods to backfill mining. While ensuring safe production, there is also a steadfast commitment to the overarching principles of sustainable development and environmental protection.

Within the realm of stope parameter design, adjusting the sublevel height is the least flexible aspect. In the caving method, the primary focus of design revolves around draw-point spacing and ore-draw layout, while for the open stope and fill mining methods, the central emphasis lies in the design of stope span. Pillar size primarily revolves around roof thickness and span research.

Stope parameter design is a comprehensive process that, built upon the selected mining method in a mine, encompasses not only factors related to rock mechanics but also considers economic and technical indicators, as well as the overall life-cycle planning of the mine. During the stope parameter design process, it is essential to thoroughly assess the significance of various factors and select the design considerations based on the working conditions.

The future of stope parameter design lies in an integrated approach, combining various methods and technologies. The design process presented in this paper comprehensively assesses the functional roles and merits of each design method, thus transcending the constraints of exclusively relying on a singular method for the design of stope structural parameters.

Optimizing stope structural parameters is a traditional method for mining companies to reduce costs and increase efficiency. In addition, this goal can also be achieved by optimizing mining processes, developing mechanized and intelligent mining equipment, and developing innovative mining methods.

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