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# Synergy Prediction Model of Information Entropy Based on Zone Safety Degree and Stope Roof Weighting Step Analysis

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**Abstract:** During the underground mining of coal resources, the rock pressure emerges acutely and the mine geological disasters occur frequently. It is of great significance to grasp the manifestation law of rock pressure in time to guide the safety production and operation in the pit. In this research, the calculation equations and concept of information entropy based on zone safety degree are primarily defined, and the synergetic theory of the maximum information entropy principle is combined to put forward the synergy prediction model of information entropy based on zone safety degree. In the meantime, the synergy prediction model of information entropy based on zone safety degree is employed to calculate and predict the first weighting step and the periodic weighting step of the main roof of the 9203 working face of Hengsheng Coal Mine in China's Shanxi Province, as well as verifying the validity and reliability of the synergy prediction model of information entropy based on zone safety degree by the comparison of similar simulation test results, which has presented a scientific basis for the effective control of rock pressure and roof management.

**Keywords:** rock pressure; stope roof caving; information entropy based on zone safety degree; synergetic theory; roof weighting step

**MSC:** 65Y99

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## 1. Introduction

With the continuously rising scale of coal mining, the geological disasters and safety problems in coal mines have become increasingly prominent, resulting in huge economic losses and casualties, which seriously threaten the social stability and harmony. Therefore, mastering the basic law of rock pressure appearance during the process of coal mining has become an urgent crucial problem to be solved in practical engineering [1–3].

Pan et al. [4] used the similar simulation test of physical material to analyze the mining pressure law of the overlying rock layers under the pre-mining and non-pre-mining conditions and conducted the on-site monitoring to determine the working resistance of the hydraulic support. Gao et al. [5] established a physical model of extremely thick coal seam under the condition of hard roof based on the similarity criterion, adopted the non-contact strain measurement system and resistance strain meter to monitor the overburden fracture structure, the supporting stress distribution and failure characteristics of coal mass, and revealed the mechanism of rock pressure induced by fracture of hard roof; Meanwhile, the effects of different levels of hard roof on rock pressure was monitored and analyzed by field measurement. Li et al. [6] employed the method of physical similarity modeling and field observation to study the fracturing migration law of the overlying rock during the mining process of extremely dense coal seam. Liu et al. [7] used the similar simulation test, the numerical simulation, the field measurement and other methods to

investigate the overburden rock movement and stress evolution law of the 12,401 working face in the Shangwan Coal Mine of Guoneng Shendong Coal Group Co., Ltd. in the Inner Mongolia Autonomous Region of China, which has provided the theoretical guidance for the development and utilization of extra-thick coal seam resources. Guo et al. [8] took the geological conditions and practical mining conditions of the 21,129 working face of Tucheng Coal Mine in China's Guizhou Province as the engineering background, and used the method of combination of similar simulation test and field measurement to study the evolution law of the stope fracture field, the stress variation trend of the roof fault and the migration characteristics of the overlying rock in the double-fault recovery process. Shi et al. [9] took the 1304 working face of Heba Coal Mine in China's Guizhou Province as the engineering background, adopted the method of combining the simulation test of similar material and field observation to explore the law of rock pressure, roof movement and falling, and obtained the first weighting step and periodic weighting step of main roof in the working face. Zhang [10] used the methods of theoretical analysis and similar material simulation test to study the stability of overburden structure and working resistance of support of fully mechanized caving face with large mining height in Baode Coal Mine in China's Shanxi Province. Wang et al. [11] utilized the similar material simulation method to investigate the development law of the water inrush channel with the hidden water-filled faults, verifying the progressive uplift theory and revealing the expansion law of the progressive uplift zone under the combined effects of rock pressure and the confined water of floor so that the possibility of water inrush can be judged. Yang et al. [12] studied the rock pressure appearance law of the stope under the occurrence of two faults in the first mining area of Zhengli Coal Mine in China's Shanxi Province through similar simulation, and explained the interaction law between mining and faults from the perspective of stress and strain rate. Ren et al. [13] adopted the method of similar simulation experiment to study the fracture characteristics of overburden rock in shallowly buried and deep longwall working face, grasping the key feature points through the mining process of overburden rock fracture in the longwall of shallowly buried coal seam and mastering the law between the working face pressure and the fracture development of overlying overburden rock combined with the field rock pressure measurement. Zhou [14] attained the influences of bedrock layer thickness on the rock pressure appearance of stope through field monitoring the pressure variations of support in the mining process of the 12,401 working face of Shangwan Coal Mine in the Inner Mongolia Autonomous Region of China. Du et al. [15] employed the mine digital manometer to continuously measure and analyze the working resistance of the working face support, and obtained the first weighting step and periodic weighting step of main roof in the 1041-2 working face of Taoyuan Coal Mine in China's Anhui Province, which has provided the reliable data and decision-making basis for mining production and management. Although the aforementioned similar simulation test method and mining pressure monitoring equipment can properly predict the manifestation law of the stope rock pressure, the similar simulation test has a long period, high cost and numerous human interference factors, which is difficult to completely reflect the practical situation of stope. In addition, the procurement cost of mining pressure monitoring equipment that is not prone to be installed and maintained performs high and it is hard to analyze the weighting situation of the entire working face roof.

During the underground mining of coal resources, the severe stope mining pressure emerges, which is prone to lead to underground mine geological disasters, such as the crush roof fall accident when the main roof is under pressure. It is of great importance to timely and accurately grasp the stope rock pressure manifestation law, which has become an essential scientific problem and engineering and technical issues. Based on this, the calculation equations and concept of information entropy based on zone safety degree are primarily defined, and a new prediction model of stope roof weighting step--the synergy prediction model of information entropy based on zone safety degree has been put forward combined with the synergetic theory of maximum information entropy principle. Simultaneously, the expression of the total excavation step of stope surrounding rock

instability is constructed and designed so that the zone safety degree can adapt to and match with the synergetic theory of maximum information entropy principle. Eventually, the synergy prediction model of information entropy based on zone safety degree is embraced to calculate and predict the first weighting step and the periodic weighting step of the main roof of the 9203 working face in Hengshen Coal Mine. In addition, the correctness and effectiveness of the synergy prediction model of information entropy based on zone safety degree are verified by an example, which has provided a scientific basis for stope roof management.

## 2. Information Entropy Based on Zone Safety Degree Using Mohr-Coulomb Criterion

Sign convention: the negative and positive values of the stress refer to the compressive stress and tensile stress, respectively, and the order of principal stress is $\sigma_1 \leq \sigma_2 \leq \sigma_3$, whereas the value range of internal friction angle can be determined as $0° \leq \varphi < 90°$.

In Figure 1, the geometric expression of the Mohr-Coulomb criterion can be obtained when the rock mass element is in the ultimate equilibrium state, i.e.,

$$AM - BM = 0 \tag{1}$$

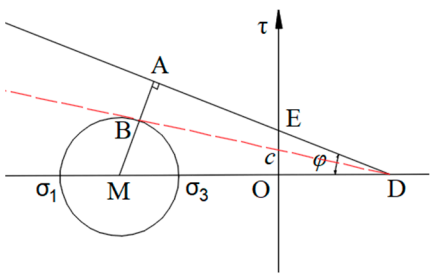


**Figure 1.** Mohr-Coulomb strength criterion.

The expression of Mohr-Coulomb criterion represented by the principal stress in Equation (1) above can be determined as:

$$\sigma_3 - \frac{1 - sin\varphi}{1 + sin\varphi}\sigma_1 - 2c\sqrt{\frac{1 - sin\varphi}{1 + sin\varphi}} = 0 \tag{2}$$

Make

$$f_s = \sigma_3 - \sigma_1 N_\varphi - 2c\sqrt{N_\varphi} \tag{3}$$

where

$$N_\varphi = \frac{1 - sin\varphi}{1 + sin\varphi} \tag{4}$$

where $\sigma_1$ depicts the minimum principal stress, $\sigma_3$ denotes the maximum principal stress, $c$ indicates the cohesion, $\varphi$ signifies the internal friction angle, and $f_s$ represents the zone shear failure safety degree. When $f_s < 0$, the rock mass element is in the stable state; At the time of $f_s \geq 0$, the shear yield failure will occur in the rock mass element.

For the case where the tensile failure of rock mass element is considered, the tensile yield expression of the Mohr-Coulomb criterion can be denoted as

$$f_t = \sigma_t - \sigma_3 \tag{5}$$

where $\sigma_3$ symbolizes the maximum principal stress, $\sigma_t$ refers to the tensile strength, and $f_t$ denotes the zone tensile failure safety degree. At the time of $f_t > 0$, the rock mass element is in the stable state, whilst $f_t \leq 0$, the rock mass element will undergo the tensile yield failure.

By introducing the definition of point safety degree in static load strength analysis, Lan [16] proposed the concept of zone safety degree in the slope engineering to quantita-

tively study the stability status of each region of complex slopes. If considering the cases for both shear yield failure and tensile yield failure of rock mass, the quantitative zone safety degree of Mohr-Coulomb yield criterion with tensile strength is adopted in this paper, i.e.,

$$\begin{cases} ZSD = \frac{AM}{BM} = \left(ccos\varphi - \frac{\sigma_3+\sigma_1}{2}sin\varphi\right)/\left(\frac{\sigma_3-\sigma_1}{2}\right) & (\sigma_3 \leq 0) \\ ZSD = min\left\{\frac{ccos\varphi - \frac{\sigma_3+\sigma_1}{2}sin\varphi}{\frac{\sigma_3-\sigma_1}{2}}, \frac{\sigma_t}{\sigma_3}\right\} & (\sigma_3 > 0) \end{cases} \tag{6}$$

where $ZSD$ refers to the zone safety degree of rock mass element. At the time of $ZSD > 1$, the rock mass element is in the stable state. When $ZSD = 1$, the rock mass element is near the failure state, whereas at the time of $ZSD < 1$, the rock mass element is in the state of failure. When $\sigma_3 > 0$, the element is in the tensile state, while the tensile strength of the general rock material performs to be smaller than the shear strength, so the zone safety degree has been taken from the smaller value of the two states.

Assuming the rock mass engineering system with given topological forms, boundary conditions and applied loads, a total of $n$ elements will enter the yield state, where the zone safety degree generated by the $i$th element is $q_i$, so the total zone safety degree of the rock mass engineering system can be signified as:

$$Q_{ZSD} = \sum_{i=1}^{n} q_i \tag{7}$$

Make

$$\lambda_i = q_i / Q_{ZSD} \tag{8}$$

So there is

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{9}$$

$$\lambda_i \geq 0 (i = 1, 2, \cdots, n) \tag{10}$$

Remarkably, the newly introduced physical quantity $\lambda_i$ is complete and non-negative, whose mechanical meaning represents the share of the zone safety degree of the $i$th element among the total zone safety degree, that is, $\lambda_i (i = 1,\ 2,\ \cdots,\ n)$ describes the distribution of zone safety degree in the rock mass engineering system. In order to comprehensively reflect the distribution of zone safety degree in different rock mass engineering systems, the information entropy function based on zone safety degree of rock mass engineering system $s$ can be defined as:

$$s = -\phi \sum_{i=1}^{n} \lambda_i ln(\lambda_i) \tag{11}$$

where $\phi$ generally symbolizes a constant of 1.

## 3. Synergy Prediction Model of Information Entropy Based on Zone Safety Degree

In accordance with the synergetic theory, the contributing factors of system evolution include two types: the control variables and the state variables. During the evolution process of any systems, the changes of many state variables can generally be expressed by a set of differential equations, while the coefficients of the state variables are the control variables. According to the critical behavior, the state variables can be divided into the fast variables and the slow variables. In general, the number of fast variables is huge, but it has little effects on the evolution of the system. Meanwhile, the number of slow variables is small, but they can control the evolution process of the system. In order to highlight the influences of slow variables on system evolution, Herman Haken et al. put forward the servo principle, and employed the adiabatic approximation method to eliminate the fast variables. At the same time, the maximum information entropy principle of non-

equilibrium phase transition is proposed, which has enabled the "synergetics" establishing its own mathematical theory and laid the foundation for its practical application [17–22].

In this paper, the Haken model [23,24] of two-dimensional system is applied to underground engineering to predict the instability step of surrounding rock and guide the safe production and operation of underground engineering. Hence, the expression of the Haken model for the two-dimensional system can be represented as follows:

$$\frac{ds}{dl_p} = as - sx \tag{12}$$

$$\frac{dx}{dl_p} = -\beta x + s^2 \tag{13}$$

where: $a \neq 0, \beta > 0$; $s$ denotes a slow variable, while $x$ signifies a fast variable; $l_p$ refers to the order parameter of excavation step under the plastic deformation of surrounding rock.

By eliminating the fast variable $x$ from the Equations (12) and (13), the following integral expression can be obtained:

$$x(l_p) = \int_{-\infty}^{l_p} e^{-\beta(l_p-\tau)} s^2(\tau) d\tau \tag{14}$$

That is

$$x(l_p) = \frac{1}{\beta} s^2 l_p - \frac{1}{\beta} \int_{-\infty}^{l_p} e^{-\beta(l_p-\tau)} 2\left(s\frac{ds}{dl_p}\right)_\tau d\tau \tag{15}$$

When the $s$ changes slowly, it can be treated as a small quantity, ignoring the integral term in Equation (15), and the following result can be attained:

$$x(l_p) = bs^2 l_p \tag{16}$$

where $b = 1/\beta$.

By substituting the Equation (16) into the Equation (12), the evolution equation of information entropy based on zone safety degree $s$ with the variation of excavation step $l_p$ of surrounding rock system in underground engineering can be obtained, i.e.,

$$\frac{ds}{dl_p} = as - bs^3 \tag{17}$$

The general solution of Equation (17) is denoted as:

$$s(l_p) = \sqrt{\frac{ae^{2al_p+2a\cdot C}}{1+be^{2al_p+2a\cdot C}}} \tag{18}$$

where $a$ and $b$ signify the undetermined coefficients, while $C$ represents the arbitrary constant.

In this research, the grey system method is adopted to accumulatively process the original sequence data of information entropy based on zone safety degree, so as to weaken the influence of random factors on the original sequence data of information entropy [25]. Let $s$ be the original non-negative sequence of information entropy based on zone safety degree, as well as generating the new sequence $s'$ after one accumulation, i.e.,

$$s = \{s(1), s(2), \cdots, s(n)\} \tag{19}$$

$$s' = \{s'(1), s'(2), \cdots, s'(n)\} \tag{20}$$

The expression for the new sequence created by a single accumulation can be determined as:

$$s'(i) = s'(i-1) + s(i) \tag{21}$$

The mean value to generate new sequence data is calculated from:

$$Z(i) = [s'(i-1) + s'(i)]/2 \tag{22}$$

Thus, the Equation (17) can be written as:

$$\frac{ds'}{dl_p} = as' - b\left(s'\right)^3 \tag{23}$$

The least square estimation method can be adopted to obtain the values of the coefficient $a$ and $b$ in Equation (23):

$$\begin{bmatrix} a \\ b \end{bmatrix} = \left(B^T B\right)^{-1} B^T E \tag{24}$$

where

$$B = \begin{bmatrix} Z(2) & -Z^3(2) \\ Z(3) & -Z^3(3) \\ \vdots & \vdots \\ Z(n) & -Z^3(n) \end{bmatrix} \tag{25}$$

$$E = [s(2), s(3), \cdots, s(n)]^T \tag{26}$$

Since $s(1) = s'(1)$, in virtue of substituting the initial value of the order parameter of excavation step $l_1$ and the corresponding initial value of accumulated information entropy $s'(1)$ into Equation (18), the special solution expression can be obtained:

$$s'\left(l_p\right) = \sqrt{\frac{a}{\frac{e^{2al_1}}{\left[\frac{(s'(1))^2}{a-b\times(s'(1))^2}\right]e^{2al_p}} + b}} \tag{27}$$

Indeed, the right-hand term of Equation (23) symbolizes the deformation rate of the surrounding rock. Therefore, the excavation step corresponding to the point with the largest deformation rate is taken as the instability excavation step of the surrounding rock system of underground engineering, and let

$$P = as' - b\left(s'\right)^3 \tag{28}$$

Make

$$\frac{dP}{ds\prime} = 0 \tag{29}$$

In this case, a maximum value $P$ is obtained, and the information entropy corresponding to the maximum value can be determined as:

$$s'\left(l_p\right) = \sqrt{a/(3b)} \tag{30}$$

By combining the Equation (27) and Equation (30), the expression of instability excavation step of the surrounding rock system in underground engineering can be attained, i.e.,

$$l_p^f = \frac{1}{2a} ln\left(\frac{a - b\times(s'(1))^2}{2b\times(s'(1))^2}\right) + l_1 \tag{31}$$

where: $l_1$ refers to the initial value of order parameter of excavation step under the plastic deformation of surrounding rock (is generally constant as 1); $l_p^f$ denotes the instability excavation step of surrounding rock.

After excavation in the underground space, the surrounding rock has a certain self-supporting capacity without yield failure. At this time, the surrounding rock is in the elastic deformation stage. However, with the increasingly expansion of excavation scope of underground space, the stress concentration of surrounding rock mass will become growingly evident, resulting in the yield failure of surrounding rock [26]. Thus, the total excavation distance of surrounding rock instability induced by underground engineering excavation comprises the ultimate excavation distance in the elastic stage and the unstable excavation distance in the plastic phrase, i.e.,

$$L = L_e + L_p^f \tag{32}$$

where: $L$ represents the total excavation distance of surrounding rock failure caused by underground engineering excavation; $L_e$ denotes the ultimate excavation distance before yielding of surrounding rock; $L_p^f$ refers to the unstable excavation distance after yielding of surrounding rock, whose value is determined by the unstable excavation distance $l_p^f$.

## 4. Stope Roof Weighting Step Analysis

To be more specific, with Dongzhuangliang in the south part and Luotuogou in the north part, the 9203 working face of Hengsheng Coal Mine of Linfen Tianyu Energy Development Co., Ltd. in China's Shanxi Province is located in the southwest of the mining well, whose corresponding ground is hilly terrain without any protection. The elevation of the ground is between +1347 m and +1396 m.

There is no magma intrusion and ancient riverbed scouring zone in the 9203 stoping working face of Hengsheng Coal Mine in China's Shanxi Province, and there may be subsidence columns. The overall structure is simple and stable. The coal and rock strata of 9203 working face are generally monoclinic, which performs higher in the northwest and lower in the southeast. The dip angle of the coal and rock strata is 1–8°, which belongs to a near-horizontal coal seam. The 9203 working face of Hengsheng Coal Mine in China's Shanxi Province is located in the coal seam 9–10, with an average thickness of 5.6 m and a working face length of 150 m, as depicted in Figure 2.

The roof of the 9203 working face only has a main roof, which is thick and hard. The main roof (the basic roof) is K2 limestone with an average thickness of 13.1 m, which belongs to a karst water-filled ore deposit with weak to medium water-rich, developed fractures, and calcite filling. In addition, the direct floor is mudstone with an average thickness of 1.86 m, and partially belongs to sandy mudstone. Moreover, the basic floor is mainly aluminum mudstone and limestone with an average thickness of 12.71 m, as exhibited in Figure 2.

In general, there are numerous factors that affect the mechanical properties of rock and rock deformation, such as the composition, texture and structure of rock, the confining pressure, the drainage conditions of groundwater, and mining sequence of working face. In order to provide the basic data for numerical simulation, it is necessary to determine the mechanical parameters of the 9203 working face and surrounding rock. In the light of the information of mechanical parameters presented in the field, and combined with the survey data and related engineering drawings, the physical and mechanical parameters of 9203 working face and surrounding rock are displayed in Table 1.

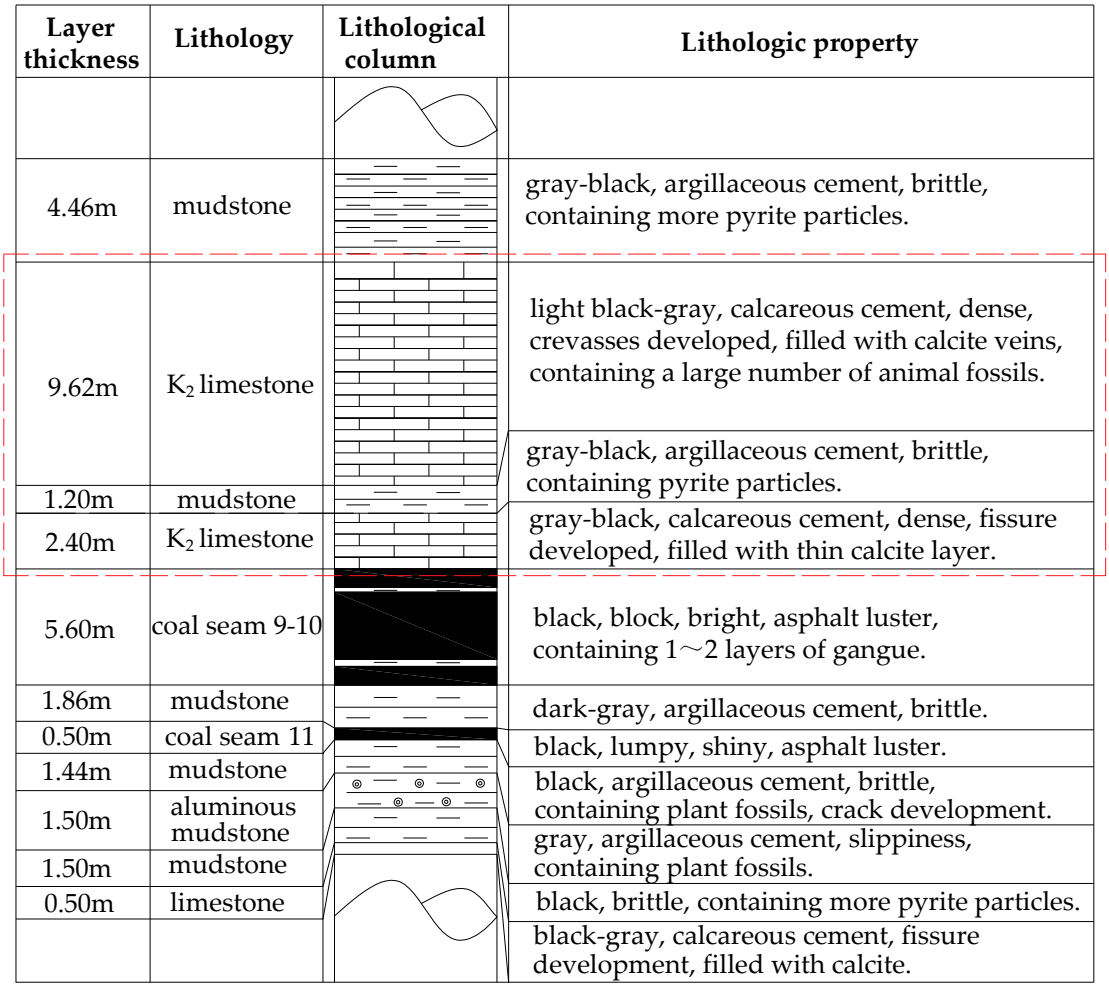


**Figure 2.** Integrated histogram of coal and rock strata.

**Table 1.** Physical and mechanical parameters of coal and rock strata.

| Lithology | Layer Thickness (m) | Density (kg/m$^3$) | Bulk Modulus (GPa) | Shear Modulus (GPa) | Cohesion (MPa) | Internal Friction Angle (°) | Tensile Strength (MPa) |
|---|---|---|---|---|---|---|---|
| mudstone | 4.46 | 2506 | 1.15 | 0.37 | 1.13 | 28 | 2.84 |
| limestone | 13.1 | 2778 | 45.3 | 11.3 | 17.1 | 53.2 | 6.55 |
| coal seam 9–10 | 5.6 | 1460 | 0.59 | 0.36 | 1.02 | 26 | 1.12 |
| mudstone | 1.86 | 2502 | 1.18 | 0.55 | 2.84 | 33 | 2.81 |
| aluminous mudstone | 12.71 | 2515 | 1.14 | 0.46 | 2.27 | 30 | 2.29 |

In order to obtain the activity law of the 9203 working face roof (exhibited as red dashed border in Figure 2) of Hengsheng Coal Mine in China's Shanxi Province of Linfen Tianyu Energy Development Co., Ltd., the synergy prediction model of information entropy based on zone safety degree is employed to calculate and predict the first weighting step and periodic weighting step of main roof of the 9203 working face, so as to provide the technical support for the safety production of the coal mining face. Hence, the prediction flow chart of numerical simulation and weighting step of the 9203 working face roof is depicted in Figures 3 and 4. There are 178,965 nodes and 869,477 units in the calculation model. In addition, the boundary conditions of the model signify that the vertical downward uniform load is imposed on the top surface, and the other five surfaces are fixed.

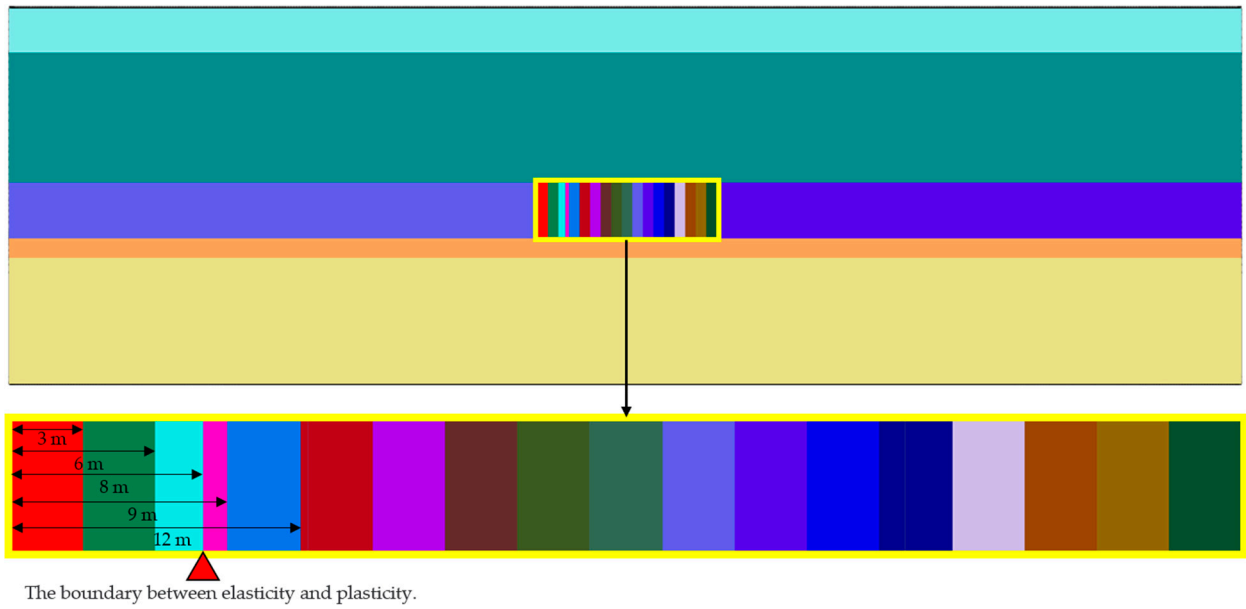


**Figure 3.** Geometrical model.

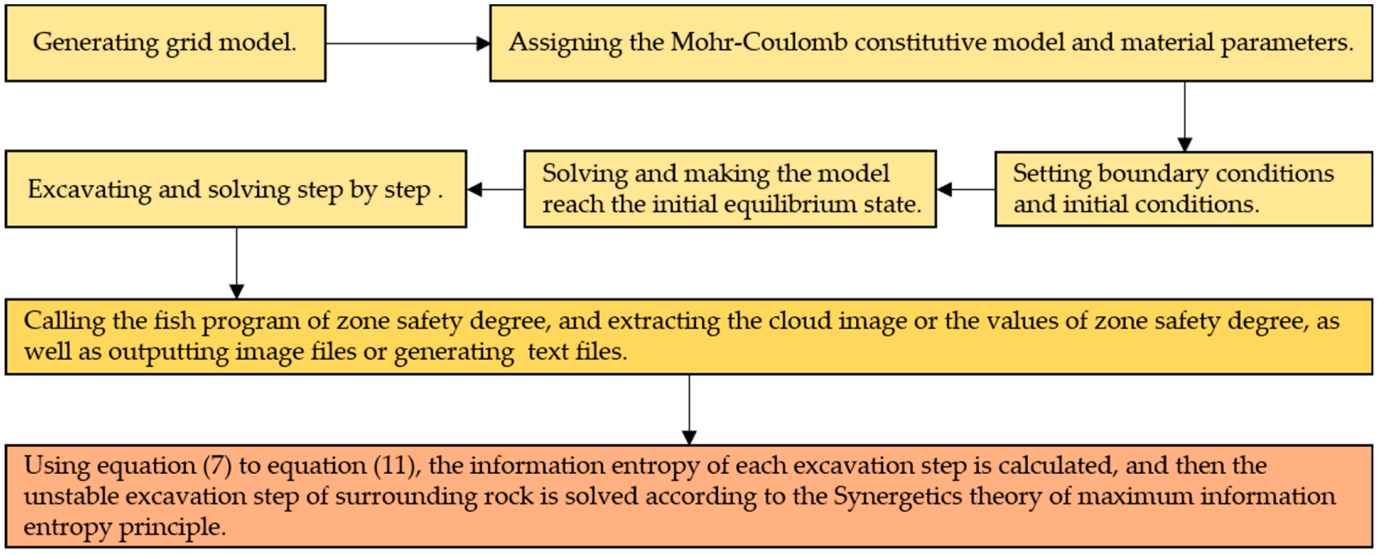


**Figure 4.** Prediction flow chart of weighting step of the 9203 working face roof.

With the mining of the 9203 working face, every advance of 3 m is an excavation, as shown in the lower left corner of Figure 3. When the first excavation of the 9203 working face refers to 3 m, the minimum zone safety degree of the working face roof (main roof) equals 2.7, as shown in Figure 5a. When the second working face is excavated to 6 m, the minimum zone safety degree of the roof is as much as 2.3, as shown in Figure 5b. When the 9203 working face is excavated to 8 m, the minimum zone safety degree of the roof is equal to 1.2, as shown in Figure 5c. However, when the 9203 working face is excavated to 9 m, the minimum zone safety degree value of the roof is equivalent to 0.9, as shown in Figure 5d. In line with the range significance of the aforementioned zone safety degree index, at the time of $ZSD < 1$, the rock mass element is in the state of failure. Therefore, the elastic ultimate excavation length of the 9203 working face equals 8 m, while the open-off cut length of the 9203 working face listed in literature [27] refers to 7.8 m, which is completely identical with the reality and has verified the correctness and reliability of the zone safety degree to solve the practical problems.

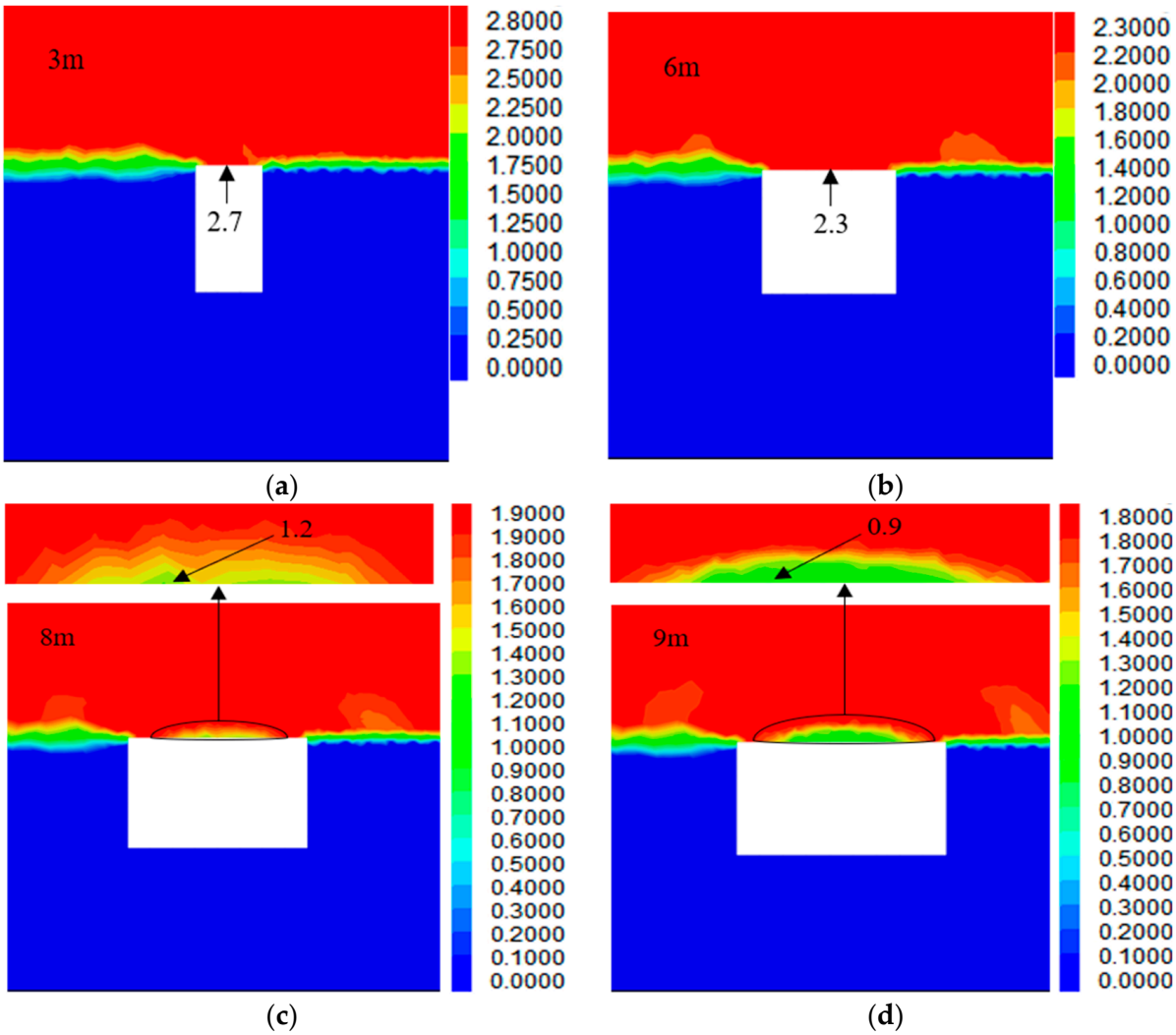


**Figure 5.** Cloud diagram of zone safety degree in elastoplastic critical states.

When the stoping of 9203 working face reaches 9 m, the yield failure of stope roof begins to appear, and the initial sequence number of the excavation step will be denoted as 1. Every advance of 3 m represents the next excavation step. For example, when the stoping of the working face reaches 12 m, the sequence number of the excavation step will be signified as 2, and so on, as exhibited in the bottom left corner of Figure 3. In the first place, the numerical value of the zone safety degree of the roof surrounding rock is extracted, and the information entropy based on zone safety degree of the main roof of the 9203 working face is calculated by the Equation (11), whose order parameters of excavation step and the corresponding information entropy based on zone safety degree are displayed in Table 2.

**Table 2.** Sequence data of information entropy based on zone safety degree.

| Excavation Step | Information Entropy | Excavation Step | Information Entropy |
|---|---|---|---|
| 1 | 6.9859 | 7 | 10.1274 |
| 2 | 8.4794 | 8 | 10.1718 |
| 3 | 9.2105 | 9 | 10.3171 |
| 4 | 9.5747 | 10 | 10.4581 |
| 5 | 9.8261 | 11 | 10.6255 |
| 6 | 9.9460 | 12 | — |

In accordance with the order parameters of excavation step and the corresponding data of information entropy based on zone safety degree in Table 2, $a$ = 0.2606 and $b$ = 0.000017385 can be calculated through the Equations (24)–(26). According to the Equations (27) and (28), the cumulative evolution curve and deformation rate curve of information entropy based on zone safety degree of main roof of the 9203 working face along with the excavation steps are obtained, as depicted in Figure 6. More apparently, the Figure 6 indicates that the synergy prediction result of information entropy based on zone safety degree is more similar to the result of Verhulst model, and the cumulative evolution curve manifests "S-shaped" (Logistic curve). Meanwhile, the deformation rate curve that exists a maximum value is shaped of upper convex. With regard to the Equation (31), the instability excavation step of the 9203 working face roof is attained as $l_p^f$= 10.65, which can be converted into the practical distance $L_p^f$= 29.95 m. Therefore, the first weighting step of the 9203 face main roof is $L = L_e + L_p^f = 8\text{ m} + 29.95\text{ m} = 37.95\text{ m}$. In line with the literature [27], the first weighting step of main roof of the 9203 working face equals 40 m by means of the similar simulation. In addition, the first weighting step of main roof of the 9203 working face obtained by the synergy prediction model in this paper is consistent with the result of similar simulation test.

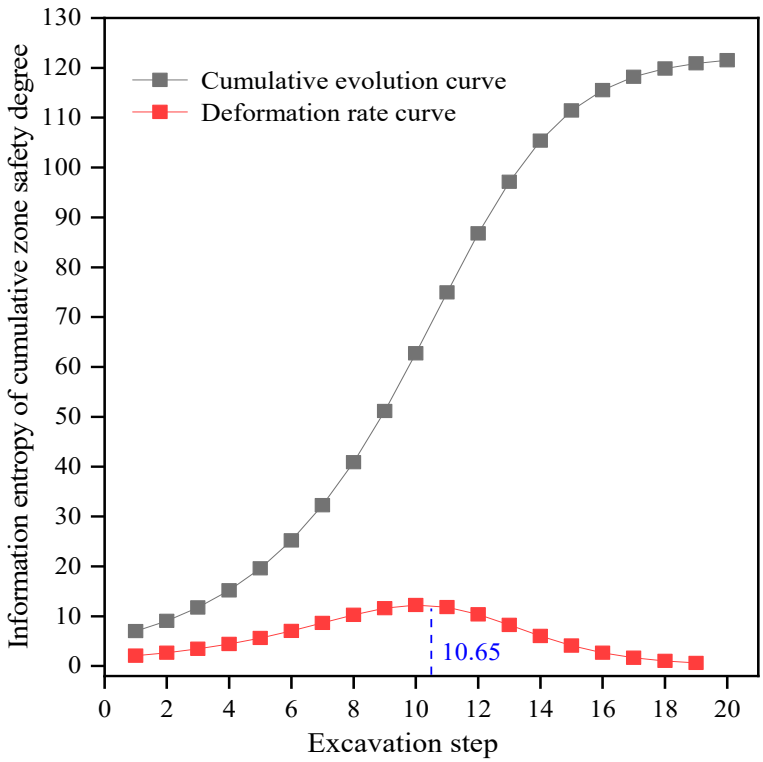


**Figure 6.** Prediction curve of weighting step of main roof.

Admittedly, the main roof is in the state of cantilever beam before the cycle pressure of the working face roof occurs, whereas the main roof is in the state of double support plate beam before the first pressure of the working face roof emerges. In the working face, the value of periodic weighting step is smaller than the one of first weighting step, while the former is equivalent to $(0.25 \sim 0.5)L$ [28,29]. Consequently, the periodic weighting distance of the 9203 working face roof in Hengsheng Coal Mine in China's Shanxi Province refers to 9.5–19 m.

## 5. Discussion

During the exploitation of underground coal resources, the stope roof caving is prone to result in the accidents, such as the casualties, the equipment damage, the production suspension and so on, which will bring about the severe harm to the production [30,31]. Therefore, the synergy prediction model of information entropy based on zone safety degree is put forward in this research to predict the first weighting step and the periodic weighting step of the main roof, and can grasp the basic law of rock pressure manifestation in stope roof, which will provide a scientific basis for the stope support and roof management.

Indeed, the theory of synergy prediction model of information entropy based on zone safety degree is deduced on the basis of the two-dimensional "Haken model", which can consider the extension and in-depth application of the external factor (the fluctuating force). However, it will obviously enable the establishment of the model more complicated and more difficult to be solved. Simultaneously, the synergy prediction model proposed in this paper is only applied to underground mining engineering, whose application scope needs to be further expanded. It can also be applied to slope engineering, tunnel engineering, deep underground disposal storage of nuclear waste and other construction projects for extending the application scope and examining its applicability.

## 6. Conclusions

(1) Under the condition of elastic deformation and plastic deformation of surrounding rock, the expression of total excavation distance of surrounding rock instability induced by underground engineering excavation is provided, which has made the synergetic theory calculate the instability excavation step expression of surrounding rock system in the plastic phase and addressed the problem of inadaptability of element information entropy and synergetic theory.

(2) In line with the synergetic theory of maximum information entropy principle, the concept and calculation equations of information entropy based on zone safety degree are defined, and the synergy prediction model of information entropy based on zone safety degree is proposed, as well as calculating and predicting the first weighting step and the periodic weighting step of the main roof in the working face, which has provided a scientific basis for the stope support and roof management.

(3) Taking the straight overburden roof with thick and hard layers of Hengshen Coal Mine in China's Shanxi Province as an example, the synergy prediction model of information entropy based on zone safety degree is embraced to calculate and predict the first weighting step and the periodic weighting step of main roof of the 9203 working face, which equals 37.95 m and refers to 9.5~19 m, respectively. Thus, the theoretical computation results are consistent with the simulating experimental results of similar materials, which has verified the validity and reliability of the synergy prediction model of information entropy based on zone safety degree.

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## References


1. Zhang, J.; Wang, B. Study on the bearing structure and stability of overlying strata: An interval gob in shallow buried coal mining of Northwest China. *Arab. J. Geosci.* **2021**, *14*, 255. [CrossRef]
2. Lv, H.Y.; Cheng, Z.B.; Liu, F. Study on the mechanism of a new fully mechanical mining method for extremely thick coal seam. *Int. J. Rock. Mech. Min.* **2021**, *142*, 104788. [CrossRef]
3. Yan, H.; Zhang, J.X.; Feng, R.M.; Wang, W.; Lan, Y.W.; Xu, Z.J. Surrounding rock failure analysis of retreating roadways and the control technique for extra-thick coal seams under fully-mechanized top caving and intensive mining conditions: A case study. *Tunn. Undergr. Sp. Tech.* **2020**, *97*, 103241. [CrossRef]
4. Pan, W.D.; Nie, X.D.; Li, X.Y. Effect of premining on hard roof distress behavior: A case study. *Rock. Mech. Rock. Eng.* **2019**, *52*, 1871–1885. [CrossRef]
5. Gao, R.; Yang, J.X.; Kuang, T.J.; Liu, H.J. Investigation on the ground pressure induced by hard roof fracturing at different layers during extra thick coal seam mining. *Geofluids* **2020**, *2020*, 8834235. [CrossRef]
6. Li, X.B.; He, W.R.; Xu, Z.H. Study on law of overlying strata breakage and migration in downward mining of extremely close coal seams by physical similarity simulation. *Adv. Civ. Eng.* **2020**, *2020*, 2898971. [CrossRef]
7. Liu, Y.J.; Wang, H.J.; Qi, Q.J.; Wang, A.H.; Zhao, Y.H. Dynamic evolution law of overburden rock in shallow-buried super-high fully mechanized working face and determination of support strength. *Shock. Vib.* **2021**, *2021*, 7649459. [CrossRef]
8. Guo, H.X.; Yu, W.J.; Liu, Y.; Li, K.; Kang, X.T.; Wang, C.; Leng, G.H. Mechanism of overlying crack-stress evolution when mining on the dual fault zone. *Geotech. Geol. Eng.* **2021**, *39*, 3729–3740. [CrossRef]
9. Shi, J.J.; Feng, J.C. Research on the regular of underground pressure by similarity simulation. *Geotech. Geol. Eng.* **2021**, *39*, 5359–5364.
10. Zhang, H.P. Analysis on stability of overburden structure and support resistance in fully mechanized top coal caving mining: Taking Baode Coal Mine as an example. *Coal. Sci. Technol.* **2022**, *50*, 48–53.
11. Wang, J.S.; Yao, D.X.; Huang, H. Critical criterion and physical simulation research on progressive ascending water inrush in hidden faults of coal mines. *J. China Coal Soc.* **2018**, *43*, 2014–2020.
12. Yang, T.; Zhang, D.Q.; Ning, T.H.; Li, S.; Zhao, Y.H. Study on characteristics of mining-induced pressure under existence of faults. *Chin. J. Undergr. Space. Eng.* **2017**, *13*, 1654–1660.
13. Ren, Y.F.; Ning, Y.; Qi, Q.X. Physical analogous simulation on the characteristcs of overburden breakage at shallow longwall coalface. *J. China Coal. Soc.* **2013**, *38*, 61–66.
14. Zhou, H.F. Research on rock pressure law of fully-mechanized mining face with ultralarge mining height influenced by thickness of bedrock layer. *Coal Sci. Technol.* **2019**, *47*, 173–179.
15. Du, F.; Yang, B.S. The application of KBJ-60 III-1 digital pressure gauge in mine pressure monitoring of single working face. *Ind. Mine. Automat.* **2007**, *2*, 51–52.
16. Lan, H. Analysis of zone safety degree of slopes and its application based on FLAC3D. *J. China Univ. Min. Technol.* **2008**, *37*, 570–574.
17. Hermann, H. Basic Concepts of Synergetics. *Appl. Phys. A Mater.* **1993**, *57*, 111–115.
18. Hermann, H.; Portugali, J. Information and Self-Organization II: Steady State and Phase Transition. *Entropy* **2021**, *23*, 707. [CrossRef]
19. Shannon, C.; Weaver, W. *The Mathematical Theory of Communication*; University of Illinois Press: Urbana, IL, USA, 1964; pp. 312–313.
20. Yu, S.W.; Huang, T.Z.; Liu, X.Y.; Chen, W.F. Information measures based on fractional calculus. *Inform. Process Lett.* **2012**, *112*, 916–921. [CrossRef]
21. Yu, S.W.; Huang, T.Z. Exponential weighted entropy and exponential weighted mutual information. *Neurocomputing* **2017**, *249*, 86–94. [CrossRef]
22. Krechmer, K. Relational measurements and uncertainty. *Measurement* **2016**, *93*, 36–40. [CrossRef]
23. Wu, D.J.; Cao, L.; Chen, L.H. *Principles and Applications of Synergetics*; Huazhong University of Science and Technology Press: Wuhan, China, 1990; pp. 72–73.
24. Xu, Q.; Huang, R.Q. Discussion on self-organizied characters in the course of slope development. *Chin. J. Geol. Hazard. Control* **1997**, *8*, 7–11.
25. Huang, R.Q.; Xu, Q. Synergetic prediction model of slope instability. *Mt Res.* **1997**, *15*, 7–12.
26. Wang, Q.; Jiang, B.; Pan, R.; Li, S.C.; He, M.C.; Sun, H.B.; Qin, Q.; Yu, H.C.; Luan, Y.C. Failure mechanism of surrounding rock with high stress and confined concrete support system. *Int. J. Rock. Mech. Min.* **2018**, *102*, 89–100. [CrossRef]
27. Li, X. *Study on Selection of Roadway Protection Mode and Surrounding Rock Controlling under Fracture Line of Thick Ha-Rd Roof*; Anhui University of Science and Technology: Huainan, China, 2015; pp. 22–31. Available online: https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4lQARvep2SAkVNKPvpjdBoadmPoNwLRuZz96sKGLU0W01HeITLaV_SuNGkQM0eySvzf1n2y8tIzQ&uniplatform=NZKPT (accessed on 18 September 2023).
28. Xu, Y.C.; Gao, Y.B.; Liu, S.Q.; Dong, J.P. Study on relationship between weighting and roof water inrush of mining face. *Coal. Technol.* **2014**, *33*, 14–17.
29. Jiang, D.H.; Gong, P.L.; Du, Z.D. Study of main roof weighting pace during the process of pillar extraction in chamber mining. *Coal. Technol.* **2014**, *33*, 144–146.

30. Smoliński, A.; Malashkevych, D.; Petlovanyi, M.; Rysbekov, K.; Lozynskyi, V.; Sai, K. Research into impact of leaving waste rocks in the mined-out space on the geomechanical state of the rock mass surrounding the longwall face. *Energies* **2022**, *15*, 9522. [CrossRef]
31. Malashkevych, D.; Petlovanyi, M.; Sai, K.; Zubko, S. Research into the coal quality with a new selective mining technology of the waste rock accumulation in the mined-out area. *Min. Miner. Depos.* **2022**, *16*, 103–114. [CrossRef]