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STRUCTURE MODEL OF ROADWAY WITH LARGE DEFORMATION AND ITS BASIC RESEARCH INTO ENGINEERING THEORIES

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Original scientific paper

With the increase in mining depths and the occurrence of worsening conditions, deep, large-scale and rapid mining may lead to more complicated dynamic features for tunnels, making them vulnerable to dynamic disasters such as rock bursts and coal/gas outbursts with subsequent heavy damage and casualties. A three-dimensional structural mechanics model for deep stopes was developed, and a dynamic disaster system model for deep mine tunnels was analysed and researched according to the catastrophe system theory; then the "large and small structural theory" of mining without coal pillars was presented, and a method for computing the range of "inner stress fields" was modified. At the same time, two structural mechanics models for tunnels, namely, "given deformation" and "finite deformation", were established and a new method of controlling dynamic disasters in tunnels is proposed. Such mining patterns can effectively absorb dynamic impact energy generated by the bending and fracturing of overlying strata. Research shows that in mining without coal pillars, large structures in the surrounding rock in the tunnel refer to strata within a "stress arch", while small structures refer to the roadside fillers, top coal, side coal, the immediate roof, baseboards and other anchoring structures, wherein the forces from the two above mentioned structures are sourced from the strata within the "stress arch", the roadside fillers force source is the fractured strata within the "breaking arch", and the side coal force source is the action of the strata within the "stress arch"; under the roadside filler mining pattern with reserved deformation, the load carrier (coal pillar or filler) only bears the load of the immediate roof within the bearing range, rather than the load applied by the movement of the overlying strata within the large structure; at the same time, it seals the tunnel and isolates the goaf, thus effectively preventing dynamic disasters such as rock bursts, etc.

Keywords: *deep mine, catastrophe system, control mode, mechanical model*

Model konstrukcije jamskog puta s velikom deformacijom i njegova temeljna istraživanja u inženjerskim teorijama

Izvorni znanstveni članak

S povećanjem dubina vađenja rude i nastanka pogoršanih radnih uvjeta, opsežno i brzo vađenje rude u dubini može voditi ka složenijim dinamičkim karakteristikama tunela, njihovom izloženošću dinamičkim nesrećama kao što su raspuknuće stijene te provale ugljena/plina koje dovode do velikih oštećenja i gubitaka. Razvijen je trodimenzionalni model mehanike konstrukcija za duboke iskope te se dinamički model za slučajeve nesreće u tunelima dubokih iskopa analizirao i istraživao u skladu s teorijom sustava katastrofe; zatim je predstavljena "velika i mala teorija konstrukcija" podzemnih iskopa bez stupova i modificirana je metoda izračuna raspona "polja unutarnjeg naprezanja". U isto vrijeme, postavljena su dva modela mehanike konstrukcija za tunele, odnosno "predviđena deformacija" i "konačna deformacija" i predložena je nova metoda praćenja dinamičkih nesreća u tunelima. Takvi načini vađenja rude mogu učinkovito apsorbirati energiju dinamičkog djelovanja razvijenu savijanjem i pucanjem gornjih slojeva. Istraživanje pokazuje da kod vađenja bez podgrađivanja jamskih prostorija stupovima, velike se konstrukcije u stijeni oko tunela odnose na slojeve u okviru "luka naprezanja", dok se male konstrukcije odnose na punila bočnih površina prolaza, ugljen na vrhu, ugljen sa strane, neposredno krovište, drvene podloge i druge uporišne konstrukcije. Izvor sila dviju gore spomenutih konstrukcija nalazi se u slojevima u okviru "luka naprezanja", izvor sile punila bočnih površina prolaza je u napuklim slojevima u okviru "lomnog luka", a izvor sile ugljena sa strana u djelovanju slojeva u okviru "luka naprezanja"; u slučajevima punila bočnih površina prolaza s rezerviranom deformacijom, nosač opterećenja (stup za podgrađivanje ili punilo) samo nosi opterećenje neposrednog krovišta u okviru raspona nosivosti, a ne i opterećenje nastalo pomicanjem gornjih slojeva u okiru velike konstrukcije; u isto vrijeme on hermetički zatvara tunel i izolira šupljinu ostavljenu nakon izvađenog ugljena te tako učinkovito sprječava dinamičke nesreće kao što je pucanje stijena, itd.

Ključne riječi: *duboki rudnik, funkcija praćenja, mehanički model, sustav katastrofe*

1 Introduction

The occurrence conditions of coal resources in China are poor, and production from underground mining accounts for over 90 % [1÷ 3]. Influenced by large scale mining in recent decades, shallow coal resources in the main coal-producing areas in the middle and eastern regions of China have been gradually exhausted [4, 5]. At present, the average mining depth in the main mining areas reaches around 700 m, with the depth increasing by 8 ÷ 12 m each year [6]. Therefore, deep coal mining and fully tapping limited energy resources can bring important economic and social benefits for the eastern regions [7, 8]. If these old mining areas are shut down due to the exhaustive exploitation of shallow coal, the resulting coal production gap cannot be filled, thus further intensifying the imbalance between coal supply and demand as well as the energy shortages in the developed eastern regions [9, 10].

Dynamic disasters in the deep mines include rock bursts, coal/gas explosions, and large deformations of the surrounding rocks in the tunnels, etc. However, the reasons and conditions for these disasters differ from one to the other [11].

There is no obvious macroscopic precursor for rock bursts, large roof pressures and mine earthquakes, and these disasters are characterized by burstiness, instantaneous vibratility and great destructive effects, making it difficult to determine the time, location and the strength of such events in advance. Several early warning and decision-making technologies [12 ÷ 14] focusing on dynamic disasters have been developed at home and abroad, and such early warning technologies are derived from a great deal of analytical investigations into dynamic disasters; however, due to great complexities and variables it is difficult to effectively control and prevent such disasters during the deep coal mining process [15, 16]. Therefore, there is an urgent requirement to improve mining technology, to change post-disaster prediction into pre-disaster control, and to reduce the possibility and severity of disaster accidents.

Mining without coal pillars represents an important direction for the sustainable development of coal resources, at the same time serving as an effective means of solving major disaster accidents during coal mining [17].

Mining patterns without coal pillars have great advantages for controlling major disaster accidents during coal mining, where the advantages in controlling accidents related to the advancement of the stope face include:

(1) Without the coal pillar, it is possible to prevent gas discharges due to the compression and destruction of the coal pillar during the process of advancing the stope face, as well as the accumulation of gas in the air return duct and the goaf at the upper corner of the stope face, thus avoiding related coal/gas accidents.

(2) Without the coal pillar, it is possible to avoid the concentrated stress and accumulated compressive elastic energy applied to the coal pillar at the front and back of the stope face during the process of advance and under conditions of entry protection; the possibility of hazardous rock bursts in the air return duct and the upper corner of the stope face can be eliminated, as well as the possibility of rock bursts and the bumping impact from coal/gas layers when digging the preparatory tunnel in the gravity stress field and tectonic stress field around the mining area.

Rock bursts not only cause serious personal safety problems, but also lead to property loss such as damage to supporting equipment and tunnel abandonment; moreover, they likely reduce the advancing speed of the working face and impact safe and efficient production at the working face [18].

(3) Without the coal pillar, it is also possible to avoid the fire disasters and gas explosions from air leakages when small coal pillars are destroyed by compression.

Coupled with the increase in mining depths in China, there are more disastrous dynamic accidents, such as rock bursts and gas explosions, causing serious casualties and property loss as well as seriously influencing the international image of the Chinese mining industry. However, there is still a lack of effective means and methods of control at home and abroad.

Therefore, research into the technology for mining without coal pillars is crucial for guaranteeing large-scale, safe and sustainable coal mining in China.

2 Macro-mechanical structural model of the stope

Given the engineering characteristics of the continuously advancing stope, namely, the continuous development of and changes to the mine ground pressure and the mine ground pressure behaviours, the rules affecting such changes are the same as those that govern stratum movements. Therefore, research into stress control in mines shall, by focusing on stratum movements, give top priority to the range of damage caused by overlying stratum movements during stope advancement and the characteristics of different structural components within that range, as well as the rules for movement and development [19]. The 3-D structure is shown in Fig. 1.

The strata overlying a coal bed can be divided into the spatial structures of overlying strata, and outside the overlying strata, of which the spatial structure outside the overlying strata refers to strata that have generated no obvious movement outside the "breaking arch". The spatial structure of the overlying strata is formed by the movement of the stratum structures within the "breaking arch" and has immediate impact on stress in the mine [20].

The double arch structure model is shown in Fig. 2.

Along with the advancement of the working face, the exposed space of the stope increases continuously, while the overlying strata also fractures continuously and in a staggered manner from bottom to top, forming a "breaking arch". At the same time, stress in the surrounding rocks of the spatial structure is redistributed, and the weight of the overlying strata which was originally loaded by mining coal at the working face is loaded instead onto the coal (or rock) on both sides. In such cases, the load supported by the coal (or rock) on both sides is sourced from two areas within a certain range: (1) the stress generated inside the coal (rock) by the weight of the overlying strata itself outside the "breaking arch"; (2) the stress transferred to the coal (rock) by the fractured strata within the “breaking arch” of the stope. A fracture may occur if the total stress loaded onto the coal (rock) exceeds its strength. Then, the peak abutment pressure will be transferred outwards. Strata fractures are always accompanied by this process, so the "stress arch" composed of the peak abutment pressure in the rock strata outside the "breaking arch" is formed, and the range of the "stress arch" continuously develops upwards as a parabola within the plane running perpendicular to the mining trend.

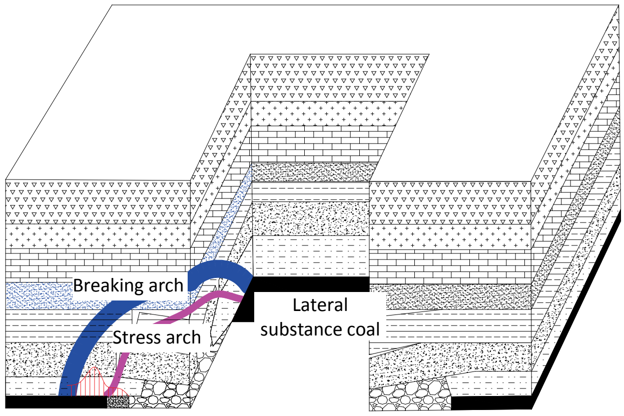


Figure1 Schematic diagram of three-dimensional structure

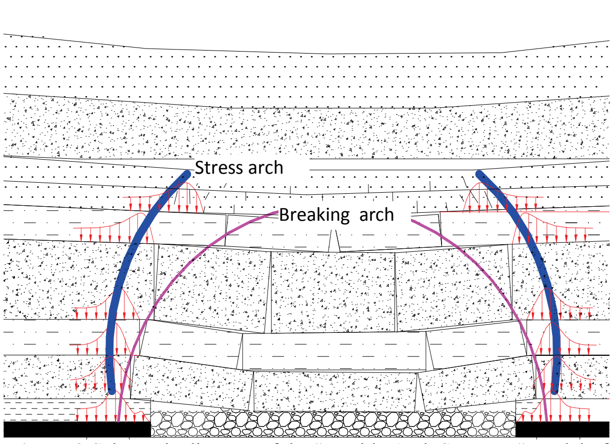


Figure 2 Schematic diagram of the "Double Arch Structure" model of a stope

The strata within the "breaking arch" play a leading role in the mine ground pressure behaviours of the stope, while the strata within the "stress arch" carry and transfer the loads of the overlying strata as the main load carrier. The "breaking arch" structure is located in the pressure relief areas within the "stress arch", and in cases of imbalance in the overlaying stratum structures within the "stress arch", major disaster accidents such as rock bursts will occur.

3 Catastrophe systems for mine roadways without coal pillars in deep mines

Large deformation is one of the major disaster response behaviours of rock systems surrounding roadways in deep mines. The causes and conditions associated with large deformation of roadway response behaviours is shown in Fig. 3.

Disaster accidents in deep mines are generated by the combined actions of a rock stress environment, surrounding rock structures and roadway support. The rock stress environment is determined by the buried depth of the coal bed, tectonic movements, the structure of the overlying strata, and the working face mining parameters; the surrounding rock structure is determined by the position of the coal bed and its sedimentary environment; the form and strength of the roadway supports are determined by current technology.

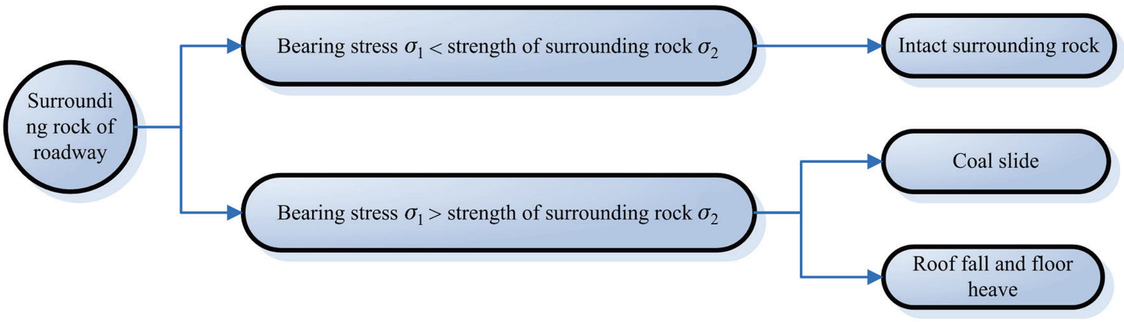


Figure 3 Causes of large deformation of roadway

Generally, the occurrence of disaster accidents (D) includes three factors: 1) a hazard-inducing environment (E), 2) hazard-causing factors (H), and 3) carriers (S). The relationship of these three factors is described as follows:

$$D = E \cap H \cap S, \tag{1}$$

where H is the sufficiency of hazard occurrence; S is the necessity of increase or decrease in disaster severity; E is the active factors affecting H and S.

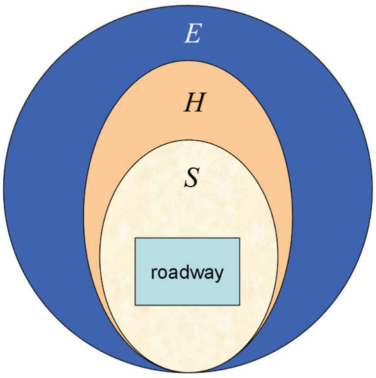


Figure 4 Roadway disaster system in deep mining

With regard to the occurrence of roadway disaster accidents in deep mines, the hazard-inducing environment (E) is represented by the range within the "stress arch", hazard-causing (H) is represented by the stress environment and the surrounding rock structure/strength, and the carrier (S) is represented by the surrounding rock of the roadway. The disaster system is shown in Fig. 4.

3.1 Surrounding rock structural mechanics model for mining without coal pillars in deep mines

Professor Hou Chaojiong at the China University of Mining and Technology put forward the stability principle concerning the large/small structure of gob-side entry driving with fully mechanized caving mining. The large structure refers to a relatively large-scale surrounding rock structure around the roadway, including top coal, the immediate roof, basic roof and load stratum acting on the basic roof; the small structure refers to the combined anchoring supports and the anchoring body composed of anchor rod and surrounding rock around the roadway. The large/small structure theory provides a theoretical basis for the successful application of gob-side entry driving in fully mechanized caving mining and anchoring support.

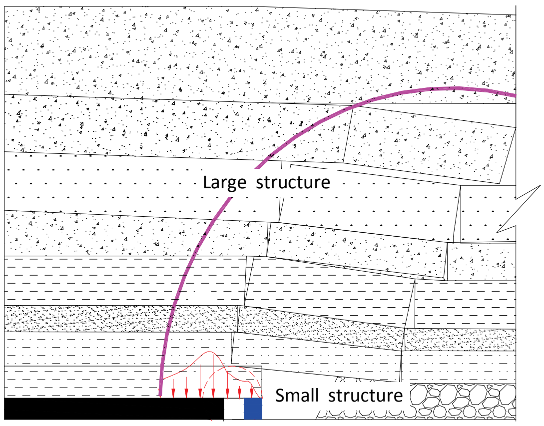


Figure 5 Mechanics model of "large/small structure" in mining without coal pillars

Surrounding rock structures in mining without coal pillars have their own unique features; therefore, the "large/small structure theory" is redefined based on the established mechanics model for mining without coal pillars.

Large structures in the rock surrounding roadways in mining without coal pillars refers to the strata within the "stress arch"; small structures refers to the roadside fillers, top coal, side coal, the immediate roof, baseboards and other anchoring structures, wherein the forces from the two above mentioned structures are sourced from the strata within the "stress arch", the roadside fillers force source is the fractured strata within the "breaking arch", and the side coal force source is the action of the strata within the "stress arch". The mechanical model is shown in Fig. 5.

3.2 Parameter determination of surrounding rock structural mechanics model

3.2.1 Mechanics parameter of the "External Stress Field"

It can be seen from study and analysis that the abutment pressure range of influence in front of the coal stope wall develops to its maximum when the stope advancing distance reaches the width of the working face. With the continuous advancement of the stope, the abutment pressure range of influence in front of the coal stope basically remains unchanged. Modelling is shown in Fig. 6.

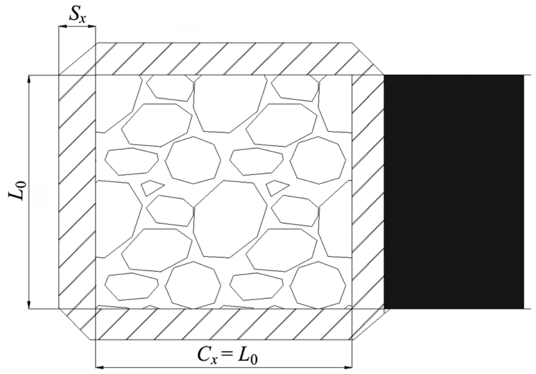


Figure 6 Diagram of abutment pressure range of distribution in stope digging

As shown in Fig. 6, when the stope advancing distance reaches the width of the working face, the overlying strata forms a pressure increase zone of width S_x around the stope under the effect of its own weight. Under the proviso that the gangue load capacity of the goaf is ignored, the equation (2) is established:

$$\begin{aligned}&(2L_0S_x + 2C_x|_{=L_0}\, S_x + 2{S_x}^2)(K_\mathrm{a}-1)\gamma H = \\ &= L_0C_x|_{=L_0}\,\gamma H - \frac{1}{2}\pi(\frac{1}{2}L_0)H_\mathrm{g}\gamma_\mathrm{g}C_x|_{=L_0}\end{aligned}, \tag{2}$$

where K_a is the mean value of stress concentration factor; H_g is height of stope "stress arch" (m); S_x is range of internal stress field.

The following is taken:

$$S_x = \frac{2L_0 \pm \sqrt{4L_0^2 + 2\dfrac{L_0^2H - 0{,}25\pi L_0^2 H_\mathrm{g}}{(K_\mathrm{a}-1)H}}}{2}.$$

Simplified to:

$$S_x \approx \left(\sqrt{1+\frac{4H-\pi H_\mathrm{g}}{8(K_\mathrm{a}-1)H}}-1\right)L_0. \tag{3}$$

3.2.2 Mechanics parameters of the "Internal Stress Field"

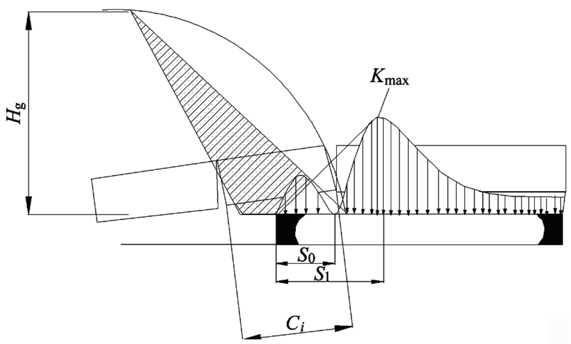


Figure 7 Calculation model for abutment pressure

(1) Stress Intensity

The "internal stress field" is calculated based on the assumption that the vertical abutment pressure distributed within the "internal stress field" on coal around the goaf is equal to the weight of the basic roof strata (plate) prior to the initial pressure on the working face. After formation of the "breaking arch", the dynamic structural mechanics model of stopes enters into a state of equilibrium, and the distribution range of "internal and external stress fields" remains stable. The equilibrium equation is as follows in Fig. 7:

$$\frac{\sigma_{y\,\max}}{K_{\max}\gamma H} = \frac{S_0}{2S_1}. \tag{4}$$

The following is taken:

$$\sigma_{y\,\max} = \frac{S_0K_{\max}\gamma H}{2S_1}. \tag{5}$$

Where S_0 is range of the "internal stress field" (m); $K_{\max}$ is stress concentration factor; H is mining depth (m); S_1 is distance between peak abutment pressure location and coal wall (m); γ is stratum unit weight (kN/m^3).

(2) Distribution range

From Fig. 7:

$$\frac{1}{2}\sigma_{y\,\max}S_0 = \frac{1}{2}\frac{H_\mathrm{g}C_i\gamma}{2}, \tag{6}$$

where S_0 is range of the "internal stress field" (m); C_i is cycle stress step of basic roof strata (m); $K_{\max}$ is stress concentration factor; H is mining depth (m); γ is stratum unit weight (kN/m^3); h_i is strata thickness of layer i (m).

The range of the "internal stress field" is obtained by substituting Eq. (5) into the Eq. (6):

$$S_0 = \sqrt{\frac{2C_i H_g S_1}{K_{\max} H}}. \tag{7}$$

4 Surrounding rock structural mechanics model for mining without coal pillars in deep mines

Coal-rock mass in deep mines is subjected to self-weight stress, tectonic stress and mining stress, so it withstands large loads and stores vast energy. If the pressure relief structural mechanics system is not adopted, the rock surrounding roadways may withstand relatively large dynamic impacts and easily generate rock bursts, gas rushes and other dynamic disasters during the bending and fracturing of stratum in "large structure" stopes; therefore, based on a full study and analysis of the surrounding rock structural mechanics model when mining without coal pillars, a new model of mining without coal pillars is proposed: the deformation allowance roadside backfill exploration technique.

With regard to the relationship between "surrounding rocks and support", the academician Song Zhenqi has proposed the two support design schemes of "finite deformation" and "given deformation", establishing a theoretical basis for selecting stope support. By expanding this concept to the roadway mechanics structure in deep mines, the "given deformation" under conditions of mining without coal pillars (namely, the location state during stable stratum movement within the "breaking arch" is determined by the strength of the strata and supporting conditions on both sides; during the entire process of strata end fracture settlement to their final position, the carrier can reduce only the movement speed of the overlying strata within a certain range, and cannot stop the movement of the overlying strata) and "finite deformation" under conditions of traditional mining (namely, the carrier necessarily restrains the movement of strata within the "breaking arch", and under the supporting action of the carrier, strata within the arch cannot settle to the lowest position; the state of strata in stabilisation is restricted by the supporting capacity of the carrier) have been separately established.

4.1 Traditional mechanics structure of mining without coal pillars, namely "finite deformation" mechanics structure

"Finite deformation" refers to a situation where the carrier withstands the load induced by overlaying strata movements within the large structure to support and protect the roadway. The mechanics structure is shown in Fig. 8

When the carrier works under the conditions of "finite deformation", there is a definite mechanical relation between the supporting force and the balanced position of broken strata within the "breaking arch", allowing the establishment of a mechanical relational equation between them.

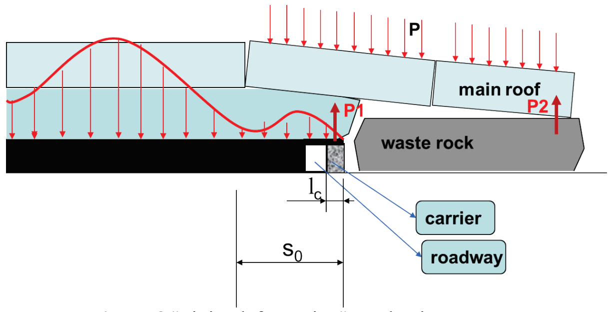


Figure 8 "Finite deformation" mechanics structure

Stress intensity within the "internal stress field":

$$\sigma_{y\max} = \frac{S_0 K_{\max} \gamma H}{2S_1}. \tag{8}$$

The strength of the carrier is greater than that of coal, and the carrier will withstand total loads prior to fracture.

Assuming the maximum bearing strength of the carrier is σ_c, and the width is l_c, then:

$$l_c \le S_0 = \sqrt{\frac{2C_i H_g S_1}{K_{\max} H}}. \tag{9}$$

Assume the bearing load of a unit area in the carrier is σ_{filling}, and the bearing force applied to the overlaying strata of the unit area within the "internal stress field" is σ_{internal}. The structural model of mining without coal pillars is the "finite deformation" mechanics model as illustrated in Fig. 8, and the acting force applied to the carrier $\sigma_{\text{filling}} \ge \sigma_{\text{internal}}$, namely:

$$l_c \sigma_{\text{filling}} \ge S_0 \sigma_{\text{internal}} = \frac{S_0^2 K_{\max} \gamma H}{2S_1}. \tag{10}$$

The following is taken:

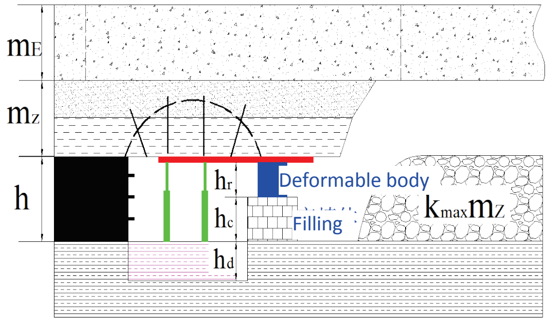
$$\sigma_{\text{filling}} \ge \frac{S_0^2 K_{\max} \gamma H}{2S_1 l_c}, \tag{11}$$

where S_0 is range of the "internal stress field" (m); C_i is basic roof strata cycle stress step (m); $K_{\max}$ is stress concentration factor; H is mining depth (m); γ is stratum unit weight (kN/m^3); H_g is height of the "breaking arch" (m).

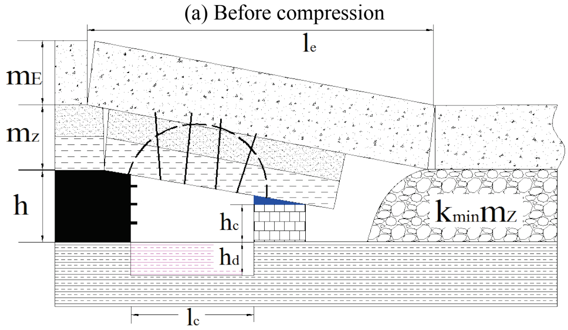
4.2 New mechanics structure of mining without coal pillars, namely "given deformation" mechanics structure

"Given deformation" refers to when the carrier (roadway protection coal pillar or filler) bears only the load of the immediate roof within the bearing range, rather than the load applied by the movement of the overlying strata within the large structure; at the same time, it seals the tunnel and isolates the goaf. The mechanics structure is shown in Fig. 9

The upper part of the carrier is filled with a deformable body to keep the carrier in full contact with the roof, for which the height of the deformable body is h_r, and the height of the filling wall is h_c; the decrement in the location of the carrier after the basic roof stably touches the gangue is Δh, and the bearing force is $\sigma_{filling}$.



(a) Before compression



(b) After compression

Figure 9 "Given deformation" mechanics structure

With the unit weight of the direct roof set as $\gamma_{directroof}$, and the thickness as h, then the bearing force of the carrier per unit length is $\sigma_{filling} = \gamma_{directroof} \cdot h$.

If the decrement in the location of the carrier when the basic roof touches the gangue is Δh_1, and the decrement in the location of the carrier after compaction of the gangue is Δh_2, then:

$$\Delta h_1 = \frac{l_c}{l_e}[h - m_z(K_{max} - 1)],$$
$$\Delta h_2 = \frac{l_c}{l_e}[h - m_z(K_{max} - K_{min})]. \tag{12}$$

Then

$$\Delta h = \Delta h_1 + \Delta h_2 = \frac{l_c}{l_e}[h - (K_{min} - 1)] \approx \frac{l_c}{l_e} h. \tag{13}$$

With the introduction of "finite deformation" conditions, rock surrounding the roadway will be subjected to a dynamic impact from the "large structure"; with disturbances from the overlaying strata layers, the energy stored in the coal-rock mass is easily released, leading to dynamic disaster accidents. Therefore, the new model of mining without coal pillars under the mechanics condition of "given deformation" is proposed since such a model can effectively absorb the dynamic impact energy during the bending and fracturing of overlaying strata in the "large structure", and effectively avoid roadway dynamic disaster accidents induced by mining disturbances.

5 Conclusion

(1) The stope model spatial structure is divided into the "breaking arch" of a moving stratum structure that directly affects the stress in the stope, and the stratum structure "stress arch" which generates no obvious movement. The roadside filler force source is the fractured strata within the "breaking arch" while that of side coal is from strata action within the "stress arch".

(2) Based on the mechanics equilibrium model, the mechanics parameters of the stress field have been resolved, and the solving formula for the distribution range of "internal and external fields" has been modified. Compared to the traditional algorithm, the range is expanded 1,4 times.

(3) The two mechanics structure models of "finite deformation" and "given deformation" are established, and the "deformation allowance roadside backfill exploration technique" – a new type of mining without coal pillars, is proposed. This confirms that the carrier (roadway protection coal pillar or fillings) bears only the load of the immediate roof within the bearing range, rather than the load applied by the movement of the overlying strata within the large structure; and at the same time it seals the tunnel and isolates the goaf.

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