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Article

A Study on the Calculation Method of Support Pressure in the Structure of Typical Upper Cladding Rock Formations

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Abstract: Aiming at the calculation problem of bearing pressure of typical overlying strata structure, in this paper, mechanical calculation, field monitoring and other methods are used to study the influence range of abutment pressure. Recently, many major rock burst accidents in working surface show that with the increase of mining depth and the change of overlying strata structure, the abutment pressure distribution has become one of the problems of safe mining. The influence range, distribution of high stress area and peak position of working surface support pressure need to be solved urgently; and through theoretical analysis, this paper reveals (whole rock single-layer structure, whole rock layered structure, whole rock single-layer structure—without arch in soil layer, whole rock layered structure—without arch in soil layer, whole rock single-layer structure—with soil arching, whole rock layered structure—with soil arching) the stress transfer mode, transfer size, and arching conditions of overlying strata in different areas. The mechanical system of abutment pressure calculation for typical overburden structure is established, which provides theoretical basis for mine optimization design scheme, mining sequence, and limited personnel distance.

Keywords: overlying rock structure; abutment pressure; rock burst; computing method

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1. Introduction

In recent years, with the increase of coal mining depth, rock burst and mine earthquake accidents occur frequently. This kind of impact often belongs to large energy disastrous impact accidents, causing serious casualties and property losses. At present, there is still a lack of effective theoretical basis for the influence range of abutment pressure of working surface and the influence degree of those areas within the influence range affected by the advance abutment pressure. Blind mining has led to a number of engineering cases of mining failure. For example, on 8 January 2017, a serious impact event occurred in a mine in Shandong Province during the mining of the working surface, which damaged the tunnel up to 70 m. Therefore, it has become one of the most concerned safety issues in coal mine to determine the advanced influence range of working surface and the advanced influence range.

Many scholars have done a lot of research on the influence range of abutment pressure, the mechanism of rock burst [1–3], and the risk assessment of rock burst, but the research on the influence of different types of overlying strata on abutment pressure distribution [4–14] is still less. Coal mining destroys the balance of original rock stress field and causes the concentration of abutment pressure of overlying strata near the coal wall. When the stress concentration exceeds the overall bearing capacity of working face, rock burst accident will occur [15,16].

According to different types of overlying strata structure, the roof structure can be divided into: whole rock single-layer structure, whole rock layered structure, whole rock single-layer structure without soil arching, whole rock layered structure without soil arching, whole rock single-layer structure with soil arching, and whole rock layered structure with soil arching. The stress transfer paths of overlying strata are different with different stratigraphic structures. Combined with field detection, engineering practice and stratigraphic structure characteristics, six stress transfer mechanisms of typical stratigraphic structures are established. It provides theoretical basis for mining design of working surface.

2. Structural Form of Overlying Strata in Working Surface

2.1. Whole Rock Layered Structure

The coal seam to the surface are all rock strata, and the overlying strata of the working surface are composed of multiple rock strata or multiple rock strata groups, which carry out stress transfer, which is called whole rock layered structure.

As shown in Figure 1, the overlying key strata are divided into N layers from 1, 2 . . . I . . . n, i represents the arbitrary number of overlying key strata, and n represents the total number of overlying key strata. With the continuous progress of the working surface, the lower strata are separated and fractured from the middle of the rock beam, which gradually expands from the bottom to the top, and the destruction occurs under the self-weight and the compressive stress of the overlying strata. When the span of the working surface reaches a certain value, the *i*-th stratum is fractured, and the stress analysis is carried out on the *i*-th stratum, The height of the *i*-th stratum is hi, and the abutment pressure of the coal body on the one side of the goaf σ consists of two parts, including self-weight stress σ_q and stress increment $\Delta\sigma$, namely

$$\sigma = \Delta\sigma + \sigma_q \tag{1}$$

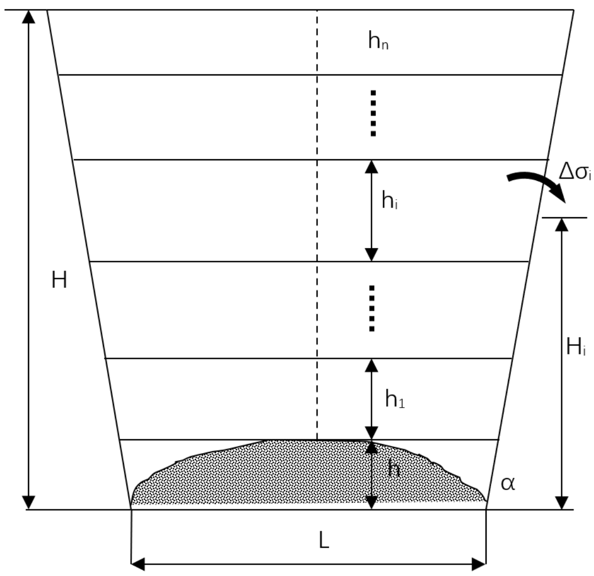

Figure 1. Diagram of stress transfer of whole rock layered structure. H—mining depth of working surface; h—caving height of goaf; hi—the height of the *i*-th stratum; L—width of goaf; α—rock movement angle; $\Delta\sigma$—stress increment transferred by the *i*-th stratum.

In Formula (1): $\Delta\sigma$ is equal to the sum of the stress increment formed by the load of the exposed part of the strata above the goaf or the load of the broken block transferred to one side of the coal body, namely $\Delta\sigma = \Sigma\Delta\sigma_i$; $\Delta\sigma_i$ is the stress increment formed by the load of the *i*-th hanging part of rock stratum or broken block transferred to one side of coal body, i = 1~n.

2.2. Whole Rock Single-Layer Structure

The coal seam to the surface is all rock strata. The overburden layer of the working surface consists of a single key rock layer or a single key rock stratum composed of multiple rock formations, the key rock layer or key rock stratum is an independent stress transfer unit, which is called the single layer structure of the whole rock.

As shown in Figure 2, the overlying key stratum is a single layer. With the continuous progress of the working surface, when the span of the working surface reaches a certain value, both ends of the key stratum crack. With the further progress of the working surface, the destruction occurs under the self-weight and the compressive stress of the overlying strata, and the central part of the key rock beam breaks. The increment of stress transmission is $\Delta\sigma$.

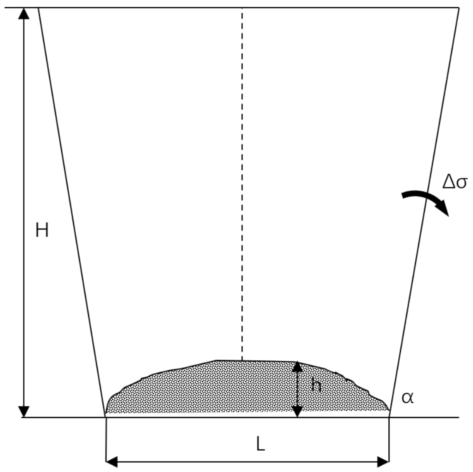

Figure 2. Schematic diagram of stress transfer of whole rock single layer structure. H—mining depth of working surface; h—caving height of goaf; L—width of goaf; α—rock movement angle; $\Delta\sigma$—Stress increment transferred by overlying strata of key strata.

2.3. The Structure of Overlying Strata Is "Rock-Soil" Composite Structure

The overlying strata are composed of "rock-soil" structure, with thick topsoil in the upper part and rock strata in the lower part. According to the deposition and bonding of topsoil, the stress transfer of topsoil can be divided into two types: arched structure and non-arched structure. According to the number of key layers, the lower strata can be divided into two types: the layered structure of the lower strata and the single-layer structure of the lower strata. The combination of the upper soil layer structure type and the lower rock layer type can be divided into four different types of overlying strata: the whole rock single-layer structure—without arch in soil layer, the whole rock layered structure—without arch in soil layer, the whole rock single-layer structure—with arch in soil layer, the whole rock layered structure—with soil arching.

2.3.1. The Type of Structure of Whole Rock Layered—Soil Structure without Arch

The layered structure of the lower strata is similar to the whole rock layered structure, but the upper soil layer structure itself cannot form the arch structure to transfer the stress, it can only transfer the self-weight of the soil layer to the lower rock mass first, and then transfer the stress indirectly through the arch structure formed by the lower rock mass, which is called the whole rock layered soil layer arch free structure type.

It can be seen from Figure 3 that there are 1, 2 . . . I . . . N key layers in the thickness H_0 of the lower strata, among which $\Delta\sigma_\mathrm{i}$ is the stress increment transmitted by the overlying strata of the *i*-th key layer, $\Delta\sigma'$ is the stress increment that the upper thick topsoil transfers the stress to the lower strata, and the stress increment transferred by the stress transfer arch formed by the strata, and the advance stress increment of the working surface is formed by $\Delta\sigma = \Sigma\Delta\sigma_\mathrm{i} + \Delta\sigma'$.

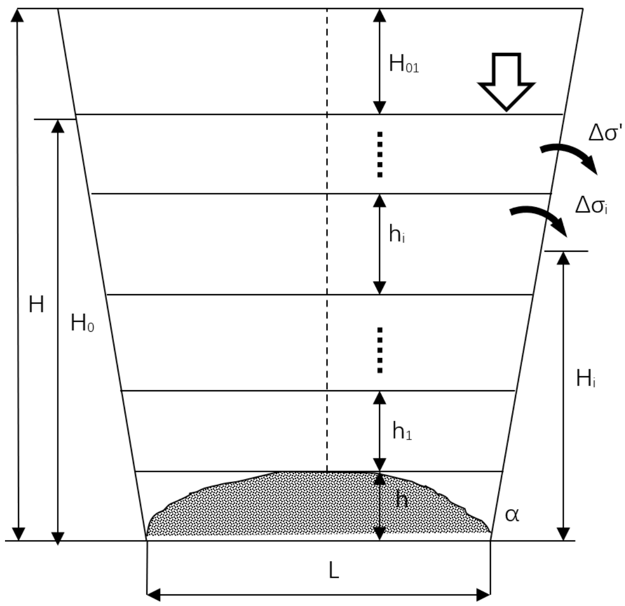

Figure 3. Stratification of the whole rock—no arched structure type. H—Mining depth of working surface; H_0—the thickness of the lower strata; H_{01}—the thickness of the upper soil layer; $\Delta\sigma'$—stress increment transmitted by upper soil layer.

2.3.2. The Type of Single-Layer Soil Structure—Without Arch in Whole Rock

The single-layer structure of the lower stratum is similar to that of the whole rock, and the stress transfer structure of the upper stratum is similar to that of the whole rock layered-soil arching structure.

It can be seen from Figure 4 that there is one key layer or group of key strata in the thickness H_0 of the lower strata, among which $\Delta\sigma$ is the stress increment transmitted by the overlying strata of the key stratum, $\Delta\sigma'$ is the stress increment that the upper thick topsoil transfers the stress to the lower strata, and the stress increment transferred by the stress transfer arch formed by the strata, and the advance stress increment of the working surface is formed by $\Delta\sigma = \Delta\sigma + \Delta\sigma'$.

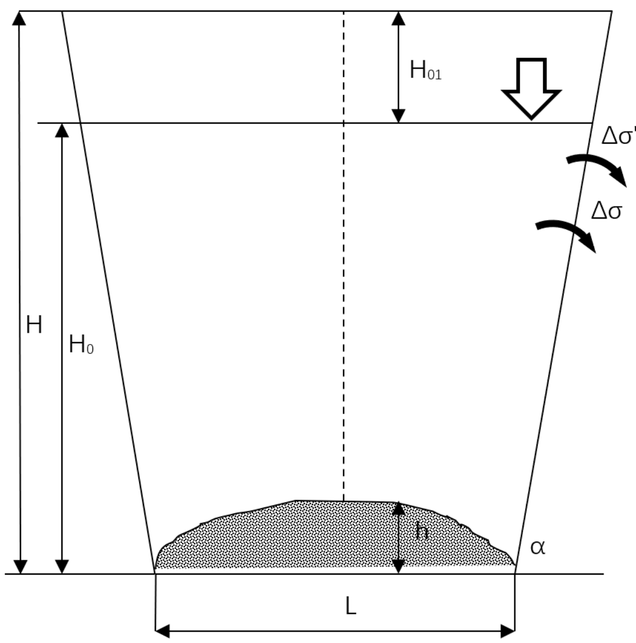

Figure 4. Single-layer structure of the rock—no arch structure type.

2.3.3. The Type of Whole Rock Layered—Soil Arching Structure

The stress transfer mechanism of the layered structure of the lower strata is similar to that of the whole rock layered structure. Because of the good deposition, strong cohesiveness and large enough thickness, the upper soil layer structure can independently form the arch structure to transfer the stress, and the stress formed by soil layer can be transferred to surrounding coal and rock mass through arch structure, which is called whole rock layered—soil arching structure type.

It can be seen from Figure 5 that the thickness H_0 of the lower strata has 1, 2 ... I ... N, and there are n key strata or key strata groups, and its stress transfer mechanism is similar to that of the whole rock layered structure, in which $\Delta\sigma_i$ is the stress increment transmitted by the overlying strata of the *i*-th key layer of the lower rock mass, $\Delta\sigma''$ is the upper thick surface layer that transmits the stress to the surrounding coal body through the arch structure formed by itself, and the arch structure formed by the soil layer transmits the stress of itself. The increment of the advance stress in the working surface is formed by $\Delta\sigma = \Sigma\Delta\sigma_i + \Delta\sigma''$.

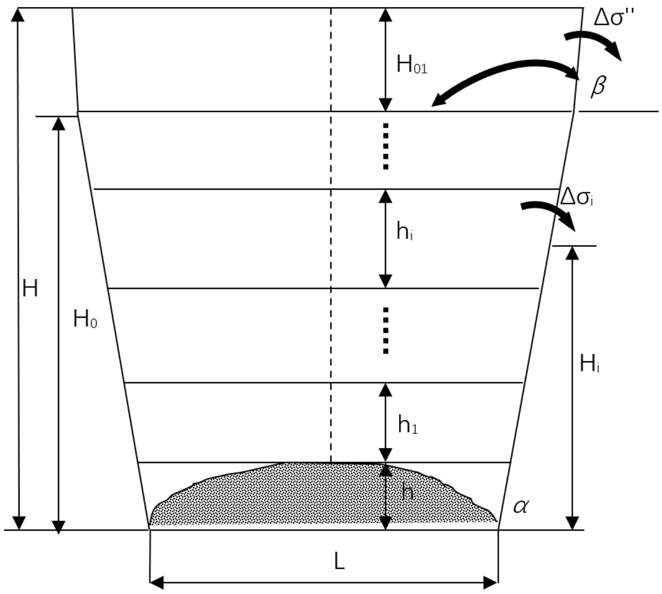

Figure 5. Stratigraphic stratification—soil layer into arch structure type. H—mining depth of working surface; h—caving height of goaf; h_i—the height of the i-th stratum; L—width of goaf; α—rock movement angle; H_0—the thickness of the lower strata; H_{01}—the thickness of the upper soil layer; $\Delta\sigma$—Stress increment transferred by overlying strata of key strata. β—Soil movement angle, $\Delta\sigma''$—stress increment transferred by soil layer.

2.3.4. The Type of Whole Rock Single Layer—Soil Arching Structure

The stress transfer mechanism of the single-layer structure of the lower strata is similar to that of the whole rock structure. The upper soil layer structure can independently form the arch structure to transfer the stress formed by the soil layer to the surrounding coal and rock mass through the arch structure, which is called the whole rock single layer—soil layer arch structure type.

It can be seen from Figure 6 that there is a key stratum or key strata group in the lower strata, and its stress transfer mechanism is similar to that of the whole rock single-layer structure, in which $\Delta\sigma$ is the stress increment transmitted by the overlying strata of the key stratum of the lower rock mass, $\Delta\sigma''$. The upper thick topsoil layer transmits stress to the surrounding coal and rock mass through the arch structure formed by itself, and transmits its own stress through the arch structure formed by the soil layer, and the advance stress increment of the working surface is formed by $\Delta\sigma = \Delta\sigma + \Delta\sigma''$.

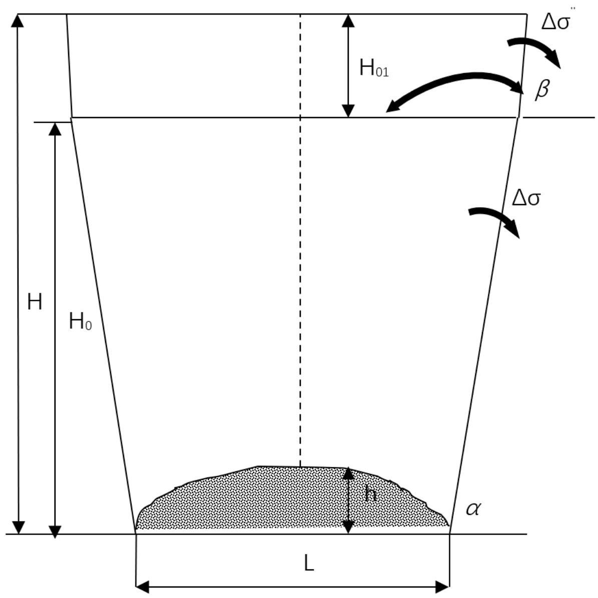

Figure 6. Single-layer structure of the whole rock—type of soil arch structure.

3. Calculation of Bearing Pressure of Different Overlying Strata

3.1. Stress Transfer Mechanism of Different Overlying Strata Structures

The structure type of overlying strata in goaf determines the mechanism of stress transfer from overlying strata to solid coal. Whether the overlying strata are in the whole rock layered structure or the whole rock monolayer structure, before the cracks at both ends of the overlying rock beam develop, the strata are in the fully suspended roof structure. Because the overlying strata are not fractured, as the key layer, the thick and hard rock strata of each formation take the rock mass on both sides as the fulcrum to bear the weight of the rock strata themselves and the upper strata. Therefore, it can be considered that the key stratum transfers 1/2 of its load to the surrounding coal and rock mass.

If the deposition of the soil layer is not complete, the cohesion is not enough, and the thickness is small, the upper soil layer structure cannot form an independent stress transfer arch, and the self-weight stress of the soil layer is transferred to the lower strata, and the stress is transferred by the stress transfer arch structure formed by the rock mass. If the soil layer has complete deposition, good cohesiveness, and large thickness, and it can form an independent stress transfer arch structure. At this time, the soil layer will transfer half of its own gravity to the surrounding rock through its own arch structure and arch foot.

For the strata, whether it is the whole rock layered structure or the whole rock single-layer structure, the stress increment formed by the load transferred from each key layer broken block to one side of the coal body is isosceles triangle distribution. For the soil layer without arch structure, the stress is transferred to the surrounding coal and rock through the arch structure formed by the lower rock mass. The stress transfer point of the soil layer is located at the soil rock interface, and the stress increment formed by the load transferred to one side of the coal body is isosceles triangle distribution. For the soil layer with arched structure, half of its stress is transferred to the surrounding rock mass through the arched structure formed by itself. The stress transfer point of the soil layer is located in the middle of the thickness of the soil layer, and the stress increment formed by the load transferred to one side of the coal body is isosceles triangle distribution.

3.2. Calculation of Bearing Pressure of Different Rock—Soil Structures

3.2.1. Calculation of Abutment Pressure When Rock Stratum Is Layered Structure

The angle α between the horizontal direction and the connecting line of the separation end on one side of the goaf is called the strata movement angle. The thickness of the i-th key layer is hi, and the distance from the coal seam is H_i. Abutment pressure of the working surface σ consisted of the self-weight stress σ_{qi} of overlying strata of working surface and the stress increment $\Delta\sigma_i$ transmitted from the overlying strata on both sides of the goaf, namely

$$\sigma = \Sigma\, \sigma_{qi} + \Delta\sigma_i \tag{2}$$

In Formula (2), self-weight stress σ_{qi} of overlying strata on working surface can be expressed as

$$\sigma_{qi} = \gamma x \tan\alpha \qquad [\frac{H_i - \frac{h_i}{2}}{\tan\alpha}, \frac{H_i + \frac{h_i}{2}}{\tan\alpha}] \tag{3}$$

In Formula (3), γ is the average unit weight of the overlying strata, H_i is the distance from the i-th key stratum to the coal body.

Stress increment $\Delta\sigma_i$ transferred from overlying strata of goaf to surrounding coal body is:

$$\Delta\sigma_{\mathrm{i}} = \begin{cases} \frac{2\sigma_{i\max} x \tan\alpha}{H_i} & [0, \frac{H_i}{2\tan\alpha}] \\ \frac{-2\sigma_{i\max} x \tan\alpha}{H_i}(x - \frac{H_i}{\tan\alpha}) & [\frac{H_i}{2\tan\alpha}, \frac{H_i}{\tan\alpha}] \\ 0 & [\frac{H_i}{\tan\alpha}, +\infty) \end{cases} \tag{4}$$

In Formula (4), in order to calculate the peak value $\sigma_{i\max}$ of stress transfer in the i-th key layer, according to the fact that the stress transmission is equal before and after, we can get the following results:

Half of the total stress of the i-th key layer:

$$\sigma_{iz} = \frac{1}{2}\gamma h_i \left[L + \frac{2H_i}{\tan\alpha}\right] \tag{5}$$

In Formula (5), σ_{iz} is 1/2 of the total stress of the i-th key layer.

Stress distribution of the i-th key layer transferred to the periphery is shown in Figure 7.

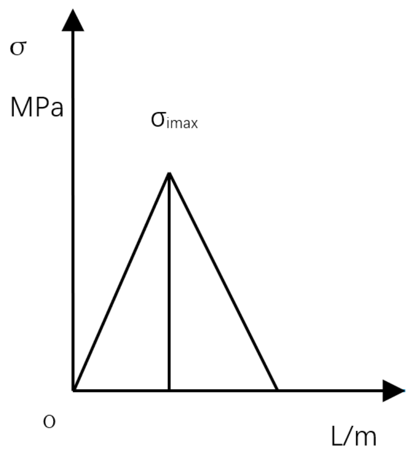

Figure 7. The stress distribution of the key layer of the i-th layer to the surrounding area.

The total stress transferred from the i-th key layer to the periphery:

$$\sigma_{iz} = \frac{\sigma_{i\max} \times 2 \times \frac{H_i}{2\tan\alpha}}{2} = \frac{\sigma_{i\max} H_i}{2\tan\alpha} \tag{6}$$

In Formulas (5) and (6), $\sigma_{i\max}$ can be concluded:

$$\sigma_{i\max} = \frac{\gamma h_i}{H_i}[L\tan\alpha + 2H_i] \tag{7}$$

3.2.2. Calculation of Abutment Pressure When Rock Stratum Is Single Layer Structure

When the stratum is single-layer structure, the thickness of the stratum is H_0, h is the height of the collapse zone. The calculation formula of the stress peak value $\sigma_{\max}$ of single structure stress of rock stratum transferred to coal body of working surface is as follows:

$$\sigma_{\max} = \gamma[L\tan\alpha + H_0] \tag{8}$$

In Formula (8), γ is the average unit weight of overlying strata, L is the width of goaf. Stress increment $\Delta\sigma$ transferred from overlying strata of goaf to surrounding coal body is

$$\Delta\sigma = \begin{cases} \frac{2\sigma_{\max} x\tan\alpha}{H_0} & [0, \frac{H_0}{2\tan\alpha}] \\ \frac{-2\sigma_{\max} x\tan\alpha}{H_0}(x - \frac{H_0}{\tan\alpha}) & [\frac{H_0}{2\tan\alpha}, \frac{H_0}{\tan\alpha}] \\ 0 & [\frac{H_0}{\tan\alpha}, +\infty) \end{cases} \tag{9}$$

In Formula (9), $\sigma_{\max}$ is the maximum value of the stress transferred from the single-layer structure to the periphery.

In Formula (10), self-weight stress σ_q of overlying strata on working surface can be expressed as

$$\sigma_q = \gamma x\tan\alpha \qquad [0, \frac{H_0}{\tan\alpha}] \tag{10}$$

3.2.3. Calculation of Bearing Pressure of Soil Structure without Arch

When the soil layer has no arch, the stress increment $\Delta\sigma'$ transferred from the overlying soil layer of the goaf to the surrounding coal body is:

$$\Delta\sigma' = \begin{cases} \frac{\sigma'_{max} x\tan\alpha}{H_0} & [0, \frac{H_0}{\tan\alpha}] \\ \frac{-\sigma'_{\max} x\tan\alpha}{H_0}(x - \frac{2H_0}{\tan\alpha}) & [\frac{H_0}{\tan\alpha}, \frac{2H_0}{\tan\alpha}] \\ 0 & [\frac{2H_0}{\tan\alpha}, +\infty) \end{cases} \tag{11}$$

In Formula (11), $\sigma'_{\max}$ is the maximum value of the stress transferred to the periphery when the soil layer has no arch.

When there is no arch in the soil layer, the calculation of the maximum value $\sigma'_{\max}$ of the stress transferred to the surrounding area is as follows.

According to the total stress conservation of soil layer, it can be known that: In Formula (12), 1/2 of the total stress of soil layer (TSS is the total stress of soil layer):

$$\sigma_{TSS} = \frac{1}{2}H_{01}\left[L + \frac{2H_0}{\tan\alpha} + \frac{H_{01}}{\tan\beta}\right] \tag{12}$$

In Formula (13), the total stress transmitted by the soil layer through the lower strata is

$$\sigma_{TSS} = \sigma'_{\max} \times \frac{H_0}{\tan\alpha} \tag{13}$$

Equation (14) can be concluded from Equations (12) and (13) simultaneously:

$$\sigma'_{\max} = \frac{H_{01}}{2H_0}\left[L\tan\alpha + 2H_0 + \frac{H_{01}\tan\alpha}{\tan\beta}\right] \tag{14}$$

3.2.4. Calculation of Bearing Pressure of Soil Structure When Soil Arching

When the overlying topsoil has "arching effect", that is, the thick topsoil can form an earth pressure arch, and the pressure arch bears the weight of all topsoil above the arch surface, and transfers the weight of topsoil to the uppermost key layer of bedrock and the front of coal wall through the arch foot of the pressure arch. The force transfer point of each rock beam structure in front of the working surface can be regarded as on the ac line, and the force transfer point of the earth pressure arch is c, as shown in Figure 8.

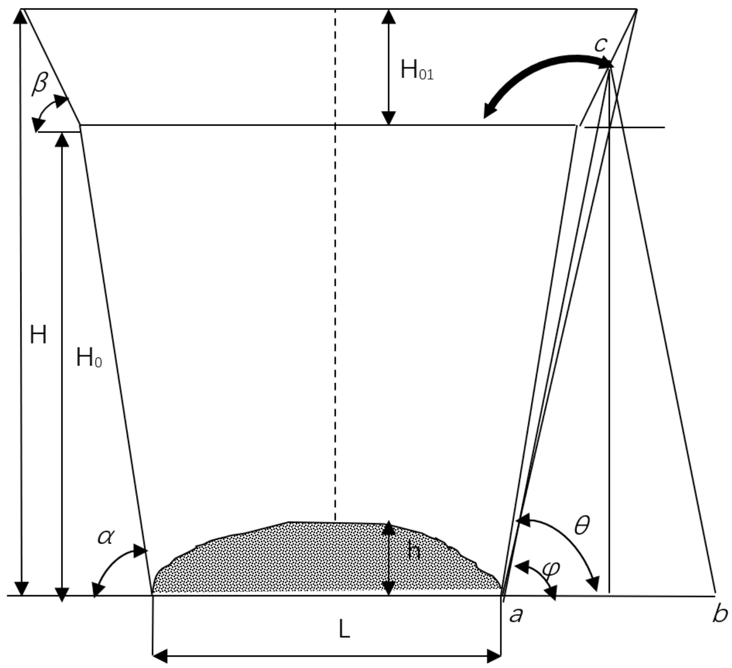

Figure 8. Calculation model of soil forming arch support pressure mechanics. φ—Soil stress transfer angle; ab—the range of soil stress transfer; c—the middle point of the soil layer (the stress transfer point of the soil arch); θ—boundary angle of topsoil.

According to the total stress conservation, the maximum abutment pressure of the earth pressure arch in the coal body is as follows:

$$\sigma_{\text{maxB}} = \left[\left(\frac{2H_0}{\tan\alpha} + L \right) + \frac{H_{01}}{\tan\alpha} \right] \times \frac{H_{01}\tan\varphi}{H_0 + \frac{1}{2}H_{01}} \tag{15}$$

In Formula (15), σ_{maxB} is the maximum abutment pressure of the earth pressure arch on the coal body in front of the working face; φ is the influence angle of bearing pressure of topsoil.

In Formula (16), abutment pressure $\Delta\sigma''$ of earth pressure arch on coal body in front of working surface is as follows:

$$\Delta\sigma'' = \begin{cases} \frac{\sigma_{\text{maxB}} x \tan\varphi}{H_0 + \frac{1}{2}H_{01}} & (0 \le x \le \frac{H_0 + \frac{1}{2}H_{01}}{\tan\varphi}) \\ 2\sigma_{\text{maxB}}\left(1 - \frac{x\tan\varphi}{2h}\right) & (\frac{H_0 + \frac{1}{2}H_{01}}{\tan\varphi} \le x \le \frac{2H_0 + H_{01}}{\tan\varphi}) \\ 0 & (x \ge \frac{2H_0 + H_{01}}{\tan\varphi}) \end{cases} \tag{16}$$

3.3. Calculation of Abutment Pressure for Six Typical Formation Structures

(1) Whole rock layered structure

$$\sigma = \Sigma\, \sigma_{qi} + \Delta\sigma_i$$

(2) Whole rock single-layer structure

$$\sigma = \sigma_q + \Delta\sigma$$

(3) Whole rock layered structure without soil arching

$$\sigma = \Sigma\, \sigma_{qi} + \Delta\sigma_i + \Delta\sigma'$$

(4) Whole rock single-layer structure without soil arching

$$\sigma = \sigma_q + \Delta\sigma + \Delta\sigma'$$

(5) Whole rock layered structure with soil arching

$$\sigma = \Sigma\, \sigma_{qi} + \Delta\sigma_i + \Delta\sigma''$$

(6) Whole rock single-layer structure with soil arching

$$\sigma = \sigma_q + \Delta\sigma + \Delta\sigma''$$

4. Problems and Discussion

In recent years, with the increase of mining depth, the structure of overlying strata is diversified, the way of stress transmission has changed substantially, and the distribution law of abutment pressure is also very different. The traditional calculation of abutment pressure distribution law has been unable to guide the safety production of coal mine. At present, the impact caused by the change of overlying strata structure is a kind of "secret" rock burst, which should be paid attention to; the accident shows that it can be used to evaluate and prevent rock burst:

(1) It is necessary to consider the influence of overlying strata structure when evaluating the impact risk area and risk of advanced working face.

(2) When one side of the adjacent working surface is mined out and a large coal pillar is left, and driving along the coal pillar, the distribution of supports should be considered to prevent the impact of driving.

(3) For the advanced support distance of working face, dangerous area classification and pressure relief mode of working face, the support distribution law should be considered to prevent roof fall and wall collapse due to insufficient support distance, to prevent heavy casualties caused by stress concentration due to insufficient pressure relief.

(4) In the area with impact risk, high strength metal mesh and anchor cable support must be used, and low strength materials such as double resistance mesh should be used carefully.

(5) The pressure relief must be in place to meet the requirements of "low density" and "low stress", and "low density" requires reasonable distance between boreholes. "Low stress" requires sufficient pressure relief.

(6) In this paper, the mechanical system of abutment pressure calculation of typical overlying strata structure is established. However, with the increase of mining depth and mining intensity, the change of abutment pressure of overlying strata structure is more complicated. In the future, the study of abutment pressure of overlying strata structure should pay more attention to the study of deep Wells and complex geological conditions.

5. Conclusions

This paper is based on the rock burst accidents caused by the change of abutment pressure distribution, which is caused by the change of overlying strata structure in recent years. The distribution law of abutment pressure of various strata types is studied by means of theoretical analysis and field detection, which provides a theoretical basis for the design of working surface anti scour mining and the prevention and control of rock burst; the main conclusions are as follows:

(1) According to the types of strata structure in different areas, the overlying strata of goaf can be divided into six typical strata structures: whole rock single-layer structure; whole rock layered structure; whole rock single-layer structure—without soil arching; whole rock layered structure—without soil arching; whole rock single-layer structure—with soil arching; whole rock layered structure—with soil arching.

(2) The abutment pressure calculation models of six typical formation structures are established to provide theoretical basis for mining design of working face.

(3) Based on the engineering background of xinjulong coal mine, it is theoretically calculated that the leading abutment pressure of working surface presents multi peak shape, the first peak is about 37 MPa, about 45 m away from the working face, the second peak is about 30 MPa, about 122 m away from the working face, and the influence range

of abutment pressure is about 244 m. Stress monitoring and microseismic monitoring are used to verify the distribution of abutment pressure.

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