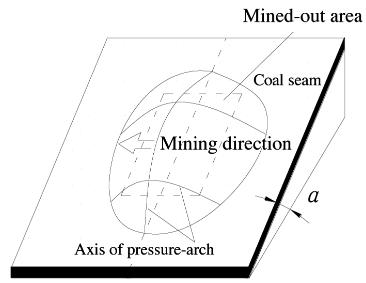
Instability mechanism analysis of pressure-arch in coal mining field under different seam dip angles



ANÁLISIS DE INESTABILIDAD DEL ARCO DE PRESIÓN EN UNA MINA DE CARBÓN BAJO DIFERENTES ÁNGULOS DE ESTRATOS HUNDIDOS

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RESUMEN

- Con el fin de estudiar el mecanismo de inestabilidad del arco de presión en una mina de carbón bajo diferentes ángulos de inclinación la veta, la estructura mecánica del arco de presión en la mina, se construye en base a la ingeniería práctica. El momento, corte y fuerza axial en cualquier sección del eje del arco de presión se obtienen a través su ecuación. A través de un análisis exhaustivo, se ha llegado a la conclusión de que toda la inestabilidad del arco de presión es causada por daño local y sus modelos de fallo son 3: fallo de la tensión de corte, fallo por cizallamiento y fallo de compresión. Los resultados muestran que, con el aumento del ángulo de la veta de carbón, los modos de fallo del arco de presión cambian de compresión de la falla en el arco de la cintura y de corte skewbacks fracaso en la rotura de la falla en la bóveda y la tensión de una falla en la parte delantera de skewback. Es importante el control de las partes más importantes y regular activamente la mina de acuerdo con criterio la inestabilidad del arco de presión en minas de pared larga.
- **Palabras clave:** Mina, arco de presión, mecanismo de inestabilidad, modos de fallo.

ABSTRACT

In order to study the instability mechanism of the pressure-arch in the mining field under different dip angles of the coal seam, the structure mechanics model of the pressure-arch in the mining field was built based on a practical engineering. The moment, shear, and axial force at any section of the pressure-arch axis are obtained through the pressure-arch axis equation. It is concluded that the entire instability of the pressure-arch is caused by local damage and the failure models of local damage has three forms, namely tension-failure, shear-failure and compression-failure through the comprehensive analysis. The results show that with the increase of the dip angle of the coal seam, the failure modes of the pressure-arch change from compression-failure at the arch-waist and shear-failure at the skewbacks to shear-failure at the vault and tension-failure at the front of skewback. It is important to control the key parts, and actively regulate the mine pressure according to the instability criterion of the pressure-arch in the longwall mining field.

Keywords: mining field, pressure-arch, instability mechanism, failure modes.

1. INTRODUCTION

With the development of mining science and technology, the longwall mining method is adopted more and more popular in mines in recent years. As indicated in Fig. (1), the longwall mining method along the strike was widely used in Kailuan Coal Mines in China. This mining method is mainly used for roof collapse easily gently inclined medium-thickness seam. The length of the coal face along the dip direction is generally 100-200 m, and the advancing length along the strike direction is generally 800-1200 m. After the underground coal was mined out in the inclined mining field, the pressure-arch with a dip angle was formed because of the self-regulating function of the surrounding rock, and the pressure-arch promoted and ensured the stability of the mining field [1, 2]. With the mining advancing, the cracks in the roof of the coal seam expanded and connected, and the immediate roof fell and the basic roof broke up, which led to that the stress peak area of the pressure-arch moved forward and the high stress area on the vault of the pressure-arch moved up. The pressure-arch of the mining field constantly moved forward along the direction of the working face advancing, and finally presented a symmetrical shape along the strike of the coal seam, but presented an asymmetric shape along the dip of the coal seam as shown in Fig. (2) [2]. The stress evolution of the pressure-arch and its stability problem both were the nonlinear problems.

In the past years, many scholars had conducted the relevant researches. For example,

B. Liu, et al. presented an analytical design method for the truss-bolt reinforcement system and analyzed the arching action by lateral behavior of the inclined roof bolts in reinforcing the fractured roof in coal mines [3]. X.P. Shao, et al. indicated that there was an unloaded arch structure existing in the overlying rock and believed that the range of the arch structure was a dynamic expanding process, which was also the reason of the mining pressure appearing on the working face [4]. Y.S. Xie, et al. had obtained the parameters about when the arch structure would be formed during the top coal caving process and discussed a new theory and technology of top coal caving with vibration to increase the top coal recovery ratio and to lower the waste content rate [5]. Y.F. Ren, et al. studied the instability criterion of the stress arch-shell of the surrounding rock in the mining filed, and believed that the stress arch-shell would eventually be instable when the mining height exceeded a certain value [6]. F. Du, et al. established the immediate roof's structural mechanics model of the longwall mining under thin bedrock and analyzed the forming mechanism and break laws of the semi-arch equilibrium structure of the immediate roof [7]. Y.P. Wu, et al. believed that the macro stress arch-shell of the pressure-arch showed an asymmetry arch shape in the large dip coal seam after the coal being mined-out, and deduced the shape equation of the stress arch-shell of the overlying rocks and put forward four kinds of instable modes [8]. Y.J. Xin, et al. found that the asymmetric caving arch was finally formed in top coal caving in the inclined coal seam by the numerical calculation and field observation of the roof movement [9]. B. Tikov, et al. conducted the laboratory tests to design and apply the paste backfill technology in the underground mine considering the arching effect of the stress in the mining field [10]. H. Alehossein presented a simple model for estimating potential maximum ground surface subsidence caused by underground coal mines based on a triangular zone of major caving, beyond which arching and within which caving was dominant [11]. M.D. Sinnott, et al. used three-dimensional discrete element to investigate the convective motion leading to arching in a vertically vibrated, deep granular bed [12]. A. Nierobisz proved that the reduction of costs between 24 and 57 % may be achieved in relation to arch support by the use of independent roof bolting in Polish coal mines [13]. A.K. Ghosh, et al. found the arch structure was formed in the caving process and analyzed a new method of vibration technique which was used to break the arch structure to improve the recovery rate in the longwall top coal mining [14].

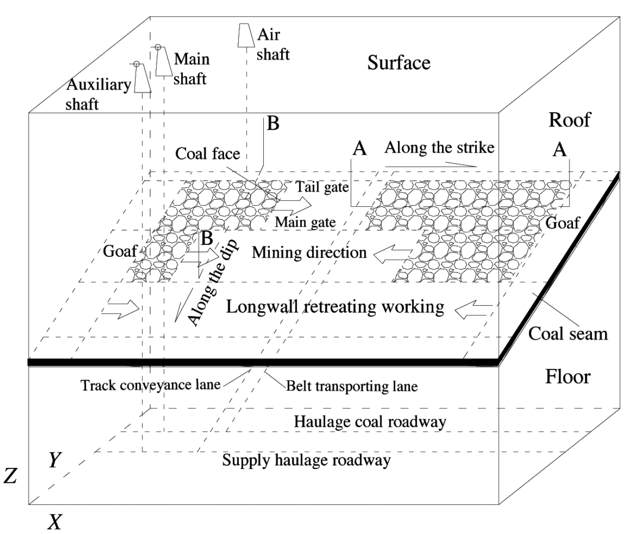
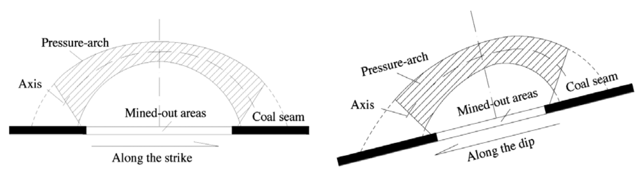


Fig. 1: The schematic drawing of the longwall mining method



(a) Section A-A (b) Section B-B

Fig. 2: The pressure-arch along the strike and dip respectively

In this paper, based on the previous results, taking the mining face of No. 9 coal of Fangezhuang of Kailuan Coal Mines as the engineering background and using the structural mechanics model, the instability mechanism of the pressure-arch in the mining field under different dip angles of the coal seam was analyzed, which was of some references and guiding significance for the safety construction of the coal mining.

2. MECHANICAL MODEL OF PRESSURE-ARCH AND ITS ANALYSIS

2.1 BUILDING MECHANICAL MODEL OF PRESSURE-ARCH

The coal production capacity of Fangezhuang Coal Mine is 4.0 Mt/a. The depth of the mining face of No. 9 coal is about 700 m and the average thickness of No. 9 coal is 3.5 m. The seam angle is mainly ranging from 5° to 15° (The local dip angle is nearly 45°). The length of the coal face along the dip direction is about 100 m, and the advancing length of the longwall mining along the strike direction is about 650 m. After the coal having been mined-out, the pressure-arch showed a skewed asymmetric shape along the dip of the coal seam with an inclined dip angle as shown in Fig. (2) [2].

Because of the complexity of the underground mining engineering, the inner and outer boundaries of the pressure-arch in the surrounding rock are not smooth but irregular even having relatively dislocation in the multilayer surrounding rock. In order to understand and treat the complex pressure-arch, the simplified axis of the pressure-arch model was carried out and the engineering model of the pressure-arch in the inclined mining filed was shown in Fig. (3). An asymmetric shape of the pressure-arch was shown in Fig. (4), which was obtained from making section along the dotted line in Fig. (3). According to the Protodyakonov's theory and the Rankine's theory [15], the rupture angle θ of the surrounding rock in Fig. (3) is defined as $\theta = 45^{0} + \frac{\varphi}{2}$, where ϕ is the inner friction angle of the surrounding rock in the mining field.

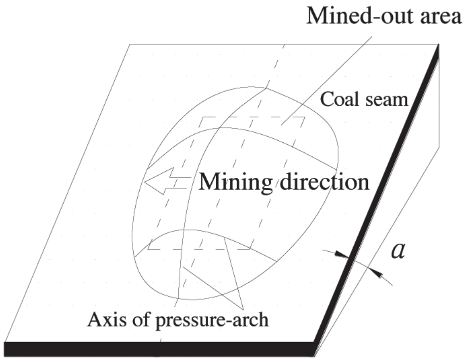


Fig. 3: The simplified engineering model of the pressure-arch

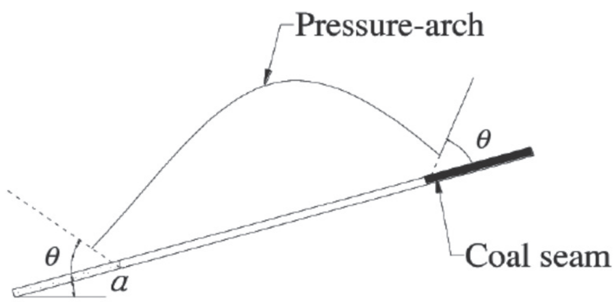


Fig. 4: The simplified pressure-arch along the dip direction

Combined with the structural mechanics model, the pressure-arch at the skewbacks can be seen as the hinge support, and since the strength on the vault may be insufficient the pressure-arch at the vault also can be seen as a hinged point. Therefore, in order to study the instability mechanism of the pressure-arch in the mining field, the axis of the pressure-arch can be assumed to be a three-hinged arch with the smooth parabola arch axis.

2.2 MECHANICAL ANALYSIS OF THE PRESSURE-ARCH

As shown in Fig. (5), the equation of the arch axis is defined as

$$y = ax^2 + bx + c \tag{1}$$

In order to simplify the computation, A (0, 0), B (L, h) and C (l_c, y_c) being defined, the hypothesis that point C is the middle point on a line along the x-axis as a special case of the pressure-arch. The angle between AB and the x -axis is α, the arch span is l which represents the length of the coal face along the dip direction and the height of the pressure-arch is defined as f. Then $L = l\cos\alpha$, $h = l\sin\alpha$, $l_c = \frac{l\cos\alpha}{2}$, $y_c = f + \frac{l\sin\alpha}{2}$ can be obtained.

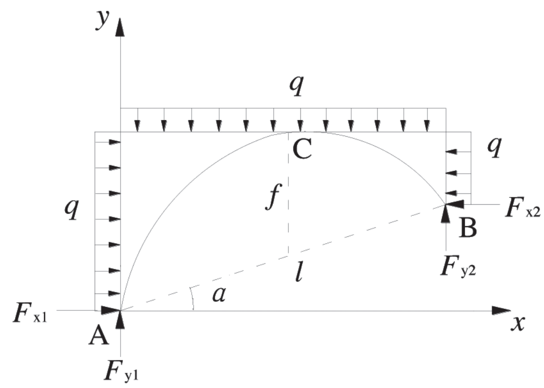


Fig. 5: The simplified mechanical model of the pressure-arch

Substituting the coordinate (0, 0), (L, h), (l_c, y_c) into Eq. (1), it yields the following equation:

$$\begin{cases} c = 0 \\ aL^2 + bL = h \\ al_c^2 + bl_c = y_c \end{cases} \tag{2}$$

The axis equation of the pressure-arch can be obtained by solving Eq. (2),

As shown in Fig. (3), suppose that the pressure-arch is forced by the uniformly distributed load q on the horizontal and vertical directions and the bearing reaction forces are F_{x1}, F_{y1}, F_{x2} and F_{y2}.

It's easy to get

$$y = -\frac{4\left[\left(f + \frac{l\sin\alpha}{2}\right)l\cos\alpha - l\sin\alpha\frac{l\cos\alpha}{2}\right]}{l^3\cos^3\alpha}x^2 + \frac{4\left[\left(f + \frac{l\sin\alpha}{2}\right)l^2\cos^2\alpha - l\sin\alpha\frac{l^2\cos^2\alpha}{4}\right]}{l^3\cos^3\alpha}x \tag{3}$$

$$F_{x1} = \frac{ql^2}{8f} - \frac{q(f + l\sin\alpha)}{2} \tag{4}$$

$$F_{x2} = \frac{ql^2}{8f} - \frac{q(f - l\sin\alpha)}{2} \tag{5}$$

$$F_{y1} = \left(\frac{ql^2}{8f} - \frac{qf}{2}\right)\tan\alpha + \frac{ql\cos\alpha}{2} \tag{6}$$

$$F_{y2} = -\left(\frac{ql^2}{8f} - \frac{qf}{2}\right)\tan\alpha + \frac{ql\cos\alpha}{2} \quad (7)$$

It is easy to obtain the moment, shear, and axial force at any section K for

$$M_k = \left[\left(\frac{ql^2}{8f} - \frac{qf}{2}\right)\tan\alpha + \frac{ql\cos\alpha}{2}\right]x - \left(\frac{ql^2}{8f} - \frac{q(f + l\sin\alpha)}{2}\right)y - \frac{q}{2}x^2 - \frac{q}{2}y^2 \quad (8)$$

$$Q_k = \left[\left(\frac{ql^2}{8f} - \frac{qf}{2}\right)\tan\alpha + \frac{ql\cos\alpha}{2} - qx\right]\cos\beta - \left[\frac{ql^2}{8f} - \frac{q(f + l\sin\alpha)}{2} + qy\right]\sin\beta \quad (9)$$

$$F_{Nk} = -\left[\left(\frac{ql^2}{8f} - \frac{qf}{2}\right)\tan\alpha + \frac{ql\cos\alpha}{2} - qx\right]\sin\beta - \left[\frac{ql^2}{8f} - \frac{q(f + l\sin\alpha)}{2} + qy\right]\cos\beta \quad (10)$$

Where β is the angle between the tangent of any section K and the x-axis.

3. FAILURE MODELS ANALYSIS OF THE PRESSURE-ARCH

Based on the formation mechanism and evolution characteristics of the pressure-arch in the mining field as well as the stability criterion of the three-hinged arch, the instability process of the pressure-arch is analyzed as shown in Fig. (6).

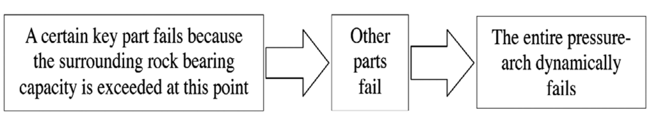


Fig. 6: The instability process of the pressure-arch

By analyzing the evolution characteristics of the pressure-arch and its mechanical structural features, it is derived that the vault, waists and skewbacks are the key parts of the pressure-arch in the mining field. And there are three forms of failure models in local damage, namely tension-failure, shear-failure and compression-failure. Such cases are the following:

(a) If the following mechanical condition is met, the tensile damage occurs.

$$\frac{F_{Nk}}{A_k} + \frac{M_k}{W_k} > \sigma_t \quad (11)$$

Where F_{Nk}, A_k, M_k and W_k are the axial force, the sectional area, the moment and the sectional flexural modulus at any section K, respectively. And σ_t is the tensile strength of the surrounding rock. The units of F_{Nk}, A_k, M_k, W_k and σ_t are N, m^2, N•m, m^3 and Pa, respectively.

(b) If the following condition is met, the compression failure occurs:

$$\frac{F_{Nk}}{A_k} - \frac{M_k}{W_k} > \sigma_c \quad (12)$$

Where σ_c is the compression strength of the surrounding rock.

(c) If the following condition is met, the shear failure occurs:

$$\frac{Q_k}{A_k} > \tau \quad (13)$$

Where Q_k is the shear of any section K, and τ is the shear strength of the surrounding rock.

4. INSTABILITY CHARACTERISTICS ANALYSIS OF THE PRESSURE-ARCH

In order to analyze the instability mechanism of the pressure-arch in the mining field under different dip angle of the coal seam, Eqs. (8), (9) and (10) are calculated for visualization using Matlab, and the resulting data is imported into graphics software Origin. The length of the coal face along the dip direction is set to 100 m and the seam angle is set to ranging from 0 to 50° in the simplified computation as an example.

4.1. VARIATION CHARACTERISTICS OF CURVES OF THE PRESSURE-ARCH

As shown in Fig. (7), when the dip angle of the coal seam was 0°, the shapes of the pressure-arch in the mining field were symmetrical to x=50 m. When the dip angle of the seam was not 0°, the pressure-arch displayed a skewed asymmetrical shape, and the greater the dip angle was, the more apparent the inclination of the pressure-arch was.

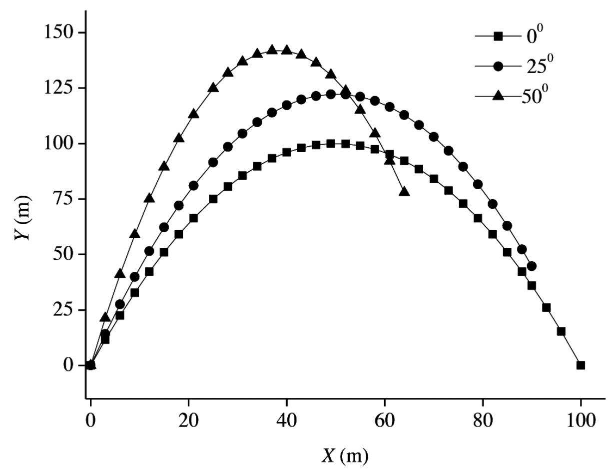


Fig. 7: Variation characteristics of the pressure-arch under different dip angles

As shown in Fig. (9), when the dip angle of the seam was 0°, the shear force curves of pressure-arch in the mining field displayed the centrosymmetric distribution. The shear at the skewbacks was greater than that at the vault and waists. Thus it is prone to create shear-failure at the skewbacks of the pressure-arch. When the dip angle of the seam was not 0°, the shear curves displayed an asymmetrical distribution. With the dip angle increasing, the shear force has significantly increased and the peak of shear force gradually shifted from the front skewback of the arch to the vault. Thus it is prone to create shear-failure at the vault of the pressure-arch.

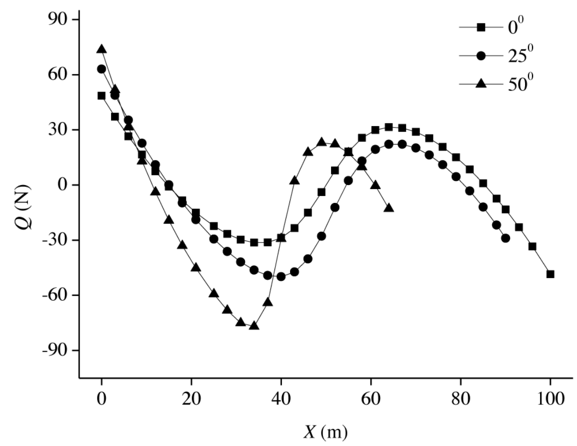


Fig. 9: Shear curves of the pressure-arch under different dip angles

4.2 VARIATION CHARACTERISTICS OF INTERNAL FORCES OF THE PRESSURE-ARCH

As shown in Fig. (8), when the dip angle of the coal seam was 0°, the bending moment curve of the pressure-arch in the mining field displayed a symmetrical distribution. The bending moment at the waists was greater than that at the vault and skewbacks, thus it is prone to create compression-failure at the waists of the pressure-arch. When the dip angle of the seam was not 0°, the bending moment curves displayed an asymmetrical distribution. Furthermore, with the dip angle increasing, the bending moment has significantly increased.

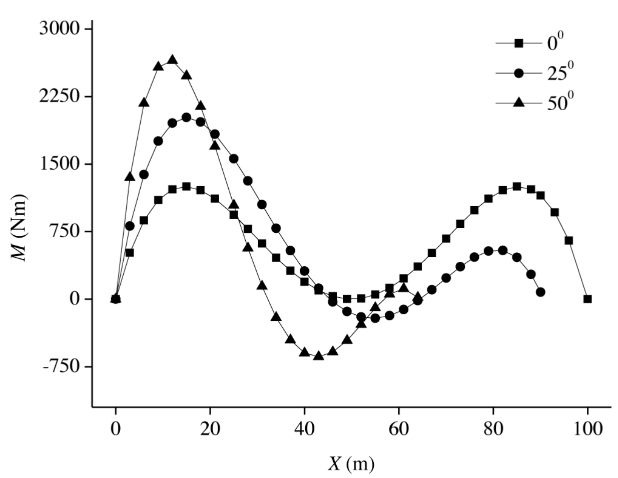


Fig. 8: Moment curves of the pressure-arch under different dip angles

As shown in Fig. (10), when the dip angle of the seam was 0°, the axial force was compression force and the axial force line in the mining field showed a symmetrical distribution. The axial force of the vault was greater than that at the waists and skewbacks. When the dip angle of the seam was not 0°, the axial force line showed an asymmetrical distribution. With the dip angle increasing, the tension force appeared at the front skewback of the arch, and significantly increased. Therefore, it can be seen that the tension-failure is prone to create at the front skewback.

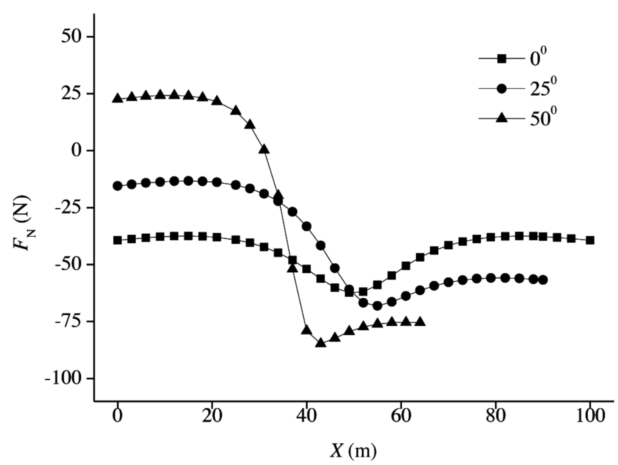


Fig. 10: Axial force curves of the pressure-arch under different dip angles

5. CONCLUSIONS

The mechanics model of the pressure-arch in the mining filed was built and analyzed, the arch axis equation and the bending moment, shear force, and axial force at any section are obtained. According to the formation mechanism and evolution characteristics of the pressure-arch in the mining field as well as the instability criterion of the pressure-arch, there are three forms of failure models, namely tension-failure, shear-failure and compression-failure.

When the dip angle of the seam was 0°, the pressure-arch in the mining field is prone to create compression-failure at the waists and shear-failure at the skewbacks. With the dip angle increasing, the internal force of the pressure-arch displayed an asymmetrical distribution. It is easy to create shear-failure at the vault and tension-failure at the front skewback and at last the local damage causes the entire structure dynamic instability.

In order to obtain the greatest benefit from the roof periodic caving and the support of the mining roadway, it is important to make full use of the capacity of self-bearing and transferring other loads of the pressure-arch, control the key parts of the local damages, and actively regulate the mine pressure according to the instability criterion of the pressure-arch in the longwall mining field under different seam dip angles.

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