B. Y. Hao[1], S. Y. Hu[1], J. Cheng[2], H. Huang[3], K. Wang[4], L. X. Kang[1]

1 – College of Mining Engineering, Taiyuan University of Technology, Taiyuan, Shanxi 030024, P.R. China
2 – State Key Laboratory of Coal Resources and Mine safety, China University of Mining & Technology, Xuzhou Jiangsu 221116, P.R. China
3 – College of safety Engineering, Chongqing Vocational Institute of Safety & Technology, Chongqing 404000, P.R. China
4 – College of Mining Engineering, Shanxi Institute of Technology, Yangquan, Shanxi 045000, P.R. China

FAILURE MECHANISM ANALYSIS ON HANGING ARCH ROOF CAVING AT END OF UNDERGROUND COAL WORKING FACE

Б. Ю. Хао[1], С. Ю. Ху[1], Дж. Чен[2], Х. Хуан[3], К. Ван[4], Л. С. Кан[1]

1– Гірничий інженерний коледж, Тайюаньський технологічний університет, Тайюань, Шаньсі, Китайська народна республіка
2 – Державна лабораторія безпеки праці в гірничій промисловості та видобутку вугілля, Китайський університет гірничої промисловості та технології, Сюйчжоу Цзянсу, Китайська народна республіка
3 – Коледж розробки засобів забезпечення безпеки, професійний інститут безпеки праці та технології, м. Чунцин, Чунцин, Китайська народна республіка
4 – Гірничотехнічний коледж, Шаньсійськкій технологічний інститут, Янцюань, Шаньсі, Китайська народна республіка

АНАЛІЗ ПОЛОМОК МЕХАНІЗМУ ПІДВІСНОГО АРОЧНОГО СКЛЕПІННЯ НА ПОЧАТКУ ОЧИСНОГО ВИБОЮ ПІДЗЕМНОЇ ВУГІЛЬНОЇ ВИРОБКИ

Purpose. Understanding the hanging arch distance of the roof in the curved triangle area at the end of an underground coal working face.

Methodology. Using mechanical analysis, we obtain the theoretical maximum roof hanging arch distance in the curved triangle area and expression of supporting pressure borne by protective coal pillars surrounding the curved triangle area. To reflect the results, mathematical derivations are done.

Findings. The mechanical model for roof hanging arch in the curved triangle area at the end of the coal working face is established; the mechanical conditions for the formation of such triangle area is analyzed; the theoretical maximum roof hanging arch distance in the curved triangle area is calculated; the formula showing the corresponding relation between the ineffectiveness of bolt (cable) support of the roadway roof and supporting pressure of coal pillars surrounding the curved triangle area is given as well.

Originality. A series of formulas for the supporting pressure borne by the protective coal pillars surrounding the curved triangle area are derived.

Practical value. If the roof support in the curved triangle area becomes ineffective after completing the corresponding support tasks, both the roof hanging arch distance and supporting pressure of the coal pillars in the triangle area reduce accordingly. These conclusions may supply instructions for designing the width of the protective pillars.

Keywords: *high gassy mine; curved triangle area; support ineffectiveness; mechanical model*

Introduction. Under complex geological conditions, there are many uncertain factors influencing the rules for the movement of rock stratum laid over the coal seam. Roadways in the mining area and mines surrounding coal body are typically under significant pressure. Therefore, it is necessary to adopt high-strength support patterns at the working face, thus bolt support is specially favored at mines due to its high strength, low cost, convenient construction and other corresponding characteristics. According to the statistical data from relevant departments and scholars, at present the rate of bolt support adopted in mine roadways in China has reached over 60 %, and is even higher at certain state-owned key coal enterprises (approximating almost 100 %). Therefore, we can say that bolt support has become the most important mine roadway support pattern [1]. The support pattern characterized by the combination of anchor bolt and reinforcing anchor cable is typically adopted in the open-off cuts and mining roadway roofs at most mines, before the mining of fully mechanized caving faces. Showing a great support effect and extremely great practicability in engineering practices, the above mentioned comprehensive support pattern is safer compared with a single bolt support or other support patterns [2].

With the application of the support technology characterized by the integration of anchor bolt and cable in set-up entry in fully mechanized caving faces, the installation of longwall shear and shields in working faces is becoming easy. And the great economic and social benefits have been acquired due to safety and reliability reasons, cost saving, construction acceleration and other advantages. However, due to the joint support of the anchor bolts and cables, the roof cannot achieve timely caving consistently and the step of the primary collapse is excessively large, thus endangering the safety of the working faces. For example, due to the excessively large roof hanging arch area, the 3043 working face in Sanyuan Wangzhuang Coal mine showed air leakage, rib fall of coal wall and other serious faults. In addition, the sudden large- area collapse of the roof with excessively large hanging arch area in the goaf of the Zhaozhuang Coal Mine under Jincheng Anthracite Mining Group respectively caused personal and equipment safety accidents in 1306 and 3305 working faces [3, 4].

After the commencement of mining, the mining roadways in the back of working face gradually become an integral part of the goaf with the advance of the working face. Under the influence of dynamic ground pressure and other factors, most of the anchorage devices in the roof of the mining roadways cannot easily be removed. Due to this fact, most of the cable anchorage devices still play the roles of roof hanging arch and reinforcement even after the roadway is not used any more. Thus, the roadway roof cannot timely collapse with the movement of the working face and a large-scope roof hanging arch at the back of the upper and lower ends of the working face is formed. Moreover, the anchor cables for open-off cut may fail to be released, which results in a large-step extraction of top coal and prevents the implementation of the normal coal caving procedure, leading to the loss of a large quantity of top coal, and increasing the perniciousness of roof collapse in a large area.

From the perspective of mechanical analysis, in this paper, first the distribution of pressure on the covering roof in the working face is discussed; then the mechanical model for curved triangle area at the end of the working face is established. Furthermore, the factors influencing the occurrence of the roof hanging arch in the curved triangle area are analyzed, in particular the influence of the curved triangle area and the supporting pressure of coal pillars after the release of bolt support. The research conclusions may supply instruction for the design of the width of protective coal pillars.

Distribution of Pressure on Roofs at the Front and Back of the Coal Face. The treatment of rock stratum laid above the roofs can be divided into four stages, from the roadway formation to excavation and the final abandonment, namely the excavation influence stage, excavation stabilization stage, mining influence stage, and mining stabilization stage. The first stage (the excavation influence stage): the stress of the surrounding rock stratum redistributes. The plastic deformation occurs in certain areas, and the roadway deformation quantity is relatively large. The second stage (the excavation stabilization stage): after the completion of the roadway excavation operation, the rock stratum surrounding the roadway is under the joint influence of the support effect and self-bearing effect. Therefore, the roadway deformation rate becomes gentle and gradually stabilized, and the deformation quantity is far less than that at the excavation influence stage. The third stage (the mining influence stage): after the mining of the working face has been completed, the stress of the overlying rock stratum redistributes once again under the effect of the advanced support pressure. Then the plastic area of the surrounding rocks continuously increases, roof sinking rate increases, and roof deformation is at the most intense stage. The fourth stage (the mining stabilization stage): after the fiercest deformation of the roof, the distribution of stress in the goaf remote from the mining face gradually becomes stabilized. The roof sinking quantity reduces significantly compared with that at the third stage, but it is still larger than that at the first and second stages. Fig. 1 shows the distribution of stress on the rock stratum laid above the roof during mining on the working face.

It can be seen from Fig. 1 that in some areas remote from the working face, the rock stratum laid above corresponding roof is free from the influence of mining pressure, and the area is exactly beyond the influence of dynamic pressure, as shown in Part A in the figure. Part B indicates the area under the influence of advanced support pressure, where the stress increase is not that significant and the pressure becomes increasingly large as the distance from the mining face becomes shorter and shorter. This area is characterized by small roadway deformation quantity and rare occurrence of mine ground pressure. Part C indicates the area where advanced support pressure occurs; being adjacent to the working face. This area is characterized by the sharp increase in stress in the surrounding rocks, and the significant occurrence of mining pressure. Part D indicates the area where the maximum dynamic pressure occurs; being 10–20 m away from the working face. The area is characterized by large roadway roof sinking quantity, severe rib fall of coal wall and occasionally occurring base plate floor heave, thus temporary support should be strengthened in this area.

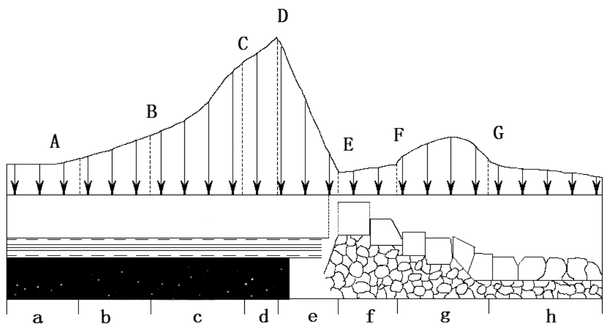


Fig. 1. Distribution of pressure on roofs at the front and back of the stope face:

a – area beyond the influence of dynamic pressure; b – area under the influence of advanced support pressure; c – area where advanced support pressure occurs; d – area where maximum dynamic pressure occurs; e – pressure reduction area; f – pressure unloading area; g – area where old roof pressure occurs; h – pressure stabilization area

Part E indicates the pressure reduction area where the stress reduces sharply. The main reason is that the stress exerted on the coal body by the overlying rock stratum is released outside through the fractures in the coal body, thus resulting in the reduction of pressure. Part F indicates pressure unloading area; after the working face is advanced to a certain distance, the immediate roof in the back collapses, leaving the force exerted by the overlying stratum working on the old roof. Therefore, the force is transferred from the old roof to the surrounding rock masses, thus resulting in the rib fall of coal wall in the front of the working face, and the caving of roofs in the goaf. Part G indicates the old roof pressure area where the masonry beam structure is formed, resulting from the collapse and caving of old roof and pressure of rocks in the goaf increasing under the influence of the weight of certain rock masses laid above. Part H indicates the pressure stabilization area; being remote from the working face. The area is beyond the influence of mining, where the overlying rock stratum and the rocks collapsed reconstitute the state of mechanical equilibrium.

Fig. 2 shows the distribution of the supporting pressure working on the coal body at both sides of the working face under the mining influence.

It can be seen from Figs. 1 and 2 that the roof hanging arch area in the back of the working face of the high gassy mine is located in the roof pressure unloading area. And the coal body in the roof hanging arch area is located in the coal body supporting pressure unloading area.

Formation of Curved Triangle Area at the End of the Working Face. It has been revealed in recent research studies that the rock stratum in the fracture belt of the goaf can form the masonry beam mechanical model and Kirchhoff plate mechanical model. According to the rule for the fracture of the overlying strata "plate", when the basic roof stratum fractures for the first time, the main fracture is in the shape of "O-X", while the structure of masonry beam in the middle of the working face and the structure of the curved triangle plate in the end part of the working face may be formed during periodic fracture, as shown in Fig. 3 [5].

In the fracture structure shown in Fig. 3, L_1 indicates the periodic roof weighting step, generally ranging from 10 to 20 m, while L_2 indicates the lateral span of the curved triangle plate, and L_2 can be regarded as being approximate to L_1. The X-O indicates the fracturing position of the curved triangle plate. That is mainly under the influence of the thickness and strength of the basic roof, the buried depth of working face and the strength and mining height of the coal and rock mass. With a value generally ranging from 4 to 8 m, the X-O is basically located in the junctions of plastic areas within the coal body.

According to wall-suspending plate theory, under the joint effect of protective coal pillars in the surrounding sections, coal body at the stope face and temporary supports, the roofs above the ends of the roadways in the working face can form the structure of the suspended roof plate in the shape of a curved triangle near the end of the mining roadway when the old roof in the goaf collapses, as shown in Fig. 4. The maximum bending moment of the curved triangle suspending plate occurs in the junctions of the free end and fixed end, namely the junction between the coal pillar and the end, and that between the end and the roof cutting line of the support. The roofs in these two junction positions are most vulnerable to damage, and a new damage limit is formed in the trace of the curved ultimate bending moment, as shown in Fig. 5. The roof in the end part fractures and collapses along the trace of the curved ultimate bending moment, and thus forms a suspended roof in the shape of a curved triangle, as shown in Fig. 4. The area of suspended roof in the shape of a curved triangle is generally

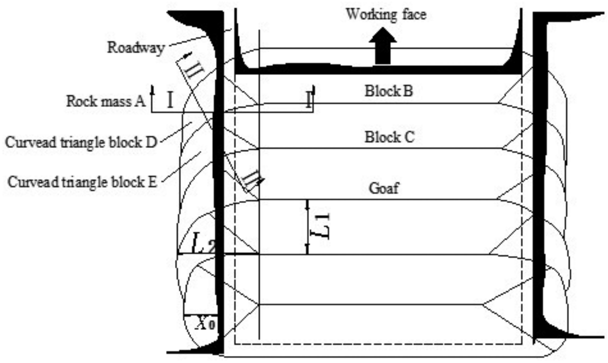


Fig. 3. Fracture forms of basic roof at overlying rock stratum

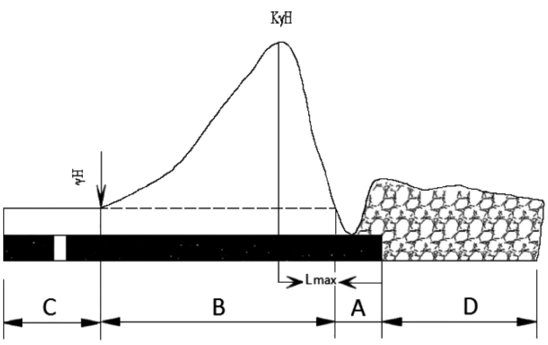


Fig. 2. Rules for the distribution of supporting pressure at both sides of the coal face:

A – unloading area; B – supporting pressure area; C – primary rock stress area; D – after-mining pressure stabilization area; L_{max} – peak position

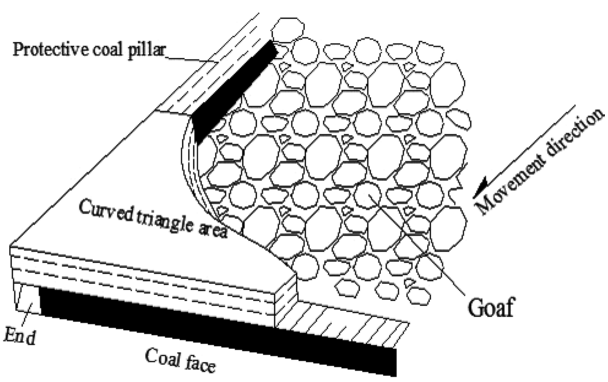


Fig. 4. Curved triangle formed at the end of the stope roadway [8]

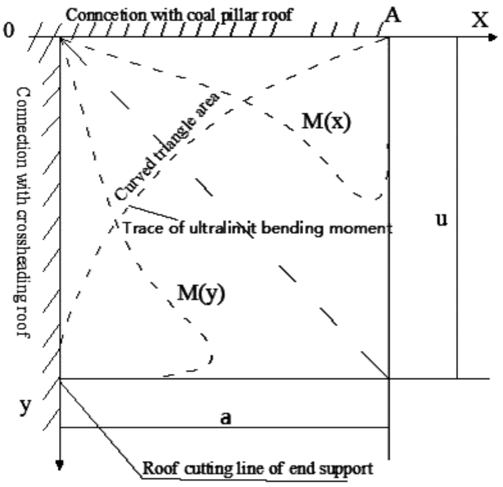


Fig. 5. Schematic diagram of the formation of suspended roof in the shape of a curved triangle

in the shape of an equilateral right triangle with a basically constant size [6, 7].

With the movement of the working face, both the suspension area of the end roof and the bending moment exerted on the roof continuously increase. When the bending moment reaches a certain limit, fracture will occur in the junction position between the coal pillar and the end, and that between the end and the roof cutting line of the support. This is followed by the collapse of the suspended roof plate in the shape of a curved triangle, and then the new suspended roof plate in the shape of a curved triangle will form at the front end with the proceeding of the working face. Therefore, it is the periodic collapse that continuously forms new suspended roof plates in the shape of a curved triangle.

Structural Mechanics Analysis on Curved Triangle Area at the End of the Working Face. According to the plate simplification theory, the suspended roof in the shape of curved triangle can be divided into several pseudo-tilt beams, and the model for each pseudo-tilt beam is shown in Fig. 6. This model can be regarded as representing a tilted rock beam, and the dip angle of the model (α) is equal to the coal seam dip angle. Tilted Beam AB can be calculated on the basis of the following two assumptions: 1) with a length of L, AB is under balanced stress, and the corresponding uniform load is q; 2) under the effect of supporting force, Points A and B are regarded as fixed ends.

According to the material mechanics formula, the bending moment of any point (x) in Tilt Rock Beam AB, namely M_x, can be shown as follows

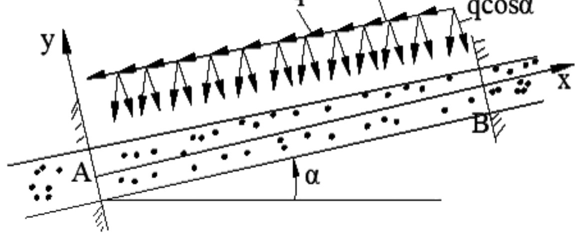


Fig. 6. Mechanical model of pseudo-tilted beam

$$M_x = \frac{q\cos\alpha}{12}(6x^2 - 6Lx + L^2),$$

where M_x is the bending moment of any point; x is the distance between any point in AB to Point A; α is the dip angle of the model; q is the corresponding uniform load; L is the length of the Tilted Beam AB.

Under the effect of M_x, the bending stress of any point in AB (σ_1) can be shown as follows

$$\sigma_1 = \frac{M_x y}{J}, \qquad (1)$$

where $y = \pm\frac{h}{2}$; the y value on the neutral axis of old roof should be positive; otherwise, it should be negative; J is inertia moment, $J = \frac{1}{12}h^3$; h is the thickness of the old roof.

When the neutral axis is under the influence of Vertical Load $q\cos\alpha$, the lower and upper surfaces in the middle are typically under tension and pressure, respectively; as the anti-pressure limit is larger than the anti-tension limit, fracture damage typically occurs first in the lower surface at the middle of AB, and then Stress σ_1 can be shown as follows

$$\sigma_1 = \frac{q\cos\alpha(6Lx - 6x^2 - L^2)}{2h^2}, \quad (0 \le x \le L), \qquad (2)$$

where α is the dip angle of the model; q is the corresponding uniform load; L is the length of the Tilted Beam AB; x is the distance between any point in AB to Point A; h is the thickness of the old roof.

The stress exerted on AB in the horizontal direction (σ_2) under the effect of the parallel load $q\sin\alpha$ can be shown as follows

$$\sigma_2 = \frac{q\sin\alpha(2x - L)}{2h}, \quad (0 \le x \le L), \qquad (3)$$

where α is the dip angle of the model; q is the corresponding uniform load; L is the length of the Tilted Beam AB; x is the distance between any point in AB to Point A; h is the thickness of the old roof.

It can be seen from the results of (1–3) that Point A and Point B are respectively under the maximum pressure stress and tension stress, and the stress in the middle is 0. The curve of presses on various points in AB can be prepared in accordance with (2, 3), as shown in Fig. 7.

Under the joint effect of σ_1 and σ_2, the stress on the lower surface of the neutral axis of AB can be shown as follows

$$\sigma = \frac{q\cos\alpha(6Lx - 6x^2 - L^2)}{2h^2} + \frac{q\sin\alpha(2x - L)}{2h}, \qquad (4)$$
$$(0 \le x \le L),$$

where α is the dip angle of the model; q is the corresponding uniform load; L is the length of the Tilted Beam AB; x is the distance between any point in AB to Point A; h is the thickness of the old roof.

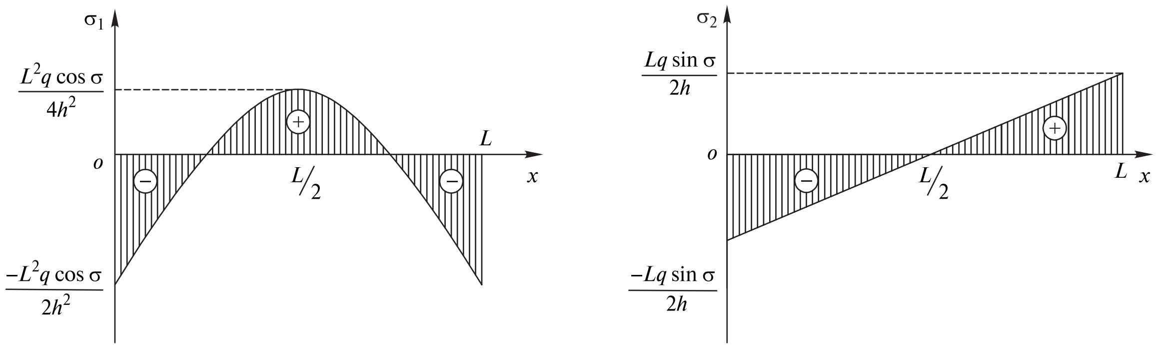


Fig. 7. σ_1 and σ_2 stress curves

The stress curve (σ) of any point in Rock Beam AB can be acquired in accordance with (4), as it is shown in Fig. 8. Proposing that $\frac{d\sigma}{dx}=0,$ when σ reaches the limit $\left(x=\frac{L}{2}+\frac{h}{6}\tan\alpha\right)$, the lower surface in the position at the neutral axis with a distance of $\frac{L}{2}+\frac{h}{6}\tan\alpha$ away from Point A is under the maximum stress, and it will be damaged first.

The fracture point of the rock beam and its maximum sinking point are generally in the same position, thus (4) can also be expressed as follows

$$\sigma_{\max}=\frac{q\cos\alpha}{2h^2}\left[6L_{\max}\left(\frac{1}{2}L_{\max}+\frac{h}{6}\tan\alpha\right)-\right.$$
$$\left.-6\left(\frac{L_{\max}}{2}+\frac{h}{6}\tan\alpha\right)^2-L_{\max}^2\right]+$$
$$+\frac{q\sin\alpha}{2h}\left[2\left(\frac{L_{\max}}{2}+\frac{h}{6}\tan\alpha\right)-L_{\max}\right],$$

where α is the dip angle of the model; q is the corresponding uniform load; $L_{\max}$ is the limit span; h is the thickness of the old roof.

The formula above can also be simplified as follows

$$\sigma_{\max}=\frac{L_{\max}^2 q\cos\alpha}{4h^2}+\frac{q\tan\alpha\sin\alpha}{12},$$

where α is the dip angle of the model; q is the corresponding uniform load; $L_{\max}$ is the limit span; h is the thickness of the old roof.

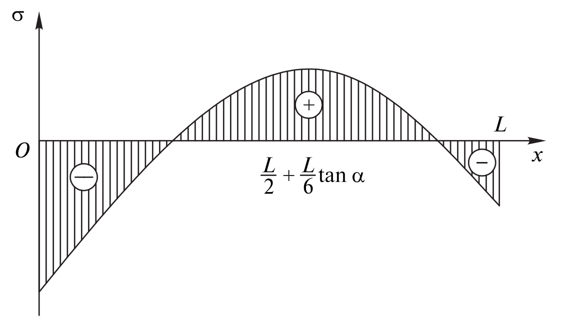


Fig. 8. σ stress curve

When Rock Beam AB fractures, $\sigma_{\max}=R_t$, its limit span ($L_{\max}$) can be shown as follows

$$L_{\max}=h\sqrt{\frac{4R_t}{q\cos\alpha}-\frac{\tan^2\alpha}{3}}, \tag{5}$$

where α is the dip angle of the model; q is the corresponding uniform load; $L_{\max}$ is the limit span; h is thickness of old roof; R_t is ultimate tensile strength.

It can be concluded from the comprehensive analysis that (5) precisely shows the limit span of the curved triangle roof.

When $\alpha = 0$, the limit span will be as follows

$$L_{\max}=2h\sqrt{\frac{R_t}{q}},$$

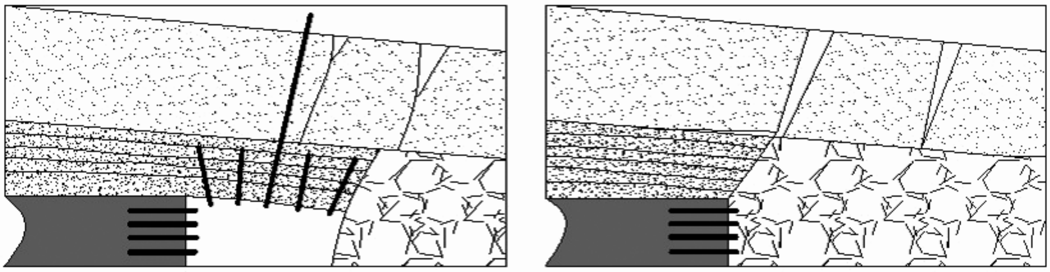
where q is the corresponding uniform load; $L_{\max}$ is the limit span; h is thickness of old roof; R_t is ultimate tensile strength.

Analysis of the Influence on Curved Triangle Area and Coal Pillar Supporting Pressure After the Release of Bolt (Cable) Support. When the release of the support adopted for the roofs in the curved triangle area fails to be smoothly conducted, certain anchor bolts and cables will still play the role of hanging arch. That may influence the collapse of the immediate roof in the curved triangle area, as shown in Fig. 9, *a*. See Fig. 9, *b* for the effect after the release of the anchor bolts and cables under ideal circumstances [6].

After the formation of the curved triangle area, the supporting pressure exerted from the overlying rock stratum on the surrounding coal body and supports increases, support contraction and expansion quantity increases, and a part of the coal body yields. Proposing that the coal pillars adopted comply with the Winkler Hypothesis and the stress structure of the surrounding coal body throughout the entire curved triangle area is in the plane state. The corresponding plane stress mechanical model is shown in Fig. 10.

According to the balance conditions for the model shown in Fig. 10, the differential equation of the deflection curve for cantilever beams in the curved triangle area can be shown as follows

$$\begin{cases} E_1 I_1 y'''' = q & (-l \le x \le 0) \\ E_1 I_1 y'''' = q-ky & (0 \le x < \infty) \end{cases},$$



a *b*

Fig. 9. States of roofs in the curved triangle area before and after support release:
a — before removing the support; b — after removing the support

where EI is the flexural rigidity; q is uniformly distributed load; k is constant terms.

The deflection curve for cantilever beams in the curved triangle area can be acquired through putting corresponding boundary conditions and continuity conditions into the above formula

$$y = e^{-\frac{\omega}{\sqrt{2}}x}\left(\frac{\sqrt{2}Q_0 + \omega M_0}{E_1 I_1 \omega^3}\cos\frac{\omega}{\sqrt{2}}x - \frac{M_0}{E_1 I_1 \omega^2}\sin\frac{\omega}{\sqrt{2}}x\right),$$

where Q_0 is the total pressure of the overhang; M_0 is the bending moment; ω is natural frequency; EI is the flexural rigidity.

And $Q_0 = qa$, $M_0 = \frac{qa^2}{2}$ and $\omega = \sqrt[4]{\frac{k}{E_1 I_1}}$, then the supporting pressure borne by coal pillars surrounding the curved triangle area can be expressed as follows

$$R = ke^{-\frac{\omega}{\sqrt{2}}x}\left(\frac{\sqrt{2}Q_0 + \omega M_0}{E_1 I_1 \omega^3}\cos\frac{\omega}{\sqrt{2}}x - \frac{M_0}{E_1 I_1 \omega^2}\sin\frac{\omega}{\sqrt{2}}x\right), \quad (6)$$

where R is supporting pressure borne; k is constant terms; ω is natural frequency; M_0 is the bending moment; EI is the flexural rigidity; Q_0 is the total pressure of the overhang.

When $x = 0$, (6) can be expressed as follows

$$R = k\frac{\sqrt{2}qa + \frac{1}{2}\omega qa^2}{E_1 I_1 \omega^3},$$

where k, q, ω, E_1 and I_1 are all constant terms (which are determined according to mechanical properties of mine stratum). It can be seen from (6) that the roof hanging arch distance in the curved triangle area is in a parabolic linear relation with the supporting pressure borne by the surrounding protective coal pillars. It can be concluded that if the bolt support for the bolt roofs in the curved triangle area fails to be released, then both the roof hanging arch distance in the area and the supporting pressure borne by the surrounding coal pillars will increase. Correspondingly, if the roof support in the curved triangle area can be effectively released, then both the roof hanging arch distance in the area and the supporting pressure borne by the coal pillars will decrease.

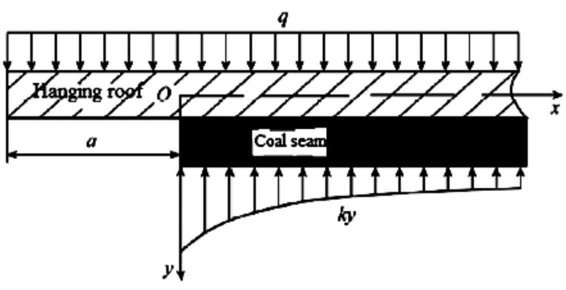


Fig. 10. Elastic force model of protective coal pillar around the curved triangle area

Conclusions. Under the joint effect of the protective coal pillars in the surrounding sections, the coal body at the working face and temporary supports, the roofs above the ends of the roadways in the working face can form the structure of the suspended roof plate in the shape of a curved triangle near the end of the roadway when the old roof in the goaf collapses. The maximum bending moment of the suspended roof plate in the shape of a curved triangle occurs in the junctions of the free end and fixed end, namely the junction between the coal pillar and the end, and that between the end and the roof cutting line of the support. These two junction positions are most vulnerable to damage. New suspended plates in the shape of curved triangles will form at the front end with the proceeding of the working face. Therefore, it is the periodic collapse that continuously forms new suspended roof plates in the shape of curved triangles.

When the roof hanging arch distance in the curved triangle area is excessively large, the danger of the sudden collapse of roofs in large area will increase. And the dead-end ventilation corner will occur at the back of the end, the supporting pressure borne by the coal pillars at both sides of the goaf will increase. At the same time, the stability of the coal pillars will reduce, thus influencing the stability and maintenance of rocks surrounding the roadways nearby, and hazards such as air leakage will occur in the face. The following conclusions regarding the problems mentioned above were acquired in the research:

1. The conditions for the formation of the curved triangle area at the end of the mining roadway are analyzed, and the maximum roof hanging arch distance in the curved triangle area is calculated, as shown in the following formula

$$L_{\max} = h\sqrt{\frac{4R_t}{q\cos\alpha} - \frac{\tan^2\alpha}{3}},$$

when $\alpha = 0$; $L_{\max} = 2h\sqrt{\frac{R_t}{q}}$.

2. If the bolt support for bolt roofs in the curved triangle area fails to be released, both the roof hanging arch distance in the area and the supporting pressure borne by the surrounding coal pillars will increase. Correspondingly, if the roof support in the curved triangle area can be effectively released, then both the roof hanging arch distance in the area and the supporting pressure borne by the coal pillars will decrease.

3. The supporting pressure borne by protective coal pillars surrounding the curved triangle area can be expressed by the following theoretical formula

$$R = k\frac{\sqrt{2}qa + \frac{1}{2}\omega qa^2}{E_1 I_1 \omega^3},$$

which can supply a theoretical basis for the design on the width of protective collars.

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Мета. Обґрунтування арочного кріплення покрівлі в забої пластової виробки на ділянці зігнутої трикутної поверхні перерозподілу тиску в масиві.

Методика. Використовуючи механічний аналіз і математичні розрахунки, отримана максимально можлива відстань кріплення склепіння виробки й значення додаткового тиску в масиві, прикладеного до запобіжних ціликів на трикутній поверхні.

Результати. Установлена механічна модель кріплення склепіння пластової виробки. Проаналізовані механічні умови утворення трикутної області перерозподілу тиску. Розраховані максимальні значення відстані закладення склепіння на вигнутій трикутній поверхні. Представлена залежність, що показує відповідність між неефективністю кріплення виробки та несучого тиску вугільних ціликів, які оточують вигнуту трикутну поверхню в масиві.

Наукова новизна. Розроблена методика розрахунку опорного тиску, що сприймається захисними вугільними ціликами, які оточують утворювану в масиві трикутну поверхню.

Практична значимість. Якщо після встановлення кріплення виробки опора склепіння на вигнутій трикутній поверхні стає неефективною, то необхідно зменшити відстань встановлення опорного склепіння, який несе тиск захисних вугільних ціликів, що дозволяє проектувати їх розміри.

Ключові слова: *шахта з високою загазованістю, вигнута трикутна поверхня, неефективність опори, механічна модель*

Цель. Обоснование арочного крепления кровли в забое пластовой выработки на участке изогнутой треугольной поверхности перераспределения давления в массиве.

Методика. Используя механический анализ и математические расчеты, получено максимально возможное расстояние крепления свода выработки и значения дополнительного давления в массиве, приложенного к предохранительным целикам на треугольной поверхности.

Результаты. Установлена механическая модель крепления свода пластовой выработки. Проанализированы механические условия образования треугольной области перераспределения давления. Рассчитаны максимальные значения расстояния заложения свода на изогнутой треугольной поверхности. Представлена зависимость, показывающая соответствие между неэффективностью крепи выработки и несущего давления угольных целиков, окружающего изогнутую треугольную поверхность в массиве.

Научная новизна. Разработана методика расчета опорного давления, воспринимаемого защитными угольными целиками, окружающими образуемую в массиве треугольную поверхность.

Практическая значимость. Если после установки крепления выработки опора свода на изогнутой треугольной поверхности оказывается неэффективной, то необходимо уменьшить расстояния установки опорного свода, несущего давление защитных угольных целиков, что позволяет проектировать их размеры.

Ключевые слова: *шахта с высокой загазованностью, изогнутая треугольная поверхность, неэффективность опоры, механическая модель*

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