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Study on action mechanism between rated working resistance of support and overburden strata movement

Liu Hao[1,a],Zhang Kebin[1,b], Xu Weizheng[1,c], Zheng Pengqiang[2,d],Zhang Quanming[3,e]

[1]Research Institute of Mining Engineering, Shandong University of Science and Technology, Tai'an 271000 Shandong; China;
[2]College of Resources, Shandong University of Science and Technology, Tai'an 271000 Shandong; China.
[3]YANKUANG ENERGY GROUP COMPANY LIMITED, Zou'cheng 273500 Shandong; China.

Abstract. Based on the pressure regulating test curve describing support–surrounding rock relationship, the relationship between rated working resistance (RWR) and overburden movement is investigated. It is discovered that between RWR and movement of direct roof strata, the relationship is "must control and must be controlled", which is qualitatively expressed as $Pze=hz\gamma z$; between movement of main roof strata and RWR, the relationship is "degree-controlling and degree controlled", which is hyperbolic and qualitatively expressed as $Pre=QSm/2Sx$; between RWR and movement of bend zone strata, the relationship is that of "unable to control and unable to be controlled", which is qualitatively expressed as $Pb=0$. Finally, the author examines the characteristics of the "hyperbola", the prerequisite for its existence, and the influence of main roof fault block movement parameters on the position of the hyperbola in the coordinate system, the degree of support control, and the degree of roof movement. This research outcome represents an innovation and a breakthrough on the basic mine pressure theory. It has great academic significance to the discipline of mine pressure and stratum control and provides theoretical basis for the application of strata control.

1 Introduction

The subject of support–surrounding rock relationship in longwall working faces revolves around strata movement control in the direct roof, main roof, and bend zone that make up the entire stope (Qian et al, 1984; Zhang, 1988). This includes analyzing the relationship between rated working resistance (RWR) of support and initial support force of support and the movement (amount and rate of subsidence) of individual strata; determining whether the support has a reasonable RWR and initial support force for controlling overburden movement; and quantitatively explaining the law of strata behavior (Zhang et al, 1991; Zhang et al, 2003; Yan et al, 2013; Gao SG et al, 1998).

In a word, the research of support–surrounding rock relationship is at the core of the discipline of mine pressure and strata control. It is also a critical subject for the safe production of coal mines all over the world. This subject dates back to the late 1950s and the early 1960s, when field or laboratory pressure regulating tests were conducted by researchers outside China. The test curve is shown in Fig.1 (Qian et al, 1984). In China, the first pressure regulating test was conducted in laboratory in 1963 by Academician Qian Minggao of Beijing Institute of Mining and Technology (now China University of Mining and Technology" et al. The test curve is shown in Fig. 2.

Despite the extensive work performed around this subject and some perceptual knowledge gained, no one has unveiled the mystery of its mechanism. No satisfactory answer has been made to this fundamental theoretical problem (Wang JC and Wang ZH, 2019; Wang GF, 2014; Wu SL and Liu SL, 2016; Hua XZ, 2004).

As a result, people are still trying to determine the working resistance of support in longwall working faces through estimation, empirical formula (Shi, 2003), mathematical statistics (Jiang et al, 2014; Yu et al, 2017; Xu et al, 2021; Yan and Sun, 2014), and numerical simulation (Xie et al, 2015; Lou WF et al, 2017; Hu SX et al, 2018; Su WP et al, 2021; Li XM et al, 2021). These methods have limitations in themselves and are not universally applicable. They are also unable to give a quantitative explanation of some mine pressure occurrences. In this context, establishing a universally applicable support–surrounding rock relationship to solve this problem quantitatively and accurately is an urgent need for the safe production of coal mines.

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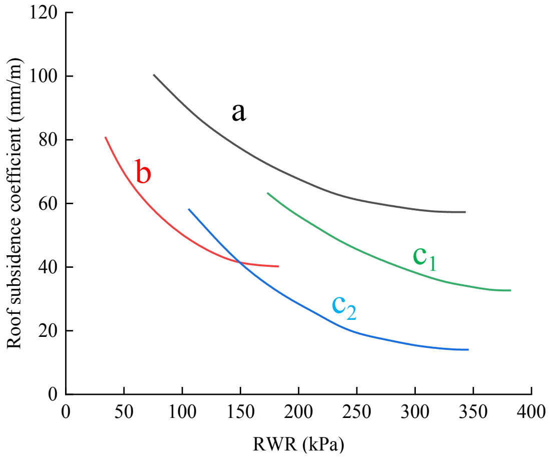
[a] zxsdn888@163.com, [b] qazwsx3909@163.com, [c] xuweizheng163@163.com, [d] pqzheng_1231@163.com, [e] 987042448@qq.com

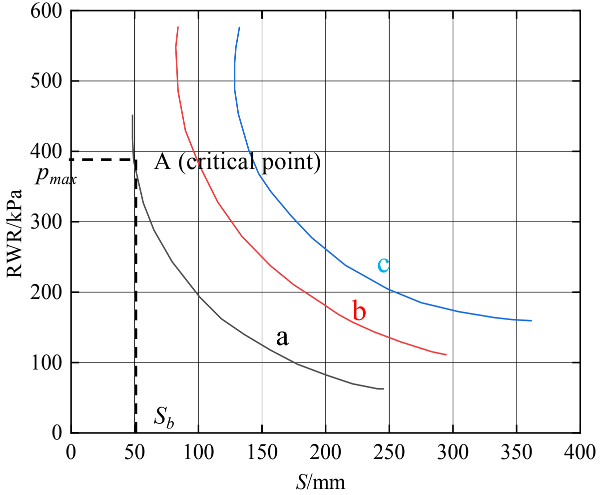


(a) Former Soviet Union (b) Britain (c) Germany

Fig. 1 Measured diagram of RWR and roof subsidence in foreign mining working faces

2 Qualitative relationship between RWR and overburden movement

The entire overburden of a stope is composed of direct roof strata, main roof strata and bend zone strata. To study the control characteristics of overburden movement is to examine the control relationship between RWR and the movement of these strata.



(a) Mining height 1.5m ; (b) Mining height 2.2m; (c) Mining height 3m

Fig. 2 The RWR–roof subsidence curve

2.1 Qualitative relationship between RWR and direct roof strata movement

It is a consensus that to prevent direct roof strata subsidence from causing roof accidents in the stope, the movement of the overlying direct roof strata due to gravity has to be controlled by RWR. Hence between RWR and movement of the controlled direct roof strata due to gravity is a relationship of must-control and must-be-controlled. For control purpose, direct roof strata can be called "strata that must be controlled by RWR" or "must-be-controlled strata". The lower part of Fig. 3 and Fig. 4 represents the quantitative relationship between RWR and movement of overlying direct roof strata due to gravity.

2.2 Qualitative relationship between RWR and main roof strata movement

Main roof strata movement acts on the support through the direct roof strata beneath it. Hence, the relationship between RWR and main roof strata movement due to gravity has to be investigated when the movement of the overlying direct roof strata is controlled by the RWR.

From Fig. 2, on the pressure regulating test curve describing the support–surrounding rock relationship, there is a critical point (point A in curve a), which divides the curve into two parts. The upper part is a straight line parallel to the longitudinal axis of the coordinate system while the lower part changes in the pattern of a curve.

From the part below the critical point, we can see that the curve corresponds to strata subsidence: it increases with the rise of RWR and vice versa. The value of the RWR needed to control strata movement is defined the degree of support control. The amount of strata subsidence controlled by RWR is defined as the degree of strata movement. This fully demonstrates that the degree of support control determines the degree of strata movement. Accordingly, between strata movement due to gravity and RWR, the relationship is that of "degree controlling" and "degree controlled", as represented by the middle part of Fig. 3 and Fig. 4.

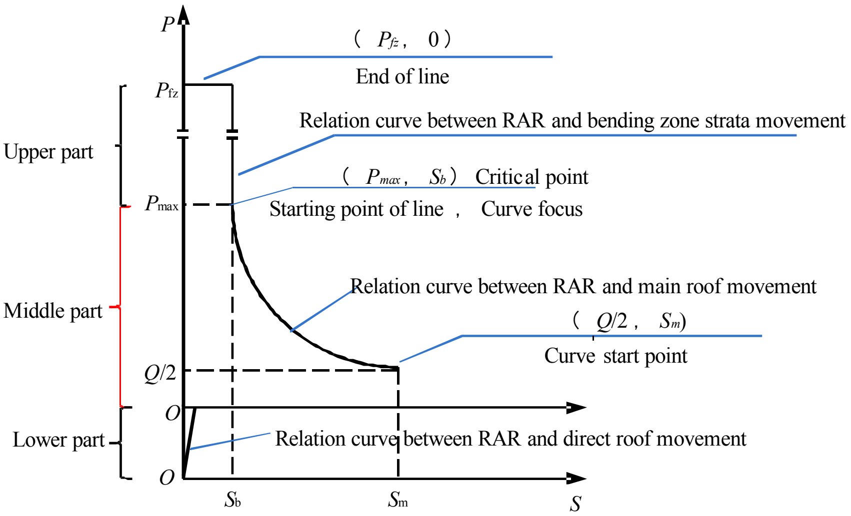


Fig. 3 The relationship between RWR and whole overburden movement

Mining practice has demonstrated that the pressure movement of the overlying main roof strata is periodic. Within this period, its movement proceeds along the advancement direction. Main roof fault blocks that detach inside the coal wall of the working face and exist in the form of a cantilever beam, when free from the control of the RWR the support beneath it, will make a pressure subsidence movement by rotating around the subsurface fracture line at its front due to gravity, with its weight on the underlying coal rock body. Consequently, a pressure subsidence is produced on the working face. The exact amount of this subsidence is determined by RWR, namely, the control degree of support. The higher the RWR (control degree), the smaller the pressure subsidence of roof (movement degree), and vice versa. Accordingly, between the pressure subsidence of main roof fault block and RWR, the relationship is also that of “degree controlling” and “degree controlled”. For control purpose, the main roof strata are defined as “degree-controlled strata”.

From the foregoing analysis, the relationship between strata movement and RWR, namely, the part of the curve below the critical point in Fig. 2, is totally the same as that between the movement of overlying main roof fault block and RWR. They are both a relationship of “degree controlling” and “degree controlled”. Hence, the relationship between RWR and strata movement presented by the strata in this part of the curve is right the relationship between the pressure movement of main roof fault block due to gravity and RWR. That is, the strata represented by the part of the curve in Fig. 2 (Fig. 3) are the main roof strata.

Given that the relationship between RWR and main roof strata movement is that of “degree controlling” and “degree controlled”, for control purpose, main roof strata can be defined as degree-controlled strata. The concept of degree-controlled strata fully reflects the qualitative relationship between RWR and main roof strata movement.

2.3 Qualitative relationship between RWR and bend zone strata movement

Bend zone strata movement covers a large area. In fact, bend zone strata accounts for approximately 90% of total thickness of the overburden. Its span is hundreds of meters or more. Hence bend zone strata movement is uncontrollable. This reality has also been proved by pressure regulating tests on working faces. In the pressure regulating test curve shown in Fig. 2, the part of the curve above the critical point is basically a straight line parallel to the longitudinal axis of the coordinate system. This suggests that the amount of strata subsidence presented by this linear part no longer changes with the increase of RWR, but basically stays at a given constant (Sb in Fig.s 2 and 4). In other words, within the peak abutment pressure on the coal seam caused by strata movement represented by the linear part (e.g., P_{fz} in Fig. 3), no RWR can change the amount of roof subsidence of the working face caused by the strata movement represented by this linear part however great its value is. What it can do is merely keep the subsidence at a given constant. This precisely proves that the strata movement represented by the linear part cannot be controlled by a support with conventional RWR. Therefore, it can be concluded that the strata presented by the linear part is the bend zone strata that cannot be controlled by RWR.

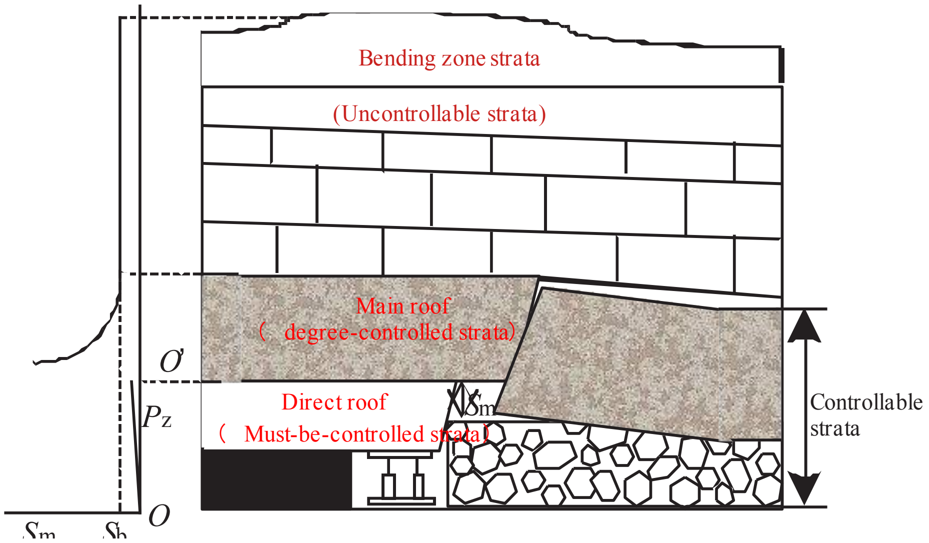


Fig. 4. Comparison of RWR and whole overburden movement

Between strata movement represented by the linear part (the bend zone strata) and RWR, RWR cannot control bend zone strata movement and bend zone strata movement cannot be controlled by RWR. Hence for control purpose, bend zone strata can be defined as "uncontrollable strata" (e.g., the upper part of Fig. 2 and Fig. 4).

Again from Fig. 2, the uncontrollable subsidence of the working face roof caused by uncontrollable strata movement, referred to as "uncontrollable subsidence" (Sb in Fig. 2) has too small a Sb to affect stope safety. Hence it is unnecessary to control the uncontrollable strata movement. A support can adapt to such uncontrollable strata movement as long as it has a substantial shrinkage. Therefore, between its movement and RWR, the relationship is that of "movement adapting" and "movement adapted".

To sum up, according to whether its movement can be controlled by RWR, the overburden can be divided into "uncontrollable strata" which need no be controlled and "controllable strata" which need be controlled. Among the controllable parts of the overburden, individual strata are further divided according to control degree into "degree controlled strata" and "must-be-controlled strata". From the movement perspective, the whole overburden is composed of direct roof strata, main roof strata and bend zone strata. For control purpose, the relationship among these strata is as shown in Fig. 4.

3 Quantitative relationship between RWR and overburden movement

3.1 Quantitative relationship between RWR and overlying direct roof strata movement

From the qualitative relationship between RWR and direct roof strata movement, between RWR and direct roof strata movement due to gravity, the relationship is that of "must control" and "must be controlled". Hence the RWR per meter of the support needed to control direct roof strata movement along the advancement direction is:

$$P_{ze}=L_k h_z \gamma_z \qquad (1)$$

The support strength of the support is:

$$P_z = h_z \gamma_z \qquad (2)$$

Where:

P_{ze}——RWR per meter of support needed to control direct roof strata movement along the advancement direction, kN;

L_k——support distance from roof, m;

h_z——thickness of direct roof strata, m;

γ_z——bulk density of direct roof strata, kG/m^3;

p_z——support strength of the support for direct roof, kN/m^2.

Eq.s (1) and (2) describe the quantitative relationship between RWR and overlying direct roof strata movement due to gravity, namely, the relationship of "must control" and "must be controlled" (e.g., the lower part of Fig. 3 and Fig. 4).

3.2 Quantitative relationship between RWR and main roof strata movement

The overlying fault zone strata are basically comprised of main roof strata. As the mining height of coal seams differs, so does the thickness of the fault zone strata and, of course, the number of main strata. For a seam with a large mining height (including top caving), the fault zone is definitely large and can contain more than several main roof strata (Key Strata). For a thin seam, it may contain only one main roof stratum. During the movement of these main roofs, different forms of mechanical structure may also be produced (Qian et al, 1984). Assuming that there is only one main roof stratum overlying the stope and that its fault block moves in the form of a cantilever beam, the quantitative relationship between RWR and overlying main roof strata movement due to gravity is analyzed. The pressure movement of main roof fault block is supported on the coal rock body inside the underlying coal wall and involves rotation around the subsurface fault line at the front. At the end of its movement (when its end touches the gangue, a pressure subsidence triangle is produced along the advancement direction of the working face (Fig. 3).

Assuming that main roof fault block is a homogeneous, isotropic rock mass with equal thickness, according to the moment balance of a rigid body rotating around a fixed axis, we get the moment balance equation of the direct roof strata fault block when under pressure due to gravity (Fig. 5):

$$P_{re} = \frac{QL_r}{2L_x} \tag{3}$$

Here, $\frac{QL_r}{2}$ is the moment of main roof fault block to its front due to gravity, referred to as the positive moment; $P_{re}L_x$ is the moment of NWS to the front of main roof fault block, referred to as the negative moment.

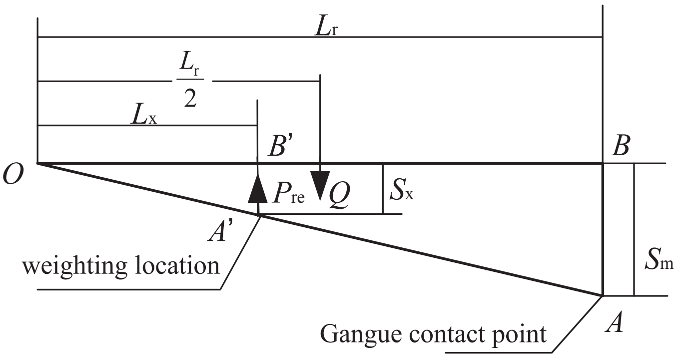


Fig.5 The relationship between the subsidence triangle formed by main roof fault block, RWR and moment of main roof fault block to its front due to gravity

Where:

Q——weight per meter of main roof fault block along the length of the working face, kG/m;

$$Q = L_r h_r \gamma_r$$

L_r——length of main roof fault block, m;

h_r——thickness of main roof fault block, m;

γ_r——bulk weight of main roof strata, kG/m$^{3;}$

P_{re}——RWR per meter of support needed to control main roof fault block movement, kN/m;

L_x——pressure distance from main roof fault block, m.

According to the relationship between △OAB and △OA′B′ in Fig. 5, we have:

$$\frac{L_r}{L_x} = \frac{S_m}{S_X} \tag{4}$$

Where:

S_m——height of the movement space at the end of main roof fault block, i.e., end subsidence, which describes the maximum subsidence of main roof fault block, mm;

S_x——roof subsidence of the working face produced at the end of the pressure movement of main roof fault block, i.e., pressure subsidence, which describes the movement degree of main roof fault block, mm (Fig. 5).

Using $\frac{S_m}{S_X}$ in Eq. (4) to replace $\frac{L_r}{L_x}$ in Eq. (3) yields:

$$P_{re} = \frac{QS_m}{2S_x} \tag{5}$$

Eq. (5) is the quantitative relationship between RWR and the pressure subsidence of main roof fault block, namely, the relationship between control degree of support and movement degree of main roof fault block. This equation is a hyperbola, further confirming the hyperbolic relationship between RWR and main roof fault block movement (pressure subsidence).

In coal seams with large mining height (including top caving), within a very thick fault zone, there can exist more than one main roof strata or critical or subcritical strata. Main roof fault block movement may involve not only cantilever beam mechanics, but also hinged beam mechanics. However, the resultant pressure subsidence triangle on the working face roof is the same. Only the structural form and the stress state of main roof fault block are different. As long as a pressure subsidence triangle is produced on the overlying main roof fault block, the relationship between RWR and the pressure subsidence movement of main roof fault block is always a “hyperbola” and this is also invariant. Therefore, the “hyperbola” between RWR and main roof fault block movement and its equation are an objective law with universal applicability. For top caving, in which the seam mining height is increased to become a large-height mining operation, this universal law also applies.

3.3 Quantitative relationship between RWR and whole overburden movement

The quantitative relationship between RWR and direct roof strata is $P_{ze}=l_k h_z \gamma_z$; that between RWR and main roof strata is $P_{re}=QS_m/2S_x$. For uncontrollable strata movement, zero RWR is needed, namely, $P_{be}=0$. To adapt to uncontrollable strata movement, the support has to have a shrinkage greater than the uncontrollable subsidence to adapt to its movement. Accordingly, the relationship between RWR (P) and whole overburden movement is quantitatively expressed as:

$$P = P_{ze} + P_{re} + P_{be} = L_k h_z \gamma_z + QS_m/2S_x + 0$$

Eq. 9 describes the quantitative relationship between RWR and the movement of direct roof strata, main roof strata and bend zone strata that make up the entire overburden of a stope. It is a full, accurate reflection of how RWR controls whole overburden movement.

4 Pressure regulating test curve and hyperbola

4.1 Hyperbola in pressure regulating test curve

1) In stope overburden, only main roof fault movement shows a "hyperbola" with RWR. No such "hyperbola" is observed in the movement of the other strata (the middle part of Fig. 3 and Fig. 4).

2) The hyperbola between RWR and main roof fault block movement is a bounded one (the middle part of Fig. 3). In the O' coordinate system in Fig. 3, the end coordinate of the hyperbola is the upper bound coordinate or the critical point coordinate, which represents the uncontrollable subsidence and its corresponding RWR. The coordinate value is [$P_{max}=\dfrac{QS_m}{2S_b}$, S_b]. The lower bound coordinate or the starting point coordinate of the hyperbola represents the end subsidence S_m of main roof fault block and the corresponding RWR. Its coordinate value is [$\dfrac{Q}{2}$, S_m]. In the O coordinate system, the upper bound coordinate value is [$P_{ze}+\dfrac{QS_m}{2S_b}$, S_b]; the lower bound coordinate value is [$P_{ze}+\dfrac{Q}{2}$, S_m].

4.2 Uncontrollable subsidence curve in pressure regulating test curve

1) The uncontrollable subsidence curve is a straight line parallel to Y axis. It is defined as S_b subsidence straight line.

2) The uncontrollable subsidence straight line is also a bounded straight line. In the O' coordinate system in Fig. 3, its upper bound coordinate value is (P_{fz}, 0); its lower bound coordinate value is [P_{max}, S_b], as represented by the upper part of Fig. 3. In other words, over the interval of RWR [P_{max}, P_{fz}], the subsidence of the working face roof is unexceptionally an uncontrollable subsidence. P_{fz} is the peak abutment pressure.

4.3 Characteristics of the entire pressure regulating test curve

The entire pressure regulating test curve is composed of an uncontrollable subsidence straight line and a hyperbola. As all of them are bounded curves, the entire pressure regulating test curve is a bounded one, too. In the O' coordinate system in Fig. 3, its upper bound coordinate is the upper bound coordinate of the uncontrollable subsidence straight line, with a value of [P_{fz}, 0]. Its lower bound coordinate is the lower bound coordinate of the hyperbola, with a value of [$Q/2$, S_m].

4.4 Substantial prerequisite for the existence of a hyperbola

The substantial prerequisite for a hyperbola is the existence of a free movement space at the end of main roof fault block, namely, a subsidence due to gravity, $S_m>0$.

The end subsidence S_m of main roof fault block is determined by the mining height m of the seam and the filling degree of the mined-out space after the overlying direct roof strata has collapsed and bulked. The expression is:

$$S_m = m-(kh_z-h_z) \tag{6}$$

Where:

m——mining height of the seam, mm;

k——bulking coefficient of main roof strata.

When the thickness of direct roof strata is h_z=0, maximum subsidence occurs at the end of main roof fault block, namely S_m=m. As the end subsidence of main roof fault block must be greater than zero, the end subsidence of main roof fault block is [$m\geq S_m>0$]. Accordingly, [$m\geq S_m>0$] is the interval in which a hyperbola exists.

When S_m=m-h_z(k-1)$>$0, i.e., $h_z<\dfrac{m}{k-1}$, there is a hyperbolic relationship between control degree of support and movement degree of main roof fault block. As the thickness h_z of main roof strata is greater than zero and is zero at the smallest, $h_z\geq 0$. Therefore, the existence of a hyperbola between RWR and main roof fault block movement (pressure subsidence) is meaningful only when there is a [$0\leq h_z<\dfrac{m}{k-1}$] interval. Accordingly, the interval of main roof thickness [$0\leq h_z<\dfrac{m}{k-1}$] is called the definition domain of the existence of a hyperbola.

When S_m=m-h_z(k-1)≤0, i.e., $h_z\geq\dfrac{m}{k-1}$, the overlying main roof strata is thick enough. The collapsed main roof strata, after bulking, has filled up the entire mined-out space, leaving almost no room for the main roof strata. Accordingly, $h_z\geq\dfrac{m}{k-1}$ is the substantial prerequisite for the nonexistence of a hyperbola.

5 Position of the hyperbola in the coordinate system

The position of the hyperbola in the coordinate system directly affects control degree of support and movement degree of main roof fault block. Therefore, the influence of the position of the hyperbola in the coordinate system is its influence on control degree of support and movement degree of main roof fault block.

According to $P_{re}=\dfrac{QS_m}{2S_x}$, when main roof fault block movement parameters are assigned, such as Q_1S_{m1},

Q_2S_{m2}, Q_3S_{m3}, and when $Q_1S_{m1} > Q_2S_{m2} > Q_3S_{m3}$, a hyperbolic chart can be plotted as shown in Fig. 6, which assumes that the bend zone movement parameter remains unchanged or that the uncontrollable subsidence S_b is a constant. Obviously, different movement parameters result in different positions of the hyperbola in the coordinate system for main roof fault block. Under larger movement parameters, the hyperbola is farther away from the coordinate origin than under smaller movement parameters, and vice versa (as illustrated by Fig. 6). That is, the position of the hyperbola in the coordinate system is determined by main roof fault block movement parameter QS_m. This way, QS_m becomes the decisive factor for the position of the hyperbola in the coordinate system.

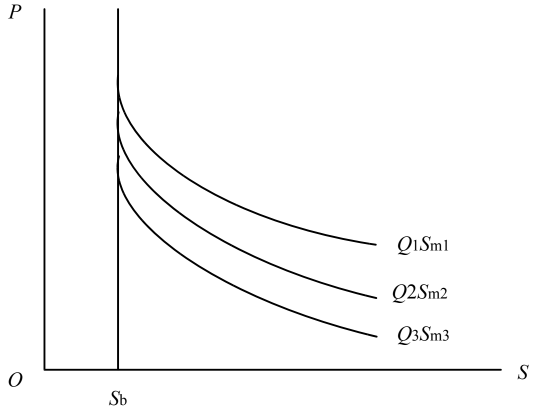


Fig. 6 The influence of main roof fault block movement parameter QS_m on the position of the hyperbola in the coordinate system

For main roof fault blocks with different movement parameters, if their movement degree is a constant, or when their movement is controlled at the same amount of subsidence, as represented by S_a in Fig. 7, the corresponding control degrees are different. As main roof fault block movement parameter increases, so does the RWR needed (e.g., $P_{re1} > P_{re2} > P_{re3}$ in Fig. 7).

Similarly, when the same RWR is used to control main roof fault block movement with different movement parameters, the corresponding pressure subsidence of main roof fault block will also be different. In Fig. 8, for example, when the control degree of support is P_{rea}, the corresponding movement degree of main roof fault block is S_1, S_2, S_3, and $S_1 > S_2 > S_3$. This suggests that in addition to affecting the position of the hyperbola in the coordinate system, main roof fault block movement parameter QS_m also determines the control degree of support (Fig. 7) and the movement degree of main roof fault block (Fig. 8). That is, it also determines the RWR of the support and the pressure subsidence of the roof.

In main roof fault block movement parameter QS_m, $Q = L_r h_r \gamma_r$, $S_m = m - h_z(k-1)$. Therefore, QS_m can be expressed as:

$$QS_m = L_r h_r \gamma_r \left[m - h_z(k-1) \right] \tag{7}$$

By substituting Eq. (7) into Eq. (5), we can find the control degree of these factors on the support. The movement degree of main roof fault block affects the quantitative relationship, as expressed below:

$$P_{re} = \frac{QS_m}{2S_x} = \frac{L_r h_r \gamma_r \left[m - h_z(k-1) \right]}{2S_x} \tag{8}$$

This equation fully reveals the control degree of support P_{re}, movement degree of main roof fault block S_x, and their quantitative relationship with main roof fault block movement parameters L_r, h_r, γ_r, mining height of the seam m, and overlying direct roof movement parameters h_z and k. Eq. (8) also covers all factors affecting the hyperbolic relationship between RWR and main roof fault block movement. Each parameter in the equation makes a difference to movement degree of main roof fault block and control degree of support, namely, RWR. These are of course all factors affecting the position of the hyperbola in the coordinate system.

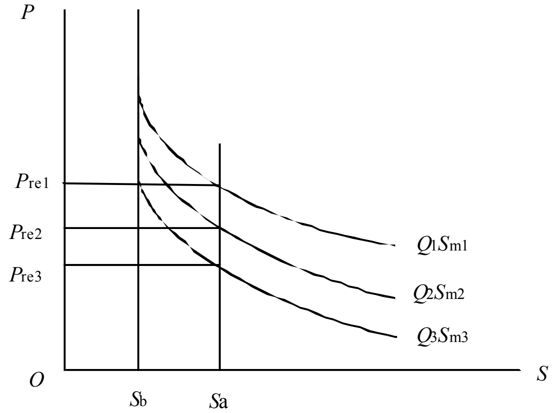


Fig. 7 The influence of main roof fault block movement parameter QS_{m1} on control degree under the same condition of

movement degree

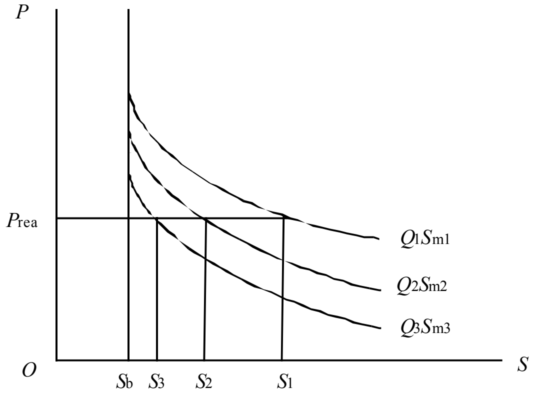


Fig. 8 Influence of main roof fault block movement parameter QS_{m1} on movement degree under the same condition of control degree

6 Conclusions

1) Stope overburden is divided into controllable strata (or strata that can be controlled or need be controlled) and uncontrollable strata (or strata that cannot be controlled or need not be controlled). Uncontrollable strata are bend zone strata. Controllable strata can be further divided into must-be-controlled strata (direct roof strata) and degree-controlled strata (main roof strata).

2) The quantitative relationship between RWR and whole overburden movement is revealed. Between movement of the must-be-controlled strata and RWR, the quantitative relationship is $P_z=h_z\gamma_z$; between movement of the degree-controlled strata and RWR, there is a hyperbolic relationship expressed as $P_{re}=QS_m/2S_x$. To adapt to the movement of the uncontrollable strata, it is unnecessary for the support to provide any working resistance, namely, $P_{be}=0$, but the support has to have a shrinkage greater than the uncontrollable subsidence.

3) The entire pressure regulating test curve is composed of an uncontrollable subsidence straight line and a hyperbola, which are all bounded curves. The prerequisite for the existence of such hyperbola is presented.

4) The reasonable RWR for the support to control overburden movement is the sum of the reasonable RWR for controlling the movement of the overlying direct roof and that for controlling the movement of main roof fault block. The concept of "allowable subsidence" of working face roof is proposed. The research outcome provides technical support for determining the reasonable RWR.

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