A study of the mechanical structure of the direct roof during the whole process of non-pillar gob-side entry retaining by roof cutting

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Abstract
The non-pillar entry (roadway) retained by roof cutting serves the two adjacent working faces. As compared with the conventional mining roadways, the roadway retained by roof cutting has a longer life cycle and receives more complicated influence from mining. Determining the location where the roof deformation and maximum deformation occur can provide an important basis for roadway support. Here, the direct roof of the roadway is studied by assuming it as an elastic deformation body. The stress features of the direct roof of the gob-side entry retained by roof cutting are analyzed, and the roof deformation is divided into five stages. The stress superposition principle is employed, and the equivalent concentrated load within the roadway is introduced. The mechanical model of the direct roof is established for the whole process of gob-side entry retaining by roof cutting. Next, the calculation formula for the concentration of direct roof at different positions is obtained for the whole process of gob-side entry retaining by roof cutting. The application scope of the calculation formula and the determination method of the key parameters are analyzed. The relationship between direct roof deformation of the roadway and stiffness of the support system is studied. The results show that the direct roof deformation has a symmetrical distribution about the midline. The maximum roof deformation occurs in the middle of the roadway, and it gradually decreases as the coal seam stiffness increases. During the example calculation, the maximum roof deformation is 280 mm for the gob-side entry retaining under primary mining. The measured maximum roof deformation is 320 m, and the error rate is

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12.5%. It is then verified that the uniform mechanical model proposed in this study applies to the calculation of direct roof deformation in the gob-side entry retained by roof cutting.

**Keywords**
Non-pillar gob-side entry retaining by roof cutting, roof structure, mechanical structure of direct roof, roof deformation, whole process

**Introduction**
Gob-side entry retaining by roof cutting (GERRC) and pressure release is a novel non-pillar mining technique proposed in recent years based on the cantilever beam theory. The GERRC labor intensity is significantly reduced due to the absence of gob-side filling body (Yang et al., 2016), and it differs from conventional techniques by the absence of any fill system and totally different composition, formation mechanism, load transfer pattern, and stabilization mechanism (Zhu et al., 2020).

Many researchers worldwide studied the roof structure and migration law in the roadway retained along the gob. For example, Li and Hua (2012, 2017) studied the roof structure and movement in the roadway retained along the gob and proposed the concepts of large and small structures, which interaction determined the roof stability in the roadway retained along the gob. In further studies of these authors (Li et al., 2012), the breaking and movement features of the main roof during GERRC were characterized. It was deduced that the stability of key block B of the main roof was the deciding factor for roof stability and support intensity, whereas the engineering formula for support resistance of the roadway sidewalls was derived. Han et al. (2018, 2019) investigated the stress distribution patterns of the surrounding rocks in the roadway retained along the gob in the presence of a filling body in the roadway sidewalls. They proposed the roof presplitting for the control of cantilever beam length, which optimized the stress distribution during the gob-side entry retaining. Gao et al. (2017) and Ma et al. (2019) studied the mechanism of non-pillar roadway formation by roof cutting and analyzed the evolution process and mechanical action of the surrounding rocks in the roadway retained along the gob. On this basis, the stability control system for the roadway formed by roof cutting was developed. Ma et al. (2019) reported that the mine pressure data over the working face in the mining test of roadway formation by roof cutting had an asymmetrical distribution along the length direction of the working face. Then, based on the study of the stress distribution rule, He et al. (2018) showed that the stress was the lowest within the influence scope of the stress normal to the direction of the working face under non-pillar coal mining. Yin et al. (2019) established the mechanical model of interfacial stress on the coal seam and the numerical model depicting the evolution of the plastic region of the coal body in the retained roadway. Using these models, they performed analytical and numerical assessments of the main roof breaking position and identified the key influencing factors as follows: coal seam thickness, mining depth, mechanical features of the coal seam interface, and stress concentration factor. Wang et al. (2018) studied the movement pattern of the overlying strata and the deformation features of the surrounding rocks in the gob area. Yang et al. (2019) showed that the surrounding rock deformation was considerable during GERRC when the working face approached the
hanging wall or the footwall of the normal fault. Yang et al. (2018; Yan, 2018) reported that an increasing depth caused a decrease in the arch height in the large structure overlying the roadway retained along the gob and an increase in the arch span and axial ratio. The skew effect occurred in the roof during the stage of primary mining-induced advance influence in the roadway retained along the gob in the deep coal mine. The roof became concave and, thus, had a very high risk of caving, while the fissure field of the compound roof contained moderate- and low-angle separated fissures.

According to this brief literature survey, some progress was made concerning the roof movement rules and roof mechanical structure in the roadway with pillars and the GERRC-produced one without pillars. The existing studies usually provide a stage-by-stage description of the influence degree of mining when discussing the mechanical structure of the non-pillar GERRC. Moreover, coal ribs surrounding the roadway are generally treated as simply supported or clamped support points, without considering the support effect provided by coal ribs to the roof strata of the roadway retained along the gob. Determining the roadway roof deformation and the occurrence position of maximum deformation provides an important theoretical basis for roadway support. In this study, the mechanical model of the direct roof during the entire process of non-pillar GERRC is constructed. A calculation method for roadway roof deformation was proposed, and the theoretical basis was laid for roadway roof support.

**Stress features of the roof during the entire process of GERRC**

Stability of the main roof during gob-side roadway retaining has a direct impact on the stability of the small structure in the lower supported surrounding rocks, which, in turn, determines roadway roof deformation. Since the supports within the roadway cannot control the main roof movement, the roadway roof finally reaches the given deformation state (Han et al., 2013; Zhang et al., 2014). As compared to the conventional mining roadways, non-pillar GERRC has a longer life cycle. Under the excavation of the working face, the retained gob-side roadway is subjected to the dynamic pressure during the entire process, including roadway tunneling, primary mining, and secondary mining. Depending on the roof movement features in this period, the mining-induced effect is subdivided into five stages within the life cycle of the retained roadway: (1) stage I or tunneling stage, (2) stage II or primary mining-induced advance effect stage, (3) stage III or the stage of primary mining-induced effect on the retained roadway, (4) stage IV or retained roadway stability stage, and (5) stage V or secondary mining-induced effect stage. The directional presplit blasting performed along the roadway axis can weaken the mechanical constraint between the roadway roof and gob roof. Based on the above mechanical constraint, the roadway roof deformation is subdivided into two stages, namely, before and after roof cutting, as shown in Figure 1. The mechanical features of the roadway direct roof vary at different stages, which implies a stage wise variation of the roadway roof deformation, as shown in Figure 2.

The deformation of the roadway direct roof is controlled by the main roof subsidence. Support within the roadway can hardly reverse the deformation state of the main roof, but it controls the deformation duration of the main roof (Li et al., 2015; Zhu et al., 2018). The deformation of the direct roof determines the roof deformation within the roadway. Stress features of the roof were analyzed for the entire process of non-pillar GERRC, and the following findings were made:
Roadway tunneling stage: At this stage, roadway roof strata undergo no mining-induced fracturing or breaking. Both sides of the direct roof are supported by solid coal. Therefore, the clamped-clamped beam model applies to both ends of the direct roof, as shown in Figure 2(a). Without considering the coal seam dip angle and tectonic stress, the direct roof is mainly exposed to support resistance within the roadway and bearing stress, which is distributed symmetrically along the midline of the roadway roof.

Stage of primary mining-induced advance effect: At this stage, advance presplit blasting is performed for the roadway roof along the axial direction. After blasting, the presplit line...
cuts off the physical connection between the direct roof of the roadway and the gob roof, as shown in Figure 2(b). The bearing stress of the main roof along the dip direction migrates deep into the solid coal, while the main roof undergoes no significant subsidence. At this stage, the direct roof is subject to the joint action of the support resistance within the roadway, support force offered by solid coal in the lower segment, and bearing stress applied by the main roof.

Stage of primary mining-induced effect on the retained roadway: During extraction along the working face, the direct roof first undergoes breaking and caving in the gob area. Meanwhile, the strata caving occurs progressively from the bottom to the top. The main roof first breaks along the presplit line, producing key blocks. Under the gravity effect and the stress imposed by overlying strata, the main roof of the roadway undergoes subsidence towards the gob area. At this stage, the main roof of the roadway can be considered as a cantilever beam, as shown in Figure 2(c). As the bending moment in the main roof increases, the main roof breaks again at the breaking point deep in the solid coal in the lower segment. The main roof undergoes rotational subsidence along the breaking point towards the gob area to form a stable load-bearing structure. The direct roof of the roadway reaches the particular deformation level and undergoes intense deformation. At this stage, the roadway direct roof is subject to support resistance within the roadway, support force offered by solid coal in the lower segment, and bearing stress imposed by the main roof.

Stage of retained roadway stability: The key blocks formed by the fracturing of the main roof interlock with each other and touch the gangues, thus forming a bearing structure that is temporarily stable at this stage. The overlying strata stress borne by this structure is transferred, on the one hand, deep into the solid coal in the lower segment, and on the other hand, to the gob gangues, as shown in Figure 2(d). The stability of this structure determines the stability of the roadway direct roof. At this stage, the direct roof is subject to support resistance within the roadway, support force offered by solid coal in the lower segment, and bearing stress applied by the main roof.

Stage of secondary mining-induced effect on the retained roadway: Under the excavation along the working face, the left-behind roadway is abandoned. Therefore, only stress features of the roof within the advance effect scope of secondary mining are considered. At this stage, the main roof forms a bearing structure. Under the secondary mining-induced advance effect acting along the working face, the main roof undergoes further rotational subsidence, leading to instability of the bearing structure. As a result, the roadway roof deformation further increases, and strata pressure becomes intense, as shown in Figure 2(d). The direct roof is subject to support resistance within the roadway, support force offered by solid coal along the working face, and bearing stress imposed by the main roof.

**Mechanical model of the direct roof during the entire process of GERRC**

**Mechanical model elaboration**

Based on the above-mentioned stress features of GERRC at different stages, the direct roof of the roadway is subdivided into two parts. The stress features of each part are analyzed below: (1) within the roadway width, the direct roof is subject to the bearing stress and support resistance within the roadway, and (2) above the coal seam, the direct roof is acted
upon by the support force imposed by the solid coal and the bearing stress imposed by the main roof.

Here, the direct roof is assumed to be an elastic body, which satisfies the small-scale deformation condition. The following assumptions are also made to facilitate theoretical analysis.

It is assumed that the stress imposed by the main roof to the direct roof above the roadway is uniformly distributed, with the load intensity $q_1$.

It is assumed that the anchoring force is uniformly transferred by the anchor bolt to the roadway roof, with the load intensity $q_3$.

The bulk force imposed by the passive support within the roadway is equivalent to the bulk load $R_b$. Here, it is used to represent the support force offered by the single prop.

It is assumed that the load imposed by the coal seam to the direct roof is linearly distributed. This distributed load is equal to $q_2$ at the sidewalls and to $\lambda q_2$ in the ultimate equilibrium position.

It is assumed that the load transferred from the main roof to the direct roof is linearly distributed. This distributed load is $q_1$ at the sidewalls and $\lambda q_1$ in the ultimate equilibrium position.

It is assumed that the roof slate layer can not collapse and fill the gob within the range of cutting height.

Based on the above assumptions, the mechanical model depicted in Figure 3 was elaborated. The left boundary of the model corresponds to the position of ultimate equilibrium in the solid coal in the lower segment; the right boundary corresponds to the pre-split line beside the roadway. This mechanical model is further simplified by the small-scale deformation condition, as shown in Figure 4. The load acting on the direct roof is subdivided into three constituents with the following specific features.

Stresses in the direct roof induced by the main roof and solid coal are superimposed. The distributed load is assessed by the superimposition of the bearing stress imposed by the main roof, gravity force of the direct roof, and support counterforce from the solid coal. This load obeys a linear distribution. Its value is $q$ at the roadway sidewalls and $\lambda q$ in the position of ultimate equilibrium, where parameter $\lambda$ reflects the stress concentration effect.

The bearing stress imposed by the main roof and the support resistance within the roadway are superimposed on the direct roof. This stress is a uniformly distributed load $q_1$.

The support force imposed by the single props is reduced to the bulk load $R_b$ within the roadway cross-section. This allows one to study the effect of equivalent bulk load exerted on the direct roof.
Basic equations of the mechanical model

Equilibrium relationship of the model. This mechanical model is a quadratic statically indeterminate model. Therefore, the equilibrium condition is not sufficient to derive all unknown forces. A plausible solving method is to transform the complex distributed force into the superposition of several simply distributed forces. Then the supplementary conditions are sought to derive all unknown forces so as to determine the deflection of the roadway roof and to analyze the roof deformation patterns at various stages. According to the stress superposition principle, the simplified mechanical model (Figure 3(b)) is equivalent to the superposition of five elementary mechanical models, as shown in Figure 4.

Expressions for the cantilever beam deflection via these models have the following forms:

A uniformly distributed load applied to the cantilever beam.

\[
\omega = \begin{cases} 
\frac{qx^2}{24EI} (6a^2 - 4ax + x^2), & 0 \leq x \leq a \\
\frac{qa^3}{24EI} (4x - a), & a \leq x \leq l 
\end{cases}
\]

Triangular load distribution applied to the cantilever beam.

\[
\omega = \begin{cases} 
\frac{px^2}{120aEI} (10a^3 - 10a^2x + 5ax^2 - x^3), & 0 \leq x \leq a \\
\frac{pa^3}{120EI} (5x - a), & a \leq x \leq l 
\end{cases}
\]

Uniformly distributed load at the end of the cantilever beam.

\[
\omega = \begin{cases} 
\frac{q_1x^2}{12EI} (3bl + 3ab - 2bx), & 0 \leq x \leq a \\
\frac{q_1}{24EI} (x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4), & a \leq x \leq l 
\end{cases}
\]
A bulk load applied to the cantilever beam.

\[
\omega = \begin{cases} 
\frac{1}{6EI} R_b x^3 - \frac{1}{2EI} R_b x_0 x^2, & 0 \leq x \leq x_0 \\
-\frac{1}{2EI} R_b x_0^2 x + \frac{1}{6EI} R_b x_0^3, & x_0 \leq x \leq l
\end{cases}
\]  \tag{4}

The bulk bending moment at the end of the cantilever beam

\[
\omega(x) = -\frac{M_b x^3}{2EI}
\]  \tag{5}

According to the stress superposition principle, at the single prop \(x_0\), the deflection of any point in the roadway is given by:

\[
y(x) = \begin{cases} 
\frac{qa^3}{24EI} (4x - a) + \frac{pa^3}{120EI} (5x - a) + \frac{q_1}{24EI} (x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
+ \frac{1}{6EI} R_b x^3 - \frac{1}{2EI} R_b x_0 x^2 - \frac{M_b x^3}{2EI}, & a \leq x \leq x_0 \\
\frac{qa^3}{24EI} (4x - a) + \frac{pa^3}{120EI} (5x - a) + \frac{q_1}{24EI} (x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
- \frac{1}{2EI} R_b x_0^2 x + \frac{1}{6EI} R_b x_0^3 - \frac{M_b x^3}{2EI}, & x_0 \leq x \leq l
\end{cases}
\]  \tag{6}

Before the roof pre-splitting, loads in both roadway sidewalls are considered symmetrical. Thus, the subsidences of both sidewalls are also symmetrical, so \((\omega)_{x=a} = (\omega)_{x=l}\). On this basis, the displacement compatibility equation is obtained as follows:

\[
\frac{qa^4}{8EI} + \frac{pa^4}{30EI} + \frac{q_1 a^2}{12EI} (3l^3 - 2la - a^3) + \frac{1}{6EI} R_b a^3 - \frac{1}{2EI} R_b l a^2 - \frac{M_b a^3}{2EI} = 0
\]  \tag{7}

The above formula can be reduced to the following form:

\[
4qa^3(a - l) + pa^3(a - l) + 3q_1(2l^2a^2 - a^4 - l^4) = 12M_b(a^3 - l^3) + 4R_b(3la^2 - 2l^3 - a^3)
\]  \tag{8}

Let the stiffness of the single prop be \(k\), then the stress \(R_b\) of the single prop can be used to determine the deformation of the rigid body. The latter is the roof deflection under the action of all external forces, that is, \(R_b = k\omega\):

\[
\frac{qa^3}{24EI} (4x - a) + \frac{pa^3}{120EI} (5x - a) + \frac{q_1}{24EI} (x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
\times \frac{1}{6EI} R_b x^3 - \frac{1}{2EI} R_b x_0 x^2 - \frac{M_b x^3}{2EI} = \frac{R_b}{k}
\]  \tag{9}
**Mechanical model of the deformation process before the roof cutting**

Before the roof splitting, \( k \) is the coal seam stiffness. By substituting \( x = x_0 = 1 \) into the above formula, we get:

\[
5qa^3(4l - a) + pa^3(5l - a) + 5q_1(3l^4 - 4a^3l + a^4) = \frac{120EI}{k} R_b + 40R_bl^3 + 60M_bl^3 \quad (10)
\]

The system of simultaneous equations can be constructed using the displacement compatibility equation (8) and equation (10), which yields the following formulas for the bending moment \( M_b \) and bulk load \( R_b \):

\[
M_b = \frac{4qa^3(a - l) + pa^3(a - l) + 3q_1(2l^2a^2 - a^4 - l^4) - 4R_b(3la^2 - 2l^3 - a^3)}{12(a^3 - l^3)} \quad (11)
\]

where:

\[
R_b = \frac{\begin{bmatrix}
5qa^3(4l - a)(a^3 - l^3) + pa^3(5l - a)(a^3 - l^3) + 5q_1(3l^4 - 4a^3l + a^4)(a^3 - l^3) \\
- 20qa^3(a - l)^3 - 5pa^3(a - l)^3 - 15q_1(2l^2a^2 - a^4 - l^4)l^3
\end{bmatrix}}{20\left[6\frac{EI}{k}(a^3 - l^3) + 3a^2l^3(a - l)\right]} \quad (12)
\]

Thus, according to the above formula (9), the displacement at any point of the roadway before roof pre-splitting can be calculated.

\[
y(x) = \frac{qa^3}{24EI}(4x - a) + \frac{pa^3}{120EI}(5x - a) + \frac{q_1}{24EI}(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
+ \frac{1}{6EI}R_bx^3 - \frac{1}{2EI}R_blx^2 - \frac{M_bx^3}{2EI} \quad (13)
\]

where \( M_b \) and \( R_b \) are known.

**Mechanical model of the deformation process after the roof cutting**

After the roof cutting, \( M_b = 0 \), and the supplementary condition is reduced to formula (14):

\[
\begin{align*}
\frac{qa^3}{24EI}(4x - a) + \frac{pa^3}{120EI}(5x - a) + \frac{q_1}{24EI}(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
- \frac{1}{2EI}R_bx_0^3x + \frac{1}{6EI}R_bx_0^3 = \frac{R_b}{k} , \quad x_0 \leq x
\end{align*}
\]

\[
\begin{align*}
\frac{qa^3}{24EI}(4x - a) + \frac{pa^3}{120EI}(5x - a) + \frac{q_1}{24EI}(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
\frac{1}{6EI}R_bx^3 - \frac{1}{2EI}R_bx_0^3x^2 = \frac{R_b}{k} , \quad a \leq x \leq x_0
\end{align*}
\]
Thus, the roof subsidence can be calculated by formula (15):

\[
y(x) = \begin{cases} 
5qa^3(4x - a) + pa^3(5x - a) + 5q_1(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
120EI + 20kx_0^2(3x - x_0) 
\end{cases}, \quad x_0 \leq x
\]

\[
y(x) = \begin{cases} 
5qa^3(4x - a) + pa^3(5x - a) + 5q_1(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
120EI + 20kx^2(3x_0 - x) 
\end{cases}, \quad a \leq x \leq x_0
\]

(15)

**Calculation model for direct roof deformation during the entire process of GERRC**

According to the stress features shown in Figures 4, 5(a) and 5(b), we get \( \lambda q - q = p \).

After substituting this expression into formula (15), the roof deformation during the entire process takes the following form:

\[
y(x) = \begin{cases} 
q(15a^3x + 5\lambda a^3x - 4a^4 - \lambda a^4) + 5q_1(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
120EI + 20kx_0^2(3x - x_0) 
\end{cases}, \quad x_0 \leq x
\]

\[
y(x) = \begin{cases} 
q(15a^3x + 5\lambda a^3x - 4a^4 - \lambda a^4) + 5q_1(x^4 - 4lx^3 + 6l^2x^2 - 4a^3x + a^4) \\
120EI + 20kx^2(3x_0 - x) 
\end{cases}, \quad a \leq x \leq x_0
\]

(16)

where \( y(x) \) is the deflection at the position \( x \) of the roadway; \( q_1 \) and \( q \) are superimposed stresses acting on the roadway roof and coal ribs, respectively; \( a \) and \( l \) are distances between the ultimate equilibrium position and the roadway left and right sidewalls, respectively; \( \lambda \) is the degree of stress concentration at the ultimate equilibrium position; \( E \) is the elastic modulus of the roadway roof (i.e., direct roof); \( I \) is the moment of inertia of roadway roof (direct roof), which is related to the roof thickness \( h \); \( k \) is the stiffness of the support system; \( x_0 \) is the single prop positions.

According to formula (16), the parameter \( R_b \) in the GERRC-produced roof uniform mechanical model is the equivalent bulk load of passive supports. Here, single props are chosen as the object of study, and \( k \) represents the single prop system stiffness. As the stiffness of the support system changes, \( R_b \) represents not only the single prop, but also such passive supports as the gob-side filling body, breaker props, and solid coal. When \( k \) is infinitely large, the roof does not deform at the support position. When \( k \) is 0, it is considered that the roadway roof has no passive supports. This mechanical model is built based on the stress features of the roof for the GERRC at different stages by assuming that the direct roof is an elastic deformation body. In fact, this model not only applies to roof deformation calculation for GERRC, but also to gob-side entry retaining with roadway side packing, and conventional excavation roadway along the working face.

**Calculation of several key parameters**

**Calculation of \( q_1 \) and \( q \).** As shown in Figure 3, \( q_3 \) is the force applied by the anchor bolt (cable), which fixed and anchor ends are located within the direct roof and the main roof, respectively.
According to Newton’s third law of motion, $q_3$, applied by the anchor bolt (cable) is not superimposed with $q_1$, as shown in Figure 5.

Therefore, the value of $q_1$ is the sum of the following two constituents: (1) weight of the key overlying strata over the main roof and below the second stratum and (2) weight of the direct roof within the roadway scope. The first constituent is calculated via formula (17) (Qian and Shi, 2010):

$$ (q_n)_1 = \frac{E_1 h_1^3 (\gamma_1 h_1 + \gamma_2 h_2 + \ldots + \gamma_n h_n)}{E_1 h_1^3 + E_2 h_2^3 + \ldots + E_n h_n^3} $$

where $E$, $\gamma$, and $h$ are the elastic modulus (MPa), volume force (kN/m$^3$), and stratum thickness (m), while indices 1 and $n$ correspond to the first and $n$th key strata, respectively.

The main roof deformation, as the first key stratum, determines the direct roof deformation. After extraction of the working face and before the formation of a stable load-bearing structure from the main roof, the weight of the main roof plus its overlying strata uniformly acts on the direct roof. Similarly, at the continuous roof deformation stage, the main roof does not form a stable load-bearing structure.

Figure 5. Analysis of stresses imposed by the anchor bolt (cable) on the direct roof.
The supporting force of the coal seam to the roof in the limit equilibrium area is generally taken as 0.1 MPa in engineering practice (Chen et al., 2019). Therefore, \( q = (q_1 - 0.1) \).

Without considering the support resistance applied by the coal ribs in the lower segment to the direct roof, this yields that \( q = q_1 \).

**Calculation of the support system stiffness**

Single props during GERRC are studied. The support system stiffness \( k \) is the roof and floor subsidence, which corresponds to the increment of the working resistance of a single prop (N/m). Due to the initial support force of a single prop, the support stiffness is considered as the ratio of the roof and floor subsidence to the increment of the prop working resistance, which is derived as:

\[
 k = \frac{\Delta p}{\Delta s} \quad (18)
\]

**Calculation of width \( a \) for the ultimate equilibrium region**

During the roadway tunneling stage, that is, when exceeding the advance working face to a certain extent, the region of ultimate equilibrium is free from the mining-induced effect. The roadway is in the in-situ stress state. In the case, the value of \( a \) is usually the scope of the broken rock zone, It is calculated by equation (19) (Liu et al., 2020):

\[
 R_p = R_0 \left[ \frac{(p_0 + cc \cot \phi)(1 - \sin \phi)}{p_1 + cc \cot \phi} \right]^{1 - \sin \phi} \frac{\tan \phi}{\sin \phi} \quad (19)
\]

where \( R_0 \) is the roadway radius, \( p_0 \) and \( p_1 \) are the in-situ stress and support counterforce, respectively, \( c \) is the cohesion, and \( \phi \) is the internal friction angle.

When the gob is formed on one side, the maximum scope of \( a \) is the position where the main roof breaks in the solid coal in the lower segment, as defined in (Chen et al., 2019):

\[
 a = \frac{\lambda m}{2 \tan \phi_0} \ln \left[ \frac{k_\gamma H + \frac{c_0}{\tan \phi_0}}{\frac{c_0}{\tan \phi_0} + \frac{c}{z}} \right] \quad (20)
\]

where \( c_0 \) and \( \phi_0 \) are the cohesion of the interface between the coal seam and the top and bottom slate, \( p_x \) is the support strength of coal wall, \( m \) is the thickness of coal seam, \( \lambda \) is the coefficient of lateral pressure, \( k \) is the factor of stress concentration, \( \gamma \) is the average rock mass force, \( H \) is the Mining depth.

The width \( a \) of the ultimate equilibrium region can also be determined by field measurements.

**Example calculation**

The gob-side entry at 7135 working face in the Qidong Coal Mine (located in Suzhou, Anhui Province of China) was chosen for an example calculation. The ventilation roadway in the working face was the gob-side entry retained by roof cutting, which covered a length of 1100 m~1434m ahead of the cutting hole. The non-pillar GERRC length was 334 m, the dip...
and strike lengths of the working face were 175 and 1688 m, respectively. The average burial depth $H$ of the working face was 520 m, the coal seam thickness $m$ was 3 m, the ventilation roadway width $b$ of the 7135 working face was 5.0 m, and the direct roof thickness $h$ was 3 m. Anchor cables and single props were used in the 7135 working face as reinforcement props to ensure the roof stability during roof cutting and gob-side entry retaining. The arrangement of supports with the density of single props of 1.75 props/m² is shown in Figure 6.

The gob-side entry retained by roof cutting in the 7135 working face was tested only at a length of 334 m. After extraction of the 7135 working face, the roof and floor deflections measured on-site and the resistance distribution of supports corresponded to stages I-IV for the retained entry, while stage V of secondary mining-induced effect on the retained entry was not reached yet. During extraction of the 7135 working face, measuring points for roof and floor displacements and stresses were selected ahead of the working face to obtain the roof and floor deformation and stress conditions under the GERRC. The roof stress distribution was analyzed by measuring the stress of the reinforcement anchor cable and the resistance of chock supports in the working face. The roof and floor displacements were measured using the cross-shaped measuring point method. Stresses in the reinforcement anchor cable were measured by the anchor cable dynamometer, and the working resistance of the chock supports by a pressure gauge. The layout of measuring points is depicted in Figure 7.

![Diagram of supports on the roadway cross-section at the stage of primary mining-induced effect on the retained roadway.](image-url)

**Figure 6.** Diagram of supports on the roadway cross-section at the stage of primary mining-induced effect on the retained roadway.
Analysis of the roof and floor deformations

The roof subsidence, floor heave, and deformation rate curves are plotted in Figure 8. The analysis of deformation patterns depicted in Figure 9 revealed the following specific features:

The deflections of the roadway roof and floor are small (not exceeding 10 mm) within the length of 40–80 m ahead of the working face. At this stage (treated as the tunneling stage),
the roadway is outside the scope of primary mining-induced advance effect, and the main roof contains no apparent mining-induced fissures or cracks. The deformation rates of the roof and floor are also low.

At distances of 0–40 m ahead of the working face, both roof deformation and floor heave increase under advance mining and pre-split blasting actions. The maximum floor heave is significantly larger than the maximum roof subsidence. The deformation rate of the floor first increases and then drops, being always larger than that of the roof, which shows a generally increasing trend. The roof and floor deformations are intense at the start of this stage, their maximum values being 61 and 106 mm, respectively. The maximum roof-to-floor convergence is 167 mm. This stage corresponds to the stage of primary mining advance effect.

At distances of 0–100 m behind the working face, the main roof of the roadway at this stage acts as a cantilever beam, which undergoes bending, breaking, rotational subsidence, and hinging to form a load-bearing structure, as well as induce compressive deformation. The roof and floor deformations are significant. The deformation rate of the roof and floor first increases and then decreases. At this stage, the floor deformation is larger than that of the roof. The maximum floor and roof deformations are 360 and 300 mm, respectively. The maximum roof-to-floor convergence is 660 mm. This stage is considered the stage of primary mining-induced effect on the retained roadway.

At distances of 100–150 m behind the working face, the roof strata are in a relatively stable state. The deformation rate of the roof and floor is low and stable. The maximum roof and floor deformations stabilize at 320 and 370 mm, respectively, while the maximum roof-to-floor convergence is 690 mm. This stage is considered the stage of retained roadway stability under primary mining.
Stress analysis of roof supports within the roadway

The influence scope of single props ranges from the distance of 40 m ahead of the working face to the region of retained roadway stability. Therefore, the monitoring scope of the working resistance of single props is from 40 m ahead of the working face to 120 m behind the working face, as shown in Figure 9.

As shown in Figure 10, at the stage of primary mining-induced advance effect, the working resistance of single props increases from 141 to 165 kN due to roof pre-splitting, i.e., by 17%. At the stage of primary mining-induced effect on the retained roadway, the working resistance of the single props at 5–100 m of the left-behind working face increases dramatically from 165 to 250 kN, i.e., by 52%. At the stage of retained roadway stability under primary mining (at 100~120 m of the left-behind working face), the working resistance of the single props stabilizes at 250 kN.

The analysis of Figures 9 and 10 revealed that, as the working resistance of the single props increased from 165 to 250 kN, the roof-to-floor convergence rose from 167 to 660 mm. Thus, the stiffness of the support system $k$ can be derived as follows:

$$k = \frac{\Delta p}{\Delta s} = \frac{1.75 \times 85 \text{kN}}{0.493 \text{m}} = 0.3 \times 10^6 \text{N/m}$$  \hspace{1cm} (21)

Model verification

The gob-side entry at 7135 working face in the Qidong Coal Mine was used to verify the applicability of the uniform mechanical model for the direct roof in GERRC. The relationship between the roadway roof deformation $y(x)$ and stiffness of the support system $k$ was analyzed. The period of roof deformation used in calculations covered stages I-IV (from the tunneling stage until the stage of primary mining-induced effect on the retained entry). The comprehensive strata log diagram of the roof stratum in the working face was drawn, and the measurement results of mechanical parameters of the strata were obtained, as shown in Table 1.
Calculation via formula (17) yields \((q_2)_1 = 0.63 \text{ MPa}\) and \((q_3)_1 = 0.62 \text{ MPa}\). The direct roof is the mudstone, whereas the elastic modulus is 0.1 GPa, volume force is 0.25 MN/m\(^3\), and stratum thickness is 3 m. Therefore, \(q_1 = 0.7 \text{ MPa}\). According to the moment of resultant force theorem and the scheme depicted in Figure 6, we get: \(x_0 = a + 2.3 \text{ m}\).

Other parameters are determined by field measurement: \(a = 4.0 \text{ m}, \lambda = 2.0, x_0 = 6.3 \text{ m}, I = 2.25 \text{ m}^4, q = 0.6 \text{ MPa}, \) and \(k = 0.3 \times 10^6 \text{ N/m}\).

Calculations via formula (16) were performed using the standard Matlab software. The relationship between roof deformation for different positions of the roadway and the support system stiffness was plotted, as shown in Figure 10.

Before roof cutting, no single props were used, while the roof deformation exhibited a symmetrical distribution about the midline. The maximum roof deformation occurred in the middle of the roadway. As the coal mine stiffness increased, the maximum roof subsidence dropped. After roof cutting, when the stiffness of the single prop system within the roadway reached \(0.3 \times 10^6 \text{ N/m}\), the maximum roof deformation, which occurred along the presplit line, was calculated as 280 mm. The discrepancy between the calculated and measured maximum deformation values was 12.5\%, which proved the proposed method feasibility and good accuracy of formula (16) for the direct roof deformation assessment.

**Conclusions**

1. Based on the mechanical features of the roof during the entire process of GERRC, the roadway roof deformation can be subdivided into the following five stages: tunneling stage, stage of primary mining-induced advance effect, stage of primary mining-induced effect on the retained roadway, stage of retained roadway stability, and stage of secondary mining-induced effect. The mechanical model of the direct roof deformation was elaborated for the entire process of GERRC. Thus, the calculation formula for the direct roof deformation in different positions during the entire process of GERRC was derived. The key parameters of the formula were analyzed and calculated.

2. The distribution rules of the roof and floor deformation and working resistance of single props were analyzed through an engineering example for different stages of GERRC. The stiffness of the single prop support system was calculated, and the relationship between roadway roof deformation and stiffness of the support system was derived and plotted. The roof deformation at the tunneling stage was found to be symmetrically distributed about the midline, and its maximum value corresponded to the middle of the roadway. As the coal seam stiffness increased, the maximum roof deformation dropped.

3. An example calculation for the particular case study (the 7135 working face in the Qidong Coal Mine, China) was performed using the uniform mechanical model of the direct roof deformation for the entire process of GERRC. At the stage of primary mining-induced effect on the retained roadway, the calculated maximum roof deformation was 280 mm.
versus its measured value of 320 mm, the error rate being 12.5%. These results demonstrate that the proposed uniform mechanical model is suitable for direct roof deformation calculation during the GERRC process.

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