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OVERBURDEN FAILURE AND GROUND PRESSURE BEHAVIOUR OF LONGWALL TOP COAL CAVING IN HARD MULTI-LAYERED ROOF

ZAWAŁ WARSTW NADKŁADU W WIELOWARSTWOWYM STROPIE I KSZTAŁTOWANIE SIĘ CIŚNIENIA WARSTW GÓRNYCH GÓROTWORU W TRAKCIE WYBIERANIA ŚCIANOWEGO PROWADZONEGO NA ZAWAŁ

In the extra-thick coal seams and multi-layered hard roofs, the longwall hydraulic support yielding, coal face spalling, strong deformations of goaf-side entry, and severe ground pressure dynamic events typically occur at the longwall top coal caving longwall faces. Based on the Key strata theory an overburden caving model is proposed here to predict the multilayered hard strata behaviour. The proposed model together with the measured stress changes in coal seam and underground observations in Tongxin coal mine provides a new idea to analyse stress changes in coal and help to minimise rock bursts in the multi-layered hard rock ground. Using the proposed primary Key and the sub-Key strata units the model predicts the formation and instability of the overlying strata that leads to abrupt dynamic changes to the surrounding rock stress. The data obtained from the vertical stress monitoring in the 38 m wide coal pillar located adjacent to the longwall face indicates that the Key strata layers have a significant influence on ground behaviour. Sudden dynamically driven unloading of strata was caused by the first caving of the sub-Key strata while reloading of the vertical stress occurred when the goaf overhang of the sub-Key strata failed. Based on this findings several measures were recommended to minimise the undesirable dynamic occurrences including pre-split of the hard Key strata by blasting and using the energy consumption yielding reinforcement to support the damage prone gate road areas. Use of the numerical modelling simulations was suggested to improve the key theory accuracy.

Keywords: multi-layer hard roof; failure of overlying strata; ground pressure behaviour; longwall top coal caving

Przy eksploatacji pokładów węgla o dużej miąższości i w warunkach stropu złożonego z wielu warstw górotworu w rejonie przodka ściany występuje szereg niekorzystnych zjawisk dynamicznych skutkujących zmianami ciśnienia górotworu: ugięcie podpór hydraulicznych stabilizujących strop, pękanie skały węglowej w rejonie przodka, silne odkształcenia chodnika od strony zrobów. W oparciu o teorię

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warstwy kluczowej (o największej nośności), zaproponowano model zawału warstwy nadkładu do prognozowania zachowania wielowarstwowej formacji złożonej ze skał twardych. Zaproponowany model w połączeniu z pomiarami zmian ciśnienia w pokładzie węgla oraz wynikami obserwacji w podziemnej kopalni węgla Tongxin umożliwia analizę zmian ciśnienia w złożu przyczyniając się do redukcji ryzyka wystąpienia tąpnięć w górotworze zbudowanym z wielu warstw skalnych. Uwzględniając charakterystyki podstawowych warstw kluczowych, model umożliwia prognozowanie wystąpienia niestabilności warstw nadkładu, które prowadzić mogą do gwałtownych zmian ciśnienia w otaczających warstwach. Dane z monitoringu naprężeń pionowych rejestrowane w filarze węglowym o szerokości 38 m zlokalizowanym w pobliżu przodka ściany wskazują, że warstwy kluczowe górotworu w zasadniczy sposób warunkują zachowanie się gruntu. Gwałtowne odprężenie warstw górotworu wskutek zjawisk dynamicznych spowodowane zawałem warstwy znajdującej się poniżej warstwy kluczowej przy ponownym obciążeniu wskutek naprężeń pionowych wystąpiło w momencie zawału nawisu górnej ławy warstwy znajdującej się poniżej warstwy kluczowej. W oparciu o te ustalenia, zaproponowano szereg rozwiązań mających na celu zminimalizowanie skutków niekorzystnych zjawisk dynamicznych, w tym wstępne rozszczepienie twardych warstw kluczowych poprzez wybuchy i zabezpieczenie obudową wejść do chodników, które mogłyby ulec uszkodzeniu. Zaproponowano wykorzystanie modelu wraz z symulacjami numerycznymi w celu poprawy dokładności teorii dotyczącej zachowania warstw kluczowych w górotworze.

Słowa kluczowe: strop złożony z wielu warstw skał twardych, zawał warstw nadkładu, zmiany ciśnienia gruntu, zawał stropu skały węglowej w rejonie przodka

1. Introduction

A distinct periodic weighting of overburden strata above the longwall panel in Tongxin underground coal mine has been observed where the strata caving process impacted the safety and production of coal. Liaoning Technical University (LNTU) had initiated the investigations to find solutions to these problems. Influence of the hard strata layers on ground behavior has been researched in the past but the underground investigations were restricted to one or two hard roof layers only. The Key strata theory was used primarily to predict the fracture formation in hard strata to control water inrush or surface strata movement/subsidence. The Key theory was not used to predict stress changes and its influence on longwall mining. The LNTU researchers applied the current Key strata theory to predict the multilayered hard strata behavior and measured the stress changes within the longwall pillar to quantify the periodic weighting impact of the ground behavior.

Previous Research

Hard roof is often referred to as being high in strength, large thickness and strong integrity immediate stone roof overlaying coal seam. It is often made of thick and hard sandstone, conglomerate or limestone that resists fracture formation. Typically, hard roof tends to overhang the excavations. As a result, a working face with hard roof often experiences strong pressures, large dynamic load concentration factors (1.5 to 3.5), first weighting intervals of more than 50-160 m and large suspended roof area of 10 000-30 000 m^2 or greater. Due to high stress concentrations ahead and above the longwall face, sudden roof falls may occur and produce great impact loads at the working face causing support damage and safety hazards to workforce (Zhu et al., 1991; Li et al., 2009).

The characteristics of high ground stress in hard roofs around the longwall face have been extensively studied. Guo et al. (2017) estimated the support resistance based on the structural characteristics of overlying strata for a thick seam longwall mining face. Wang et al. (2008)

developed an elastic bedding strata mechanical model to analyse the caving process of the roof (Wang et al., 2008). Li et al. (2015) studied the overlying strata caving procedure of a hard roof face and established a mechanical model to determine the criterion of support loads yielding. Shen et al. (2016) proposed a mechanical mode to study the caving interval for two layers of hard overlaying strata located close together in extra-thick coal seam mining. The authors found that roof instability in this type of strata was related to a lower cantilever beam and an upper voussoir beam structures. Pang and Zhang (2013) established a thin roof mechanical model for hard roof 'island' longwall face where goaf exists on all sides. The energy exchange characteristics of the hard roof were studied before and after roof caving. Based on field measurements, Wei et al. (2002) established a hard roof cantilever beam model for top coal caving longwall face, and improved the calculation method for support resistance. Shi and Wang (2010) studied the failure behavior of thick hard roof using fixed beam gravity loaded model, and developed a method to identify three kinds of failure modes for this strata. Based on the characteristics of hard roof longwall face, such as large initial collapse interval and long subsequent suspension length, Wang et al. (2009) developed three methods to control caving for the initial roof fall and calculated the probable suspension length in periodic roof falls. Palchik (2003, 2005) divided the fractured zone into three sections: rock blocks, vertical penetration fractures and horizontal fractures caused by bedding strata separation. Yu (2016) studied the overlying strata of extra-thick coal seams mined using top-coal caving method and found that certain hard strata units play an important role in overlying ground movement. The hard roof deformation was analysed using square-form model under four-edge-clamped thin-beam assumption (Xu et al., 2016). The Winkler beam model was used by Wang et al. (2016), who studied the failure process of hard and thick strata located far from the coal seam. Wen et al.(2016 and 2019) established overlying strata structural modeling to study failure characters and calculate support load. Jiang et al. (2016) established a front abutment stress model to study the deformation and energy distribution in hard roof prior to periodic weighting.

In this paper, the overlying strata caving process and corresponding ground pressure development under multi-layered hard roof are analysed from Tongxin coal mine data in Datong, China. The characteristics of the ground behaviour development under multi-layer hard roof are further analysed here to provide a guidance for mining safety and economy.

2. Overview of engineering geology in Tongxin mine

Tongxin coal mine is located in Datong coalfield, Northern China, as shown in Fig. 1. No. 3 coal seam that belongs to permo-carboniferous system is being mined. The coal seam is inclined at 1-4°, with an average dip of 2°. The upper multi-Jurassic coal seams have been mined out. The overlying strata include fine sandstone, coarse grained sandstone, siltstone, medium sandstone and sandy mudstone (Table 1), among which the sandy rock strata account for 9095%, whereas mudstone and coal seam only account for 5-10%. No.8105 longwall working face was located adjacent to No.8104 longwall face development (Fig. 2). The barrier pillar 38 m wide separated the single entry gate roads of each longwall. The No.8105 longwall working face was 200 m wide and 1757.1 m long and 440-450 m deep. The average coal seam thickness was approximately 15.3 m. Fully mechanized top-coal caving mining method was employed. The coal was cut to a height of 3.9 m while the top coal caving height averaged 11.4 m. ZF/15000/27.5/42 hydraulic supports were used. No.5404 and No.5105 tailgate roads were used for ventilation of No.8104 and

No.8105 longwall working faces, respectively. The 5 m wide and 3.7 m high rectangular tailgate roadways were used while the main gate roadways No.2104 and No.2105 were rectangular in shape and 5.6 m wide and 3.4 m high.

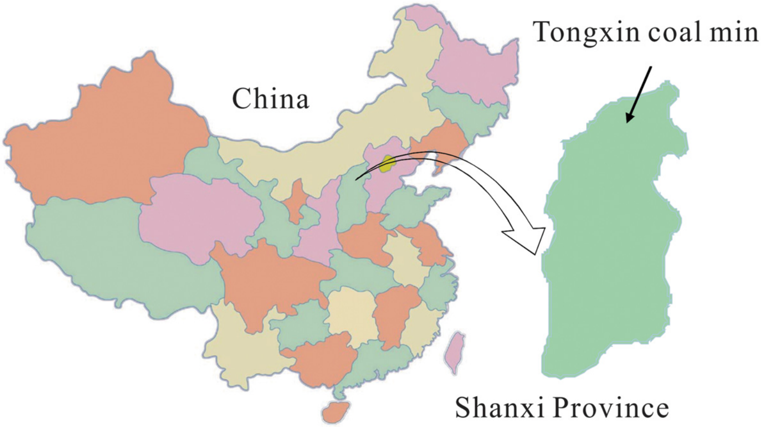

Fig. 1. Geographical location of Tongxin coal mine

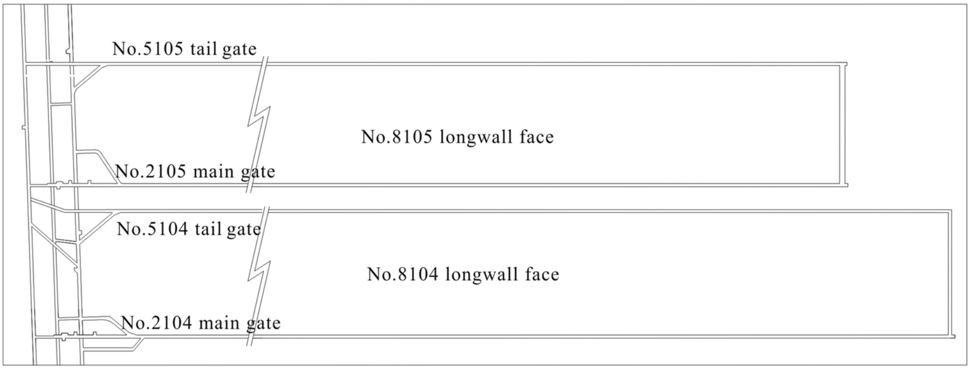

Fig. 2. Layout of No.8104 and No.8105 longwall faces

During mining, working face experienced frequent strong ground pressure causing the hydraulic supports to yield and coal face to spall. The goaf-side entry also experienced large dynamic ground pressure, causing significant roof deformation and convergence, bolt failure and distortion of steel straps. The additional support with extra bolts and cables were installed to control the goaf-side tailgate entry which increased the total working load and caused safety problems. The ground behavior under this condition is higher than that of conventional working face, mainly because the thick hard roof is not easy to fall, and the large-area suspended roof increases the stress concentration of the coal around goaf. It is therefore important to analyse the overlying strata movement and vertical stress changes around the longwall top coal caving to understand the strata behavior and provide data for more stable and safer longwall designs.

TABLE 1

Characteristics of overlying strata

No.	Lithology	Actual thickness (m)	Bulk force (kN/m^3)	Tensile strength (MPa)	Elastic modulus (GPa)
Y1	Sandy Mudstone	3.2	26.31	5.47	18.35
Y2	K3 Sandstone	5.3	25.44	7.68	36.21
Y3	medium sandstone	7.7	26.73	6.14	29.57
Y4	fine sandstone	2.1	27.12	7.81	35.54
Y5	siltstone	5.3	26.45	4.97	23.64
Y6	4 coal	2.1	10.36	1.27	4.20
Y7	siltstone	2.4	25.78	4.25	23.35
Y8	kernstone	4.3	24.21	4.82	20.32
Y9	fine sandstone	14.8	25.62	8.20	35.62
Y10	conglomerate	12.9	27.35	4.34	28.43
Y11	kernstone	3.5	23.89	5.24	19.98
Y12	conglomerate	12.0	27.10	4.34	28.74
Y13	medium sandstone	13.7	25.52	7.01	29.62
Y14	siltstone	3.2	24.58	4.45	23.48
Y15	fine sandstone	10.7	27.17	7.93	35.21
Y16	conglomerate	4.6	26.95	4.23	28.64
Y17	fine sandstone	10.3	26.51	7.87	36.01
Y18	siltstone	10.5	25.20	4.52	23.17
Y19	sandy mudstone	6.9	25.98	5.81	18.46
Y20	conglomerate	5.1	27.15	3.92	28.42
Y21	sandy mudstone	2.9	26.51	4.14	18.56
Y22	fine sandstone	10.7	26.82	8.11	36.12
Y23	kernstone	14.3	25.24	5.34	21.31
Y24	fine sandstone	6.2	27.54	8.64	35.87
Y25	kernstone	25.4	25.37	5.42	20.12

3. Prediction of overlying strata movement based on the Key Strata Theory

The overlying strata failure process is affected by the tensile strength of the Key strata, the deformation capability of the soft rock strata, the free space height beneath the stratum, and the mining distance of the working face. The proposed failure process flowchart is shown in Fig. 3.The overlying strata caving procedure can be determined based on the relationship between the Key strata and the weak strata, and the free space height beneath them.

For the Key Strata, when its suspension distance is greater than its limited span, the Key Strata and its control rock strata are broken, and the overburden damage develops to the uppermost rock layer controlled by the Key Strata. When the Key Strata suspension distance is less than its limited span, it is unbroken, and overburden damage develops to this layer.

For the weak layer, When the weak layer suspension distance is greater than the span of its maximum horizontal tensile strain, the weak layer breaks and the overburden damage develops

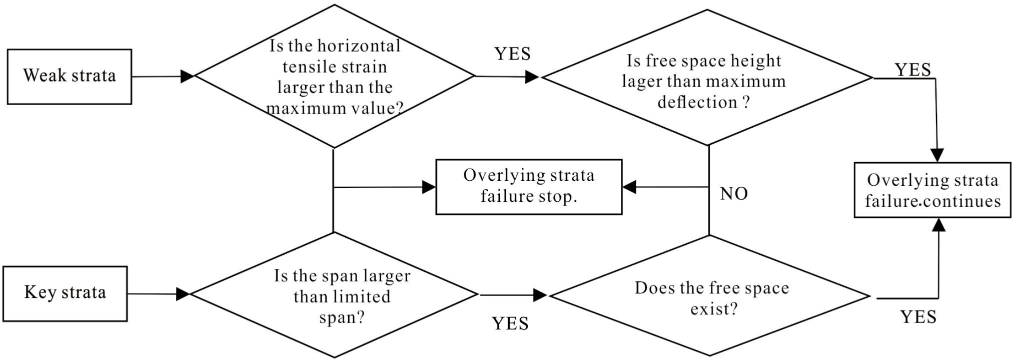

Fig. 3. Process flowchart for overlying strata failure

to this layer. When the weak layer suspension distance is less than the span of its maximum horizontal tensile strain, this weak layer is not broken, and the overburden failure do not develop to this layer.

3.1. Determination of Key Strata

Rock layers above the immediate roof vary in thickness and strength. Among them, there is one or several competent massive rock strata layers hard enough to control the overall movement of the part or entire overlying strata. This type of hard rock layer is called "Key Strata". When the Key strata unit breaks and the whole overburden strata above will subside immediately, this Key strata unit is defined as a primary Key strata unit. If the Key strata failure results in only a partial caving of above strata, this Key strata unit is defined as a sub-Key stratum.

For hard overlaying strata with different thickness, the bearing capacity of each strata unit should be known. The bearing capacity of the multi-strata structure (Yong et al., 2015; Miao & Qian, 2000) satisfies the following relationship:

$$(q_n)_m = E_m h_m^3 \sum_{i=m}^{n} h_i \gamma_i \Big/ \sum_{i=m}^{n} E_i h_i^3 \tag{1}$$

where $(q_n)_m$ is the load produced by n^{th} strata on m^{th} strata; m, n, i are the number of roof layers; E_m is the elastic modulus of the m^{th} strata; h_m and h_i are the thickness of the m^{th} and i^{th} strata, m; and γ_i is the volume-weight of the i^{th} stratum.

During the process of the Key stratum deformation, concurrent deformations occur in the overlying strata, whereas the lower strata are not deformed. Thus, strata below the Key stratum bears the load of above strata. If the n^{th} stratum is the Key stratum, the following relationship should be satisfied:

$$(q_n)_m < (q_{n-1})_m \tag{2}$$

where $(q_n)_m$ is the load produced by the n^{th} stratum on the m^{th} stratum, and $(q_{n-1})_m$ is the load produced by the $(n\text{-}1)$ stratum on the m^{th} stratum.

At the same time, the strength of the Key stratum should satisfy certain conditions. If the hard stratum is the Key stratum, its broken span should be less than that of all hard strata layers above it. The strength criterion of the Key stratum would be:

$$l_{n+1} > l_1 \tag{3}$$

where l_{n+1} is the broken span of the $(n+1)^{\text{th}}$ stratum, and l_1 is the broken span of the l^{th} stratum.

3.2. Failure process analysis of overlying strata

A fixed beam mechanical model is used to estimate the limited span of a hard stratum (Kai et al., 2009):

$$l_G = h\sqrt{\frac{2\sigma_t}{q}} \tag{4}$$

where h is the thickness of the stratum, σ_t is the tensile strength of the stratum, and q is the stratum load.

For the weak stratum, the limited span at the maximum horizontal tensile strain (Xu & Qian, 2000) is

$$l_R = h\sqrt{\frac{8E\varepsilon_{\max}}{3q}} \tag{5}$$

where E is the elastic modulus of the weak stratum, and $\varepsilon_{\max}$ is the maximum horizontal tensile strain of the weak stratum.

The maximum deflection of weak stratum (Xu & Qian, 2000) is:

$$\omega_{\max} = \frac{5ql^4}{384EI} \tag{6}$$

where l is the limited span of the stratum, and I is the inertia torsion moment.

The free space height underneath the rock stratum is:

$$\Delta_{\mathrm{i}} = M - \sum_{j=1}^{i-1} h_j(k_j - 1) \tag{7}$$

where Δ_i is the free space height underneath the i^{th} stratum, M is the coal seam mining height, h_j is the thickness of the j^{th} stratum, and k_j is the residual coefficient of the j^{th} stratum.

The critical mining length when the stratum fractures is:

$$L = \sum_{i=1}^{m} h_i \cot\varphi_q + l + \sum_{i=1}^{m} h_i \cot\varphi_h \tag{8}$$

where m is the number of strata layers between the coal seam roof and the lower part of the strata, h_i is the thickness of the i^{th} stratum, and φ_q and φ_h are the front and rear fracture angles of the strata, respectively.

3.3. Stress in coal around the longwall face under multi-layered hard roof

Both, the theoretical predictions of vertical stress variation and the underground stress change monitoring in coal seam pillar in the Tongxin mine are presented here.

As longwall mining progresses under the multilayered hard strata, a cascade of periodic events occur. Fig. 4 shows the overburden caving process and stress development in the coal under two Key strata. At the initial stage of mining, the vertical stress in surrounding coal increases (Fig. 4A). When the suspension distance of the sub Key stratum reach its broken span (Fig. 4B), the sub Key stratum breaks (Fig. 4C) and a drop of vertical stress in coal ahead of the longwall face occurs. As the working face retreats further, the sub Key stratum forms a cantilever. With gradual increase of its length, the vertical stress of face coal increases. When the cantilever beam of the sub Key stratum reaches its periodic fracture span (Fig. 4D), it collapses (Fig. 4E) together with the stratum above, a sudden increase of the surrounding vertical stress occurs. When the working face continues to advance (Fig. 4F) the sub Key stratum forms a cantilever shape gradually increasing arm length, and the vertical stress of face coal increases again.

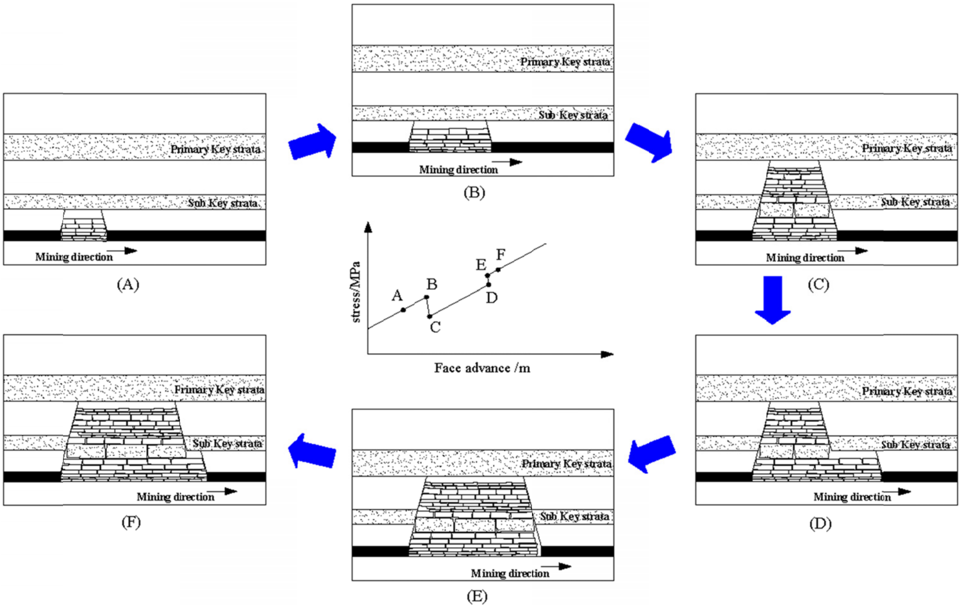

Fig. 4. Evolution process of overlying strata structure under multi-layer hard roof

4. Overlying strata caving process in Tongxin coal mine

4.1. Identification of Key strata

The previously formed goaf was located approximately 200 m above the No. 8105 working face. Based on the rock property values in Table 1 the primary and sub-Key strata were determined. The layer Y25 consisting of the sandstone and conglomerate layers (Table 1) between No. 8105 working face and the Jurassic coal seam were used as the primary Key stratum while the Y22 hard sandstone layer was determined as the sub-Key strata layer. All Key strata of the No. 8105 working face were identified using formulas (1)-(3) and the results are shown in Table 2.

TABLE 2

Key strata identification

No.	**Lithology**	**Thickness /m**	**Key stratum**	**Failure span /m**	**Distance from the coal seam /m**
Y25	kernstone	25.4	primary Key stratum	104.18	174.6
Y22	fine sandstone	10.7	sub Key stratum III	76.82	143.5
Y9	fine sandstone	14.8	sub Key stratum II	67.44	32.4
Y2	K3 sandstone	5.3	sub Key stratum I	52.18	3.2

4.2. Analysis of overlying strata failure

According to the formulas (4)-(8) and the failure height identification process (Fig. 3), the development of overlying strata caving process was determined with working face retreat distance (Table 3). It can be seen that the sub Key stratum I and II broke when the working face advanced to 55 and 109 m, respectively. The failure heights were 47.7 m and 158.8 m, respectively. When the face advanced to 193 m, the sub-Key stratum III broke. An overlying strata fracture developed at the bottom of the primary Key stratum and the overlying strata failure height reached its maximum of 190 m As the face continued to advance, the fracture height ceased to increase as the suspension span of the primary Key stratum was less than its span limit.

TABLE 3

Initial failure of each Key stratum with the working face advance

Advancement of face (m)	Failure height of overlying stratum (m)	Initial failure of Key stratum
55	47.7	Y2 (sub Key stratum I)
109	158.8	Y9 (sub Key stratum II)
193	190	Y22 (sub Key stratum III)

4.3. Vertical stress monitoring and analysis

The vertical stress of face coal was monitored using a stress meter. From a viewpoint of the monitoring continuity, a monitoring stress probe (Figs 5 and 6) was placed into the 38 m wide coal pillar from the gateroad ahead of the working face. The stress instrument was located at 20 m from the No. 2105 maingate road rib side. After installation, a data logger readout unit was used to monitor the stress changes during mining.

From the monitoring of hydraulic support loads and face coal spalling, the first weighting and subsequent periodic weighting can be estimated. Table 4 shows the estimated periodic weighting positions from the underground information. Figure 7 shows the borehole stress variation during the No. 8105 working face mining process. According to the buried depth of the mining face, the initial vertical stress is 11.2 MPa. Drilling is required before installing the stress probe. Since the

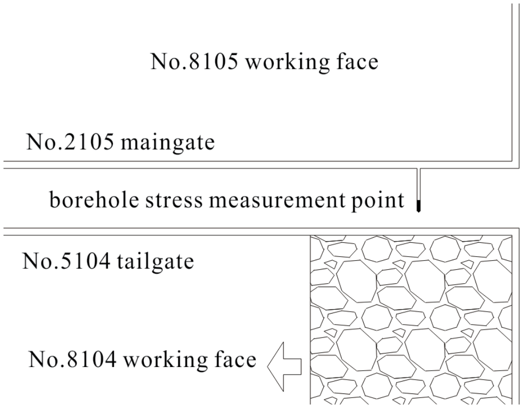

Fig. 5. Layout of the borehole stress measurement location

Fig. 6. GMC20 stress sensor

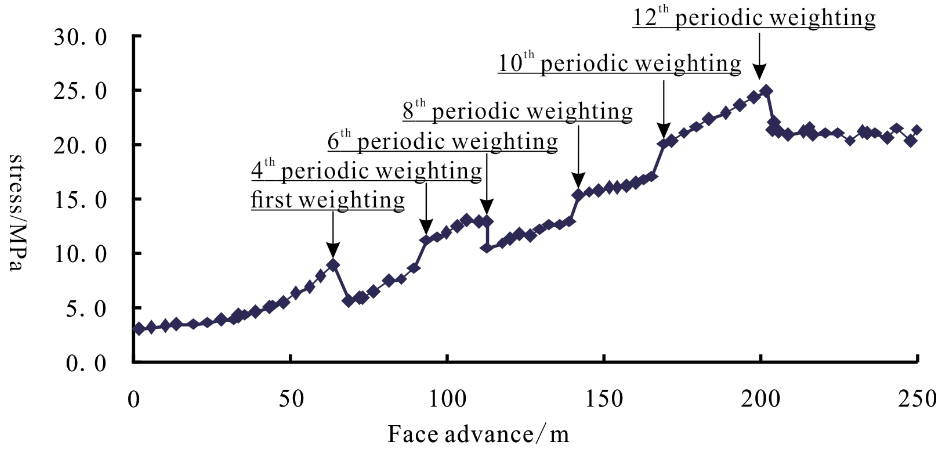

Fig. 7. Borehole stress changes during working face advancement

TABLE 4

Weighting positions of No.8105 longwall face

Weighting Number	Working face moved distance (m)	Weighting interval (m)	Weighting intensity
First weighting	**64**	**64**	**strong**
2nd periodic weighting	72	8	light
3rd periodic weighting	82	10	light
4th periodic weighting	**90**	**8**	**light**
5th periodic weighting	101	11	light
6th periodic weighting	**113**	**12**	**strong**
7th periodic weighting	126	13	light
8th periodic weighting	**142**	**16**	**light**
9th periodic weighting	152	10	light
10th periodic weighting	**165**	**13**	**light**
11th periodic weighting	171	16	light
12th periodic weighting	**202**	**31**	**strong**
13th periodic weighting	214	12	light
14th periodic weighting	227	13	light

diameter of the borehole is smaller than the diameter of the probe, and to some extent the stress is relieved. The actual measured stress is lower than the normal stress. However, the relative changes in stress can be beneficial for analyzing changes in overburden structure.

The stress meter recorded 3.0 MPa when the longwall face was located adjacent to the stress meter. A steady stress increase was monitored until the working face advanced to 64 m past the instrument measuring 8.8 MPa. However shortly after the first weighting occurred the vertical stress dropped to 5.6 MPa. Subsequent two periodic weightings did not produce sudden stress changes only a steady vertical stress increase to 8.6 MPa. The fourth periodic weighting seemed to be the cause of a sudden stress increase to 11.2 MPa. A steady increase in stress followed raising the vertical stress to 12.8 MPa until the 6th periodic weighting occurred dropping the vertical stress back by 2.3 MPa to 10.5 MPa. A steady increase of vertical stress continued reaching 12.9 MPa when the 8th periodic weighting caused a sudden stress increase to 15.2 MPa. The vertical stress continued to increase to 17.0 MPa when the 10th periodic event suddenly increased stress by 3 MPa to 20.0 MPa. The gradual increase in vertical stress continued to 24.8 MPa until the final 12th periodic weighting occurred dropping the stress reading to 21.1MPa. From then on the vertical stress remained relatively steady with the final reading of 21.3 MPa when the longwall face advanced to 250 m past the instrument.

The monitored data indicated that the first, sixth and the twelfth periodic weighting relieved the vertical stress significantly dropping the vertical stress up to 3.2 MPa. Likewise the 4th, 8th and 10th periodic event increased the vertical stress by as much as 3 MPa. This indicates that the Key strata layers have a significant influence on ground behaviour.

The vertical stress suddenly dropped when the No. 8105 face advanced to 64 m, 113 m and 202 m, respectively (Table 4). The measured borehole stress sudden reduction at these three weighting locations were caused by overlying strata instability of the sub-Key stratum I, II and III. At the fourth, eighth and tenth periodic weighting location, the borehole stress suddenly increased, which was probably caused by the horizontal extension of the overlying strata due to failure of one sub-Key stratum. After the 12th periodic weighting, a large overlying strata structure controlled by the sub-Key stratum III was formed and become unstable. The overlying strata movement appeared to be gentle, and the vertical stress in the face coal stabilised. For some periodic weighting cases, sudden stress change of the borehole did not occur because those weightings were influenced by non-Key strata failure. The weighting cycles and instability of large rock structures were found to be the major reason of stress variations in the mined coal strata.

5. Ground pressure at longwall face under multi-layer hard roof

To study the ground pressure characteristics of the working face under multi-layer hard roof, the support loads of the No. 8105 longwall face was monitored in real time. 15000 KN low-position top coal caving hydraulic supports ZF15000/27.5/42 were used to support the coal face (Fig. 8). The hydraulic supports are 8.6 m long, 1.86 wide and 4.2 m high. During the mining process, loads of the fully mechanized support was monitored by the KJ216 support resistance monitoring system. Monitoring equipment instruments were arranged starting from the ninth support at intervals of every 10 supports that is, at supports 9, 19, 29, 39, 49, 59, 69, 79, 89, 99 and 109 (Fig. 9). Instantaneous pressure gauges were installed on the hydraulic support to monitor the pressure in the chambers of front and rear columns. The measured load values were transmitted to the ground computer system for data analysis via data lines. The support loads were recorded during mining with the results shown in Fig. 10. The values shown in this figure were calculated as average for all monitored supports. The locations where large support loads were measured correlate with the major structural instability and stress increase that was measured by the stress borehole monitor. When the large structure is unstable, the support loads increase close to 15000 kN, while under normal conditions their typical operating loads are between 10000-12000 kN.

Fig. 8. ZFl5000/27.5/42 hydraulic support

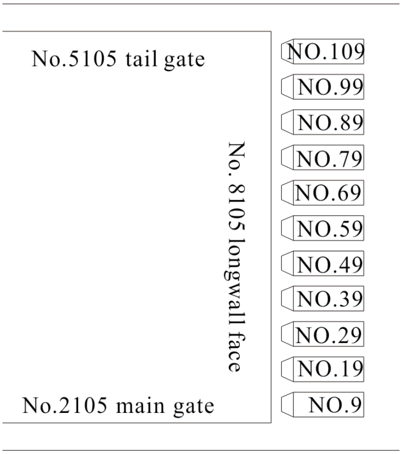

Fig. 9. Layout of No. 8105 face ground pressure observation station

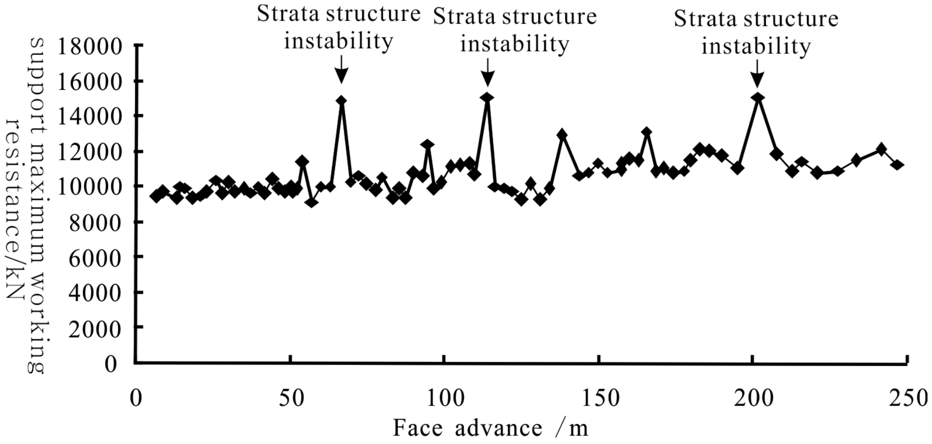

Fig. 10. Change in hydraulic leg pressures during longwall advance

Support data show that instability of large overlying strata structure causes significant support pressure increase in hydraulic legs, often accompanied with yielding or even crushing of the supports. The excess force on the support is generated by dynamic events associated with failure of the hard Key strata in the overburden.

6. Ground pressure analysis and control measures under multi-layer hard roof

A large mining space in an extra-thick coal seam causes a large range of the overlying strata movement. Together with the effects from the multi-layered hard roof, instability of the overlying strata occur during mining, forming different ground pressure behavior characteristics to those of a conventional longwall top coal caving face. The specific analysis can be divided into three parts:

(1) During the early stage of mining, the overlying strata can be simplified as the structural model of multiple Key strata. The formation and instability of the structure correspond to the behavior of the surrounding rock pressure on the working face. The stress of the surrounding rock shows a certain periodicity owing to the influence of the covered multi-layered hard roof. Large and small periodic weightings alternate, and abrupt changes to the stress on the surrounding rock occur during the large periodic weighting.

(2) The dynamic load damage characteristics along a goaf-side entry are significant. Owing to the multi-layer hard and thick roof, the dynamic load generated by overlying strata structure instability is intensive. A serious floor heave, and severe damage to the cable anchors, rock bolts and other support structures typically occur.

(3) A cantilever structure is formed at the rear of the working face. The free space formed in the mined-out area of the top-coal caving longwall face is relatively large. The hard roof increases the size of the cantilever structure, and the deflection of the cantilever beam exacerbates the top coal deformation above the canopy rear, resulting in an insufficient connection with the roof at the back of the support.

Considering the above characteristics of the ground pressure behavior, weakening of the hard roof and strengthening the support of the gob-side entry can be trialed to prevent ground pressure from occurring. Suggested control measures are as follows:

(1) Weakening of hard roof.
The three-layer hard roof of the overlying strata can be weakened by pre-split blasting. A number of blastholes can be set within the hard roof strata along the working face at 50 m intervals from the maingate and tailgate so as to pre-split the hard roof. During mining advance the hard roof may collapse more frequently, reducing the surrounding rock stress at the longwall face and gateroads along the mined-out area. Minimizing the span of the multi-layered hard roof will weaken the effect of the dynamic loads and improve strata conditions.

(2) Use of the energy consumption reinforcement to support the roadway along the mined-out area
Because a failure of the cables and rock bolt is caused by a strong dynamic load, an anchor bolts with constant resistance capable of large deformation can be used to support the surrounding rock of the gateroads (He & Guo, 2014; He et al., 2014). If the rock bolts can provide a constant working resistance and achieve stable deformation, better strata conditions can be expected.

7. Conclusions

In this study, the evolution model of the overlying strata under multi-layer hard roof was proposed, which provides a new idea to analyse the ground pressure behavior and mimimise rock bursts in multi-layered hard rock ground. Based on the Key strata theory, stress measurements and observations in the Tongxin coal mine, where top coal caving method under multi-layer hard roof was used, the failure process and the ground pressure behavior was studied. The findings are:

(1) An evolution model of the overlying multi-layer hard roof strata was proposed. The model predicted the formation and instability of the overlying strata that lead to abrupt changes to the surrounding rock stress. The model can analyze roof falling process under the condition of multi-layer hard roof, and it is helpful to analyze the mechanism of ground behaviors and rock bursts.

(2) The multi-layered hard strata was divided into four types: the sub key strata I, the sub key strata II, the sub key strata III and the primary Key strata. Their fracture length was also predicted using the rock tensile strength data within the Key strata theory.

(3) The vertical stress monitoring indicated the steady stress increase due to longwall mining and measured stress fluctuations caused by the periodic weightings of the Key strata. The strata failure mechanisms proposed in Figure 4 and the vertical stress measurements presented in Figure 8 clearly indicate the driving force that causes the stress fluctuations. Sudden dynamically driven unloading of strata was caused by the first caving of the sub-Key strata while reloading of the vertical stress occurred when the goaf overhang of the sub-Key strata failed. Experience shows that all dynamic events contribute to the damage of longwall equipment and surrounding strata, affecting the safety and coal production.

(4) Several measures to minimise the dynamic occurrences and their implications were proposed. These are:
   a) Pre-slitting of the hard rock Key strata to minimize their span and thus decrease severity of the dynamic occurrences.
   b) Using the energy consumption reinforcement to support the roadway along the mined-out area where the difficult strata conditions are expected.
   c) Plan the longwall production to minimise the longwall downtime in areas where the periodic weighting is expected.

Future work is recommended to improve the knowledge of the dynamic phenomena experienced in these conditions. The numerical modeling may be one of the best methods to provide more detailed information on strata behavior, improve the understanding of the dynamic loading mechanisms and provide more accurate information on the pre-splitting methods.

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