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Application of the coal mine floor rating (CMFR) to assess the floor stability in a Central Appalachian Coal Mine

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Abstract

Estimating the overall floor stability in a coal mine using deterministic methods which require complex engineering properties of floor strata is desirable, but generally it is impractical due to the difficulty of gathering essential input data. However, applying a quantitative methodology to describe floor quality with a single number provides a practical estimate for preliminary assessment of floor stability. The coal mine floor rating (CMFR) system, developed by the University of New South Wales (UNSW), is a rock-mass classification system that provides an indicator for the competence of floor strata. The most significant components of the CMFR are uniaxial compressive strength and discontinuity intensity of floor strata. In addition to the competence of the floor, depth of cover and stress notch angle are input parameters used to assess the preliminary floor stability. In this study, CMFR methodology was applied to a Central Appalachian Coal Mine that intermittently experienced floor heave. Exploratory drill core data, overburden maps, and mine plans were utilized for the study. Additionally, qualitative data (failure/non-failure) on floor conditions of the mine entries near the core holes was collected and analyzed so that the floor quality and its relation to entry stability could be estimated by statistical methods. It was found that the current CMFR classification system is not directly applicable in assessing the floor stability of the Central Appalachian Coal Mine. In order to extend the applicability of the CMFR classification system, the methodology was modified. A calculation procedure of one of the CMFR classification system's components, the horizontal stress rating (HSR), was changed and new parameters were added to the HSR.

Keywords

Rock mass classification; Coal mine floor rating (CMFR); Floor heave; Floor failure; Buckling failure mechanism

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1. Introduction

Sears et al. stated that an increasing problem in deep cover coal mines is that floor heave is usually observed when there is a presence of weak and moisture-sensitive immediate floor strata (typically clay) and the load-bearing capacity of floor strata is exceeded due to a high vertical or horizontal stress state [1].

The excessive amounts of floor heave cause narrowing of the mine entries and has the potential to lead to the closure of entries. The unplanned closure of mine entries disrupts the production and ventilation of the mine and increases the difficulty for personnel traveling escapeways, causing trip hazards in certain cases of local instability [2]. For a robust ground stability design, estimating the rock-mass behavior is imperative. The coal mine floor rating (CMFR) classification system was developed to assess practically the potential behavior of floor strata in Australian coal mines [3]. The CMFR system was composed of two components: coal mine floor rating (CMFR) and horizontal stress rating (HSR). CMFR is created to quantify the competence of floor, and HSR was created to include the effect of overburden stress and alignment of maximum principal horizontal stress with respect to the entries. In order to assess the stability of the floor in comparison with other failure and non-failure cases in the database, the floor heave index (FHI) was also created by Mo, which incorporates the CMFR and HSR into a graphical tool [3]. FHI is employed to depict the correlation between failure and non-failure cases from actual floor failure cases based on statistical methods. In this study, the CMFR system developed for Australian floor failure cases is applied to a Central Appalachian Mine that intermittently experiences floor stability problems. It is observed that the estimation of floor stability of the case study mine using the FHI as defined by Mo is not as accurate as it is for the Australian mines [3]. Due to these inaccuracies, a modification to the HSR calculations, including additional factors and different constants, are proposed in this study.

2. Floor heave mechanism

There are different mechanisms of floor heave based upon the floor geology and operational conditions with different driving factors. Nemcik states that the mechanisms of floor heave at the longwall gate roads can be classified into three categories: bearing capacity failure (Fig. 1a), swelling (Fig. 1b), and buckling (Fig. 1c) [4]. These three mechanisms of floor heave are also illustrated in Fig. 2.

Bearing capacity failure of floor strata happens when the load transmitted from pillars to floor exceeds the load-bearing capacity of immediate floor strata. If the floor cannot provide a foundation for the pillar any longer, the pillar starts moving downward into the floor and gradual pillar punching leads to failure of the floor. The punching of the pillar into the floor results in movement of floor material beneath the coal pillar outward and upward towards the ground surface [9]. Speck stated that the load carried by a coal pillar before pillar punching is transferred upon floor failure to surrounding immediate roof/floor strata and adjacent pillars [9]. The additional load exerted on the floor contributes to the bearing capacity failure and increases the severity of the failure. The successive occurrence of floor failure and continuous load transfer to the adjacent pillars causes propagation of floor-bearing capacity failure throughout the mine.

Swelling is another mechanism of floor heave. Faria Santos and Bieniawski stated that swelling is observed as a result of exposure of clay-rich materials, such as fireclays, mudstone, claystone, and shale, to moisture [10]. Exposure to water or moisture is one of the major components of all types of floor heave mechanisms; however, the role of water is crucial as a swelling mechanism. Swelling is defined as the expansion of floor material due to the interaction between moisture and floor material, such as the Smectite group of clay which tends to shrink and swell. Clay mineral/water interaction causes a dramatic decrease in the mechanical properties of the material and ultimately results in floor failure, which endangers the functionality of mine entries.

The aforementioned floor heave mechanisms, bearing capacity and swelling, are associated with the existence of weak immediate floor stratum. However, buckling, the third type of floor heave, occurs where the immediate floor layer is stronger than the layers underneath. Buckling is typically observed where the strong immediate floor behaves as hardpan, a hard and compacted layer. The presence of sufficiently high horizontal stress initiates buckling of the immediate floor layer and causes floor heave [11]. An example of buckling failure is seen in the Beckley Coalbed in West Virginia, where the competent and relatively strong floor has failed in a buckling manner due to the existence of a high horizontal stress field [12].

3. Coal mine floor rating (CMFR)

Brady and Brown stated that understanding the complex nature of rock mass and making future predictions for rock-mass response in advance is not simple [13]. They support applying the previous experiences of mining operations for the future decisions of similar conditions. Towards this endeavor, rock-mass classification systems based on empirical approaches are developed in order to apply the gained experience to the similar conditions in other mines based on a standardized procedure.

There are numerous rock-mass classification systems that incorporate sub-ratings of different parameters with varying weighting factors into an overall rock-mass rating. These systems became a reliable methodology to follow in the pre-design stage of many areas, such as tunneling, slopes, and foundations because of their ease of applicability. The pioneering studies on rock-mass classification systems were performed by Deere et al. [14–17]. The most well-known and commonly practiced classification in U.S. coal mines is the coal mine roof rating (CMRR) system [18]. And recently, the coal mine floor rating (CMFR) system was proposed for Australian coalfields [3]. Application of the CMFR to assess the stability of floor strata follows calculating the CMFR, horizontal stress rating (HSR), and plotting floor heave index (FHI).

3.1. Components of the CMFR

The CMFR is designed to represent the competency of floor strata based on geomechanical and lithological properties of immediate floor rocks. First, the CMFR divides the floor strata into different floor units based on the geological differences and calculates unit rating for each division. Uniaxial compressive strength of intact rock and discontinuity characteristics, more specifically the average discontinuity spacing of beddings and other discontinuities, are the main parameters used in the computation of unit ratings. Then, the thickness-weighted average of unit ratings is calculated. Since the configuration of the strong unit in floor strata also affects the overall behavior of the floor, the effect of the strong unit is integrated into the CMFR value using the strong unit adjustment (SUA) calculation.

3.1.1. Uniaxial compressive strength—

Uniaxial compressive strength (UCS) is widely used by a large percentage of rock mechanics engineers to represent the strength of rock for surface and underground designs. UCS can be obtained through indirect tests, such as the point load test, Schmidt hammer test, sonic logging, and so on. Sliwa et al. states that sonic logging has become an increasingly widespread method for rock strength estimation in Australia [19]. Analogously, the UCS scale for the CMFR system was developed for the UCS values obtained by sonic logging (Table 1). It is believed that the competence of floor stratum with less than 10 MPa is governed only by UCS, i.e., not influenced by the average discontinuity spacing any longer.

3.1.2. Discontinuity spacing—

In rock engineering, two main classification terms exist to define rocks: intact rock and rock mass [20]. Intact rock refers to the rock material in an ideal state where there is not any discontinuity or fracture (massive) in the rock matrix, whereas rock mass refers to rock material in the in-situ condition with a possible discontinuity/fracture network. For simplicity, rock masses are sometimes assumed to be intact rock. However, in real-world application, discontinuities always exist within the rock matrix.

Discontinuities in rock mechanics serves as an inclusive term for all fractures, such as faults, joints, shears, weak bedding planes, and contacts [13]. The intensity of weakness planes within the rock governs the mechanical behavior of rock mass in the sense that densely packed planes of discontinuities adversely affect the strength of rock mass [21]. Therefore, discontinuity properties, more specifically discontinuity spacing, are commonly used as a measure of rock-mass quality and employed in many rock-mass classification systems.

The CMFR system, discontinuity spacing is applied to implicate frequency of weakness planes, including bedding, lamination, joints, fractures, and any other kind of planes that result in weakness in a rock-mass. Discontinuity spacing, the average distance between each discontinuity plane per unit length along a drill core, can be calculated by dividing unit thickness of layer with the number of discontinuities + 1. The CMFR system scale for discontinuity spacing is shown in Table 2.

3.2. Strong unit adjustment

In the stratified depositional nature of coal roof and floor geology, it is likely to find several different units with varying geomechanical properties. Mark and Molinda state that the strongest layer within the bolted area in the roof heavily influences the roof performance [22]. Similarly, the presence of a strong unit in the floor strata is considered by the CMFR system while predicting the competence of floor strata. Since the application of bolts in floor strata is very rare, the existence of a bolted area concept that is used in CMRR for floor strata is not applicable. Instead, the first 3-m interval of floor strata is taken into consideration in order to investigate the effect of a strong unit on the floor performance. Including the adjustment for a strong unit depends on the stratigraphic sequence of strong units within 1 m of floor strata. In order to apply the strong unit adjustment (SUA) calculation, the strongest layer within the 1 m of floor interval must have a minimum thickness of 0.7 m.

CMRR considers how much stronger the strong unit is than the others in the strata [22]. Analogously, the CMFR distinguishes the strongest layer with the highest unit rating. Then, the strong unit difference (SUD) calculation is established to understand the relative strength of layers. The SUD is calculated by subtracting the unit rating of the strong layer from the thickness-weighted average unit rating within 3 m of floor strata. If the SUD is greater than 20, 5 is added to the thickness-weighted average unit rating as the SUA.

3.3. Calculation of the CMFR

The CMFR calculation starts with the evaluation of unit ratings, which consist of a UCS rating (Table 1) and a discontinuity spacing rating (Table 2). A minimum unit rating of 25 is applied to all floor units. Upon the calculation of unit ratings for each floor stratum, a strong unit adjustment can be added to the corresponding strong unit. Then, the thickness-weighted average of unit ratings is calculated within 3 m of floor strata in order to achieve an overall CMFR number based on a 0–100 scale, which represents the competence of the floor strata within 3 m. Table 3 shows the calculation of the unit rating of each stratum and thickness-weighted averaged CMFR value for an available drill core from the case study mine. It should be noted that the last 0.27 m of the bottom unit with a thickness of 0.55 m is excluded from the CMFR calculation as it is not within the 3 m of floor strata.

3.3.1. Horizontal stress rating (HSR)—The stress state of the floor strata is as important as the floor material quality to assess the floor stability in a coal mine. In order to include the stress state of floor into the FHI system, the horizontal stress rating (HSR) was established. The HSR is composed of depth rating and angle rating.

Depth rating is simply the division of depth of cover in meters by 10. Angle refers to the angle between the entry and major horizontal stress. The angle rating scale for the HSR is shown in Table 4.

3.3.2. Floor heave index (FHI)—FHI is an empirical method developed from statistical methods. FHI is employed in order to combine the CMFR value and HSR into one output. Incorporating CMFR and HSR of failure and non-failure cases into FHI provides a visual comparison of binary outcomes of failure and non-failure cases using the logistic line.

FHI was developed for the case study mines in Australia, shown in Fig. 3 [3]. The addition of new case studies using FHI by calculating CMFR and HSR can assist in the estimation of floor stability conditions of other mines for future geotechnical investigations.

4. Case study mine

4.1. General and geological information on case study mine

In the case study mine, metallurgical coal is extracted by utilizing the longwall mining method. The longwall mine is located in Central Appalachia. The mine extracts from the Pocahontas #3 coal seam, which belongs to the western part of the Valley and Ridge physiographic province; this province is characterized by folded and faulted thrust belts that cause steep-sided mountain ridges and valleys that follow a northeast trend.

The operating depth of the mine exceeds 600 m. The overburden thicknesses range from 426.7 to 670.5 m. The width and length of the entry are 6.1 and 24.4 m, respectively. The coal seam thickness ranges from 1.5 to 1.8 m. The longwall panels are approximately 220 m wide by 3660 m long. In the studied part of the mine, the depth of cover ranges from 457 and 731 m, and the coal seam thickness varies from 1.7 to 3.2 m.

Van Dyke et al. stated that geology in the studied area of the mine significantly alters from mains adjacent to pillar 25 through pillar 28; they constructed generalized vertical geological columns (Fig. 4) in the interest area based on nearby drill cores [7]. From the analysis of drill cores, it is observed that the floor strata is composed of 0.15 m of shale and 0.7–1.8 m of fireclay, which is overlaid by bedded sandstones. The roof in the studied area is qualified as competent. The immediate roof consists of 2.74 m of massive sandstone with an underlying 0–3 m of silty shale.

This study focuses on the southeastern mains of the mine along both entries and crosscuts, which experience floor heave problems. The mine layout part of the case study mine where floor heave is observed is shown in Fig. 5, along with yield-abutment-yield gate road design. The longwall panels are extracted from bottom to top, and extraction advances from left to right through the mine. Due to the split in the top of the seam, which led to a very weak clay roof, the direction of mine advance was changed and oriented 45° towards the south starting from Panel 25.

According to the published paper about the floor heave in the area of interest in the case study mine by Van Dyke et al., an initial unexpected occurrence of floor heave, of an inch or less, was observed in the recovery area of Panel 25, which is overlaid by thick overburden strata with the thickness ranging from 610 to 730 m [7]. It was noted that floor heave in the vicinity of Panel 25 remained the same during the extraction of Panel 26. After the extraction of Panel 26, a significant increase in the amount of floor heave (up to 1.2 m) was observed. As the mining resumed down to Panel 29, it was recorded that the floor heave progressed through Panel 29. Fig. 5 shows the area that intermittently experienced floor heave.

Available drill cores close to the floor heave areas and discussions with the geologist of the mine were utilized in order to characterize the floor geology in failure cases. Fig. 6 shows the location of the drill cores which were used to characterize three failure and eight non-failure cases used in the analysis.

4.2. Application of the CMFR methodology to the U.S. case study mine

The CMFR methodology, described in the preceding sections, was applied to the Central Appalachian Coal Mine. The CMFR and horizontal stress rating (HSR) were calculated for eleven drill core samples in the case study and is summarized in Table 5.

The CMFR and HSR values are summarized in Table 5 used to plot floor heave index for the U.S. case study mine shown in Fig. 6.

4.3. Modifications on floor heave index (FHI)

Fig. 6 shows that FHI could not accurately separate failure and non-failure cases from each other for the Central Appalachian case study mine. It is hypothesized that the inaccurate classification of failure and non-failure cases for the Central Appalachian Mine results from the angle rating calculations used in the horizontal stress rating. In the Central Appalachian case, the angle between mine entry and maximum horizontal stress is 90° and 45° for failure and non-failure cases, respectively. The angle rating developed for the Australian mines assigns a rating of 5 for any angles larger than 30°. Therefore, the same angle rating of 5 is assigned to all cases in the Central Appalachian Mine regardless of different maximum horizontal stress alignments. In order to examine the hypothesis, a modified horizontal stress rating with the more detailed scale of angle is derived for the Central Appalachian Mine.

In the case study mine, maximum and minimum principal stresses (σ_1 and σ_3) are the horizontal stresses, while intermediate principal stress (σ_2) is the vertical stress. For more realistic in-situ vertical stress calculations, including the effect of topographic relief in stress conditions, a large-scale model is constructed through a collaborative use of boundary element software, LaModel, and stability mapping [23]. In-situ vertical stress distribution, a result of the effect of topographic stress on the mine floor, for the case study mine is shown in Fig. 7. The area shown in Fig. 7 is meshed with 1400 × 1400 3-m elements in the LaModel software.

The total horizontal stress applied to the floor strata is the summation of the tectonic stress and the stress resulting from the Poisson's effect and can be calculated using Eqs. (1) and (2).

$$\sigma_{\mathrm{h,\,Poisson's\ effect}} = \sigma_{2,\,\mathrm{total}} \times \frac{\upsilon}{(1+\upsilon)(1-2\upsilon)} \quad (1)$$

$$\sigma_{\mathrm{h,\,tectonic\ stress}} = \varepsilon_{\mathrm{tectonic\ strain}} \times E \quad (2)$$

where σ is the Poisson's ratio of rock mass; ε the tectonic strain; and E the elastic modulus of rock mass.

Sears et al. state the elastic modulus of shale in the case study area as 14.01 GPa [1]. For the case study mine, the tectonic strain is calculated as 1070 microstrain and verified with the high tectonic strain of 1040 microstrain, which is specified for the Central Appalachian mines by Dolinar [24]. The input parameters for the total horizontal stress calculation are: elastic modulus of 14.01 GPa for shale, the tectonic strain of 1.07×10^{-3}, and Poisson's ratio of 0.2. The calculated total horizontal stress is considered as the maximum total horizontal stress (σ_1, σ_{h1}). The maximum horizontal stress to the minimum horizontal stress ratio is stated as 1.5 by Sears et al. [1]. The same ratio is used for the stress calculations in the case study mine, and the maximum principal stress (σ_1, σ_{h1}) is set to be 1.5 of the minimum principal stress (σ_3, σ_{h3}).

The horizontal stress rating is modified by changing the calculation procedure of angle rating. The counterclockwise 2D stress transformation formula from continuum mechanics is implemented to the angle rating calculation procedure, which makes it possible to calculate the rating for every single angle value from 0° to 90°, shown in Eqs. (3) and (4).

$$\sigma'_{xx} = \frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right) + \frac{1}{2}\left(\sigma_{xx} - \sigma_{yy}\right)\cos(2\theta) + \sigma_{xy}\sin(2\theta) \quad (3)$$

$$\sigma'_{yy} = \frac{1}{2}\left(\sigma_{xx} + \sigma_{yy}\right) - \frac{1}{2}\left(\sigma_{xx} - \sigma_{yy}\right)\cos(2\theta) - \sigma_{xy}\sin(2\theta) \quad (4)$$

Through Eqs. (3) and (4), maximum principal stress (σ_1, σ_{h1}) and minimum principal stress (σ_3, σ_{h3}) are rotated for angles of 45° and 90°. In addition to rotating the principal stresses, the horizontal stresses are normalized by dividing the minimum principal stress (σ_3, σ_{h3}) by the maximum principal stress (σ_1, σ_{h1}). The coefficient calculated upon normalization provides a value between 0 and 1 which enables an easy comparison between minimum and maximum principal stresses. By rotating and normalizing the principal stresses, the effect of horizontal stress orientation is calculated. The ratio of average maximum horizontal stress (σ_1, σ_{h1}) to average in-situ vertical stress (σ_2, σ_v) is calculated as 1.23, which includes the effect of horizontal stress magnitude to the modified horizontal stress rating. It should be noted that this ratio is specific to the case study mine and has to be calculated individually for other mine sites. To integrate the effects of orientation and magnitude of horizontal stress into the modified horizontal stress rating, previously calculated normalized coefficients corresponding to horizontal stress orientation are multiplied by the ratio of average maximum horizontal stress and average in-situ vertical stress, and new horizontal stress coefficients are obtained for corresponding angles.

Lastly, the new horizontal stress coefficient that corresponds to the angle between maximum horizontal stress and the gate road is multiplied by the in-situ vertical stress, provided by LaModel, for each drill core, which gives the modified horizontal stress rating. Table 6 summarizes the modified horizontal stress rating calculation steps for each drill core sample.

Floor heave index for the U.S. mine study case is plotted using the modified horizontal stress rating in Fig. 8. The dashed line is established to separate failure and non-failure cases from each other. However, it should be noted that the line is not established for design purposes and can be modified in the future if new case studies are included to the database.

5. Conclusions

The coal mine floor rating (CMFR) classification methodology was developed for preliminary assessment of the floor stability. Application of the CMFR to assess the stability of floor strata follows calculating the CMFR, horizontal stress rating (HSR), and plotting floor heave index (FHI). The CMFR value represents the competence of floor strata based on uniaxial compressive strength and intensity of discontinuities in the floor strata. The horizontal stress rating (HSR) brings the effect of mining depth and horizontal stress alignment with respect to the entries into the analysis. The floor heave index (FHI) incorporates the CMFR number and HSR into a plot, which depicts the correlation to each other. Also, the logistic regression line in FHI is derived with statistical methods to sufficiently separate the failure and non-failure cases from each other.

In this study, the CMFR system is applied to a Central Appalachian Coal Mine to examine the applicability of CMFR, purely developed based on Australian case studies for a U.S. mine. It was found that the logistic regression line in FHI developed for the Australian database is not adequate to separate failure and non-failure cases from each other for the U.S. case. It is believed that the insufficient separation results from the angle rating in the horizontal stress rating. For this reason, HSR is modified and an elaborative way of calculation for angle rating is implemented into the HSR where angle rating is calculated for each angle separately. A better separation of failure and non-failure cases from each other is observed with FHI using the modified horizontal stress rating. Future studies will aim at expanding the database with case studies from the U.S. mines in order to suggest a design line for future floor stability assessments. Further, the effect of moisture to the competency of the floor unit will be investigated in order to integrate moisture sensitivity to the CMFR system.

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References

[1]. Sears M, Van Dyke M, Klemetti T, Su WH, Tulu IB. The effect of floor strength and horizontal stress orientation on floor heave in a deep U.S. longwall mine. In: Proceedings of the 52nd U.S. Rock mechanics/geomechanics symposium. Seattle: Washington; 2018.

[2]. Klemetti T, Van Dyke MA, Evanek N, Compton CC, Tulu IB. Insights into the relationships among the roof, rib, floor and pillars of underground coal mines. Mining Metall Explor 2020.

[3]. Mo S Floor heave mechanics in underground coal mine roadways. Doctoral dissertation. Sydney: University of New South Wales; 2019.

[4]. Nemcik J Floor failure mechanism at underground longwall face. In: Doctoral dissertation. Wollongong: University of Wollongong; 2003.

[5]. Tyler K, Sutherland T. The Duncan method of partial extraction at Tasman mine. In: Proceedings of the 11th Underground coal operator’s conference. Wollongong: University of Wollongong & the Australasian Institute of Mining and Metallurgy; 2011. p. 8–15.

[6]. Vasundhara. Geomechanical behavior of soft floor strata in underground coal mines. In: Doctoral dissertation. Sydney: University of New South Wales; 1999.

[7]. Van Dyke M, Sears M, Klemetti T, Tulu IB, Wickline J. Geological evaluation of floor heave in a longwall mine under deep overburden. In: Proceedings of the 52nd US Rock Mechanics/ Geomechanics Symposium. Seattle: Washington; 2018.

[8]. Whittles DN, Reddish DJ, Lowndes IS. The development of a coal measure classification (CMC) and its use for prediction of geomechanical parameters. Int J Rock Mech Min Sci 2007;44(4):496–513.

[9]. Speck C The influence of certain geologic and geotechnical factors on coal mine floor stability – a case study. In: Proceedings of the 1st annual conference on ground control in mining. Morgantown: West Virginia; 1981. p. 44–49.

[10]. Faria Santos C, Bieniawski Z. Floor design in underground coal mines. Rock Mech Rock Eng 1989;22(4):249–71.

[11]. Peng SS, Wang YJ, Tsang P. Analysis of floor heave mechanism. In: Proceedings of the SME Annual Meeting. Morgantown: West Virginia University; 1995.

[12]. Aggson J Coal mine floor heave in the Beckley coalbed, an Analysis. Report of Investigations 8274. Pittsburgh: U.S. Department of Interior, Bureau of Mines; 1978.

[13]. Brady B, Brown E. Rock mechanics for underground mining. Dordrecht: Springer; 2004.

[14]. Deere DU. Technical description of rock cores for engineering purpose. Rock Mech Eng Geol 1963;1(1):16–22.

[15]. Bieniawski Z Engineering classification of jointed rock masses. Johannesburg: South African Institute of Civil Engineers 1973;15(12):335–43.

[16]. Barton N, Lien R, Lunde J. Engineering classification of rock masses for the design of tunnel support. Rock Mech 1974;6(4):189–236.

[17]. Hoek E Strength of rock and rock masses. ISRM News J 1995;2(2):4–16.

[18]. Mark C, Molinda G. The Coal Mine Roof Rating (CMRR)-a decade of experience. Int J Coal Geol 2005;64(1):85–103.

[19]. Sliwa R, Hatherly P, Medhurst T, Turner R. Quantitative geophysical log interpretation for geotechnical and geological assessment of coal measure rocks. In: Proceedings sixth international mining geology conference. Melbourne: Australia; 2006. p.117–125.

[20]. Priest S Discontinuity analysis for rock engineering. Dordrecht: Springer; 1993.

[21]. Hoek E, Brown E. The Hoek-Brown failure criterion and GSI-2018 edition. J Rock Mech Geotechnol Eng 2019;11(3):445–63.

[22]. Mark C, Molinda GM. Development and application of the coal mine roof rating (CMRR). In: In: Proceedings of the international workshop on rock mass classification in underground mining. p. 95–110.

[23]. Heasley K Numerical modelling of coal mines with a laminated displacement code. Doctoral dissertation. Golden: Colorado School of Mines; 1998.

[24]. Dolinar D Variation of horizontal stresses and strains in mines in bedded deposits in the Eastern and Midwestern United States. In: Proceedings of the 22nd international conference on ground control, Morgantown: West Virginia University; 2003. p. 178–185.

Fig. 1.
Floor heave examples for three main mechanisms [5–7].

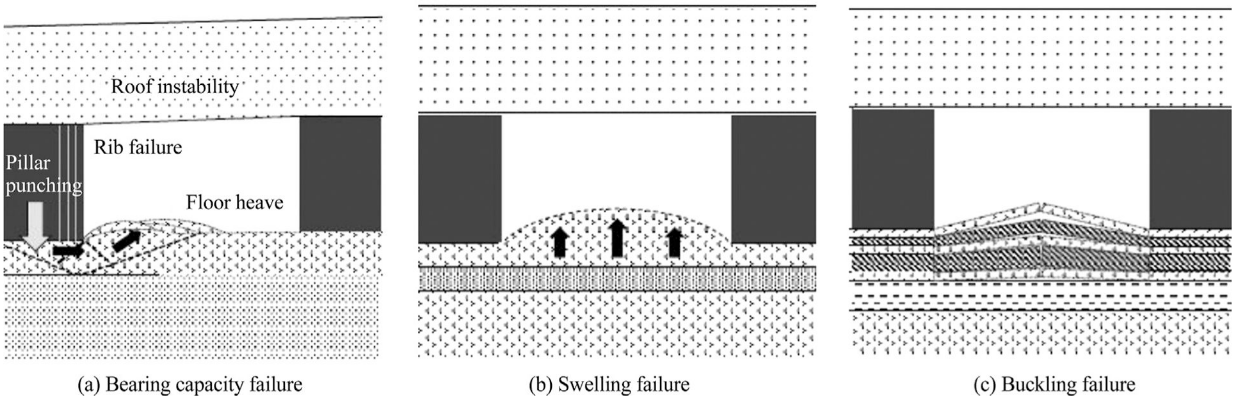


Fig. 2.
Three main floor heave mechanisms [3] (After [8]).

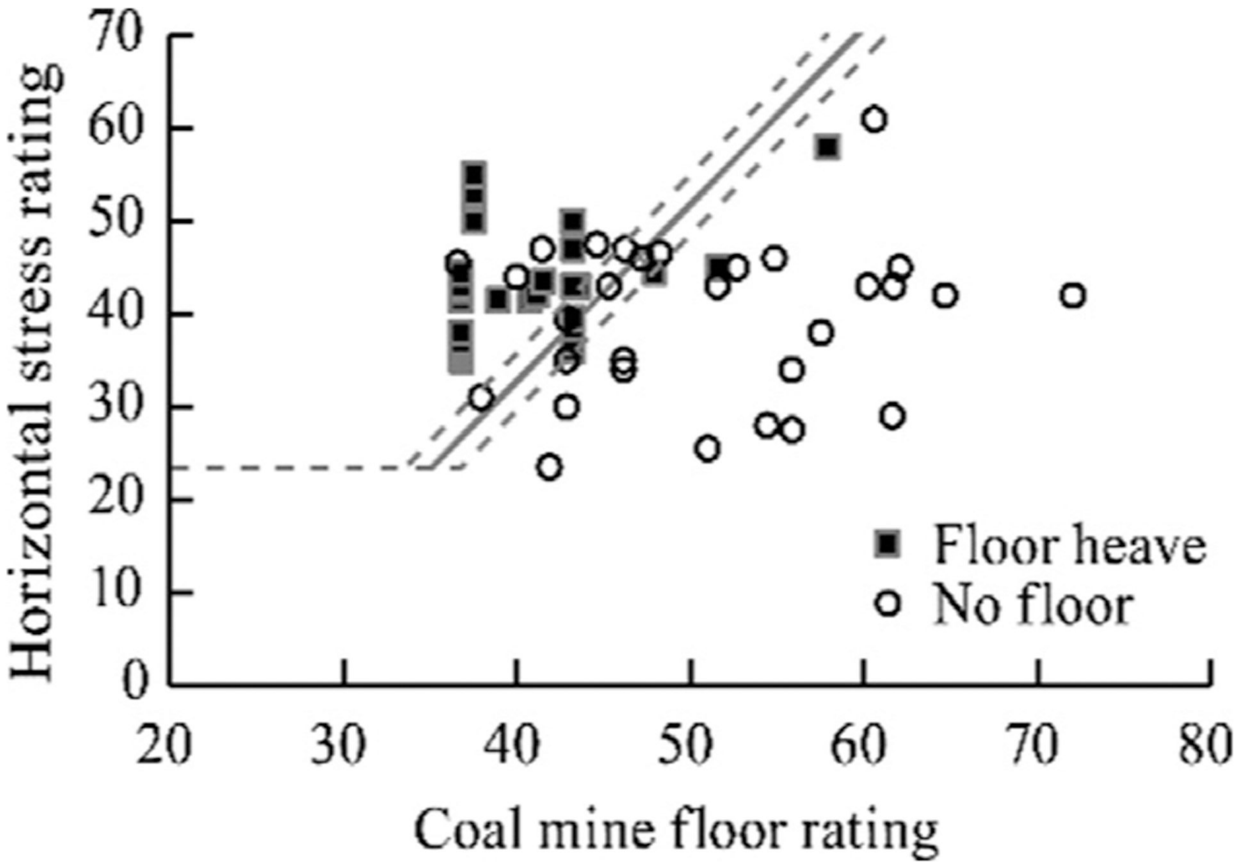


Fig. 3.
Floor heave index for Australian mines [3].

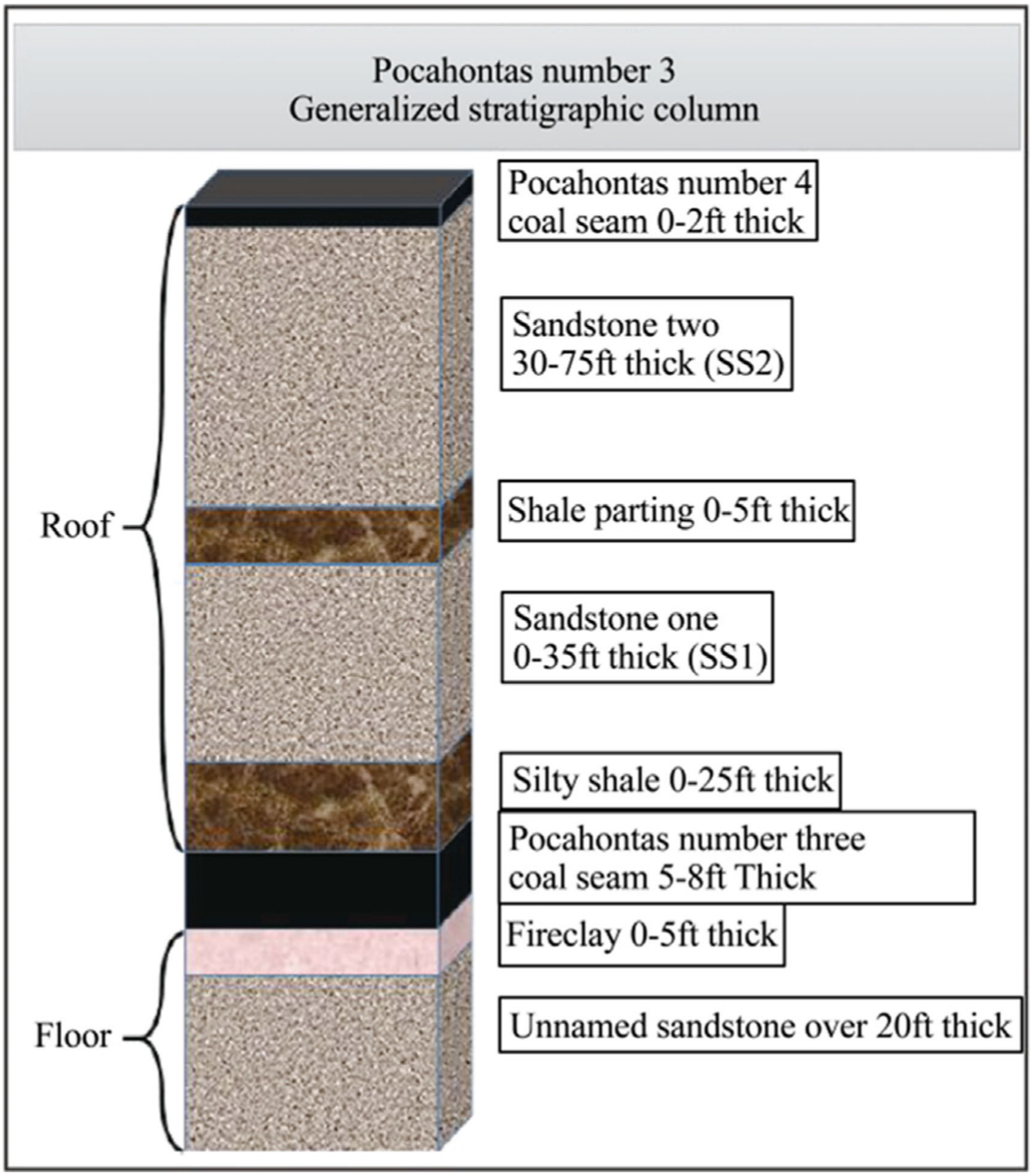


Fig. 4.

Generalized stratigraphic column of the Pocahontas Number 3 Seam for floor heave in the case study mine [7].

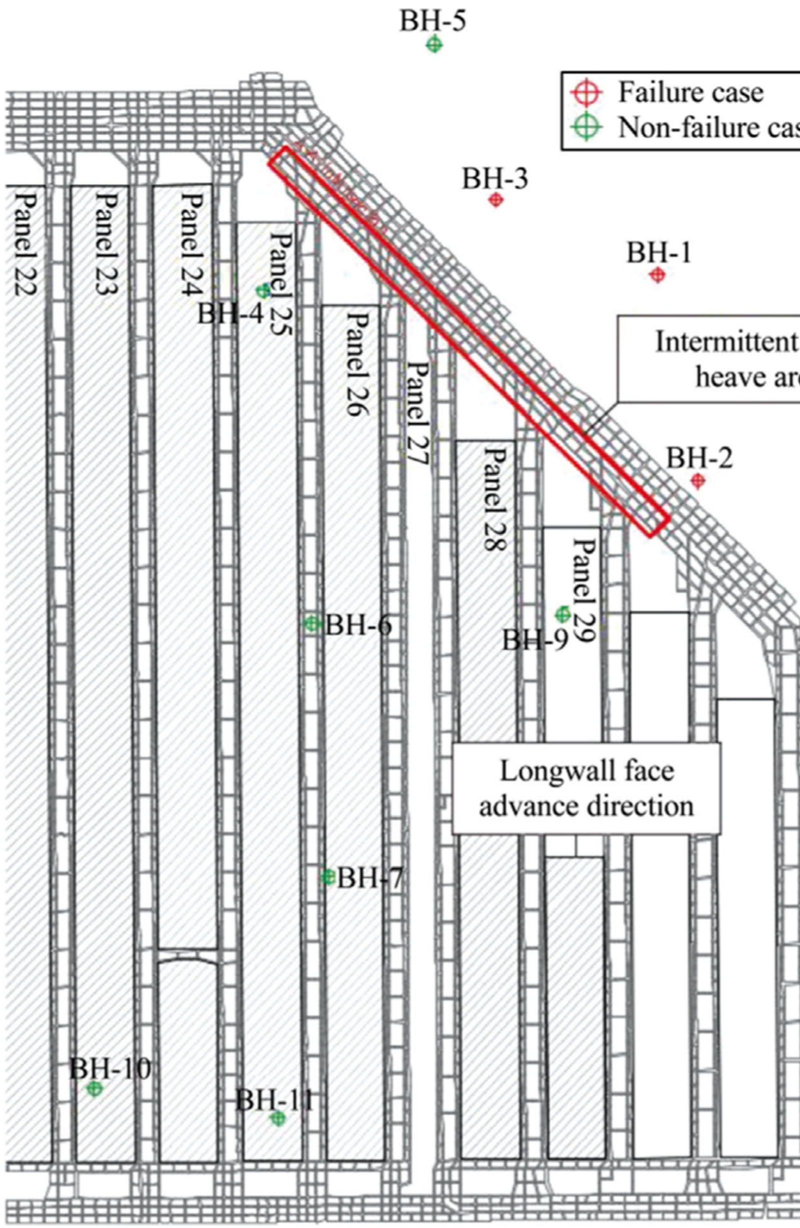


Fig. 5.
Mine layout and drill core locations for failure and non-failure cases in the U. S. case study mine.

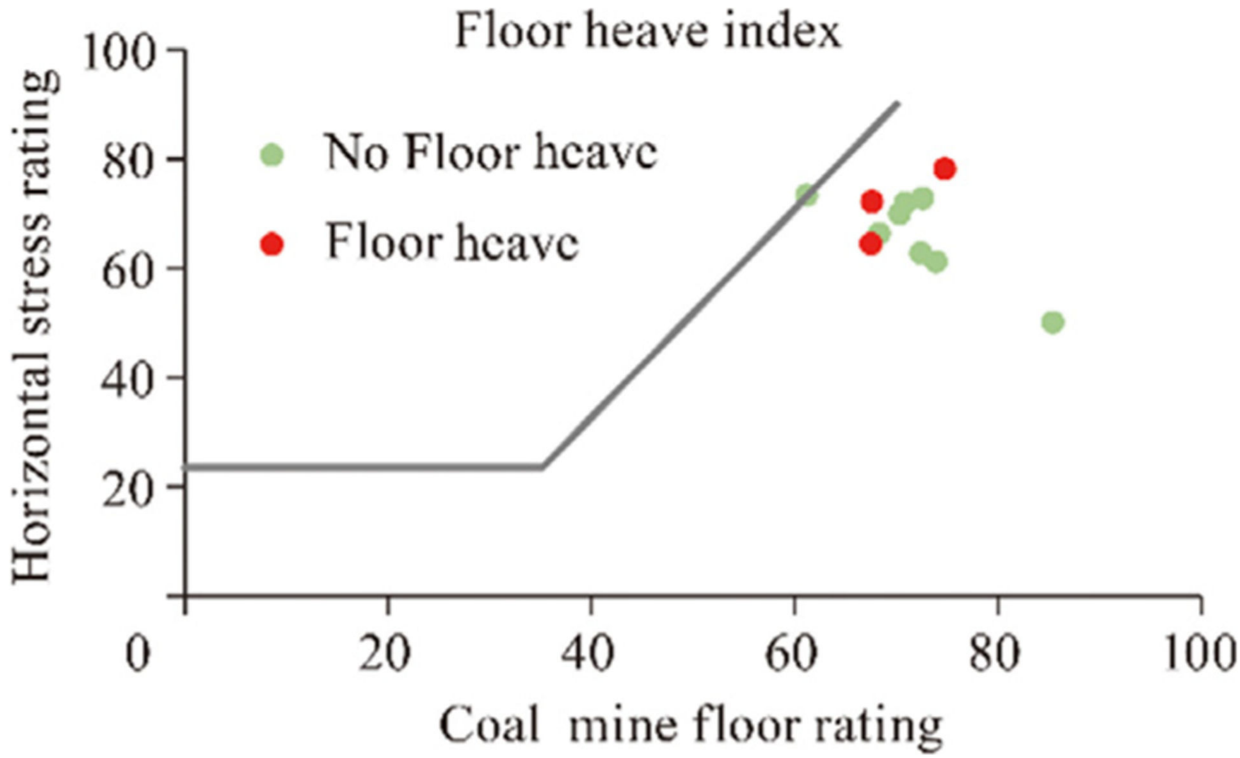


Fig. 6.
Floor heave index for the U.S. case study mine.

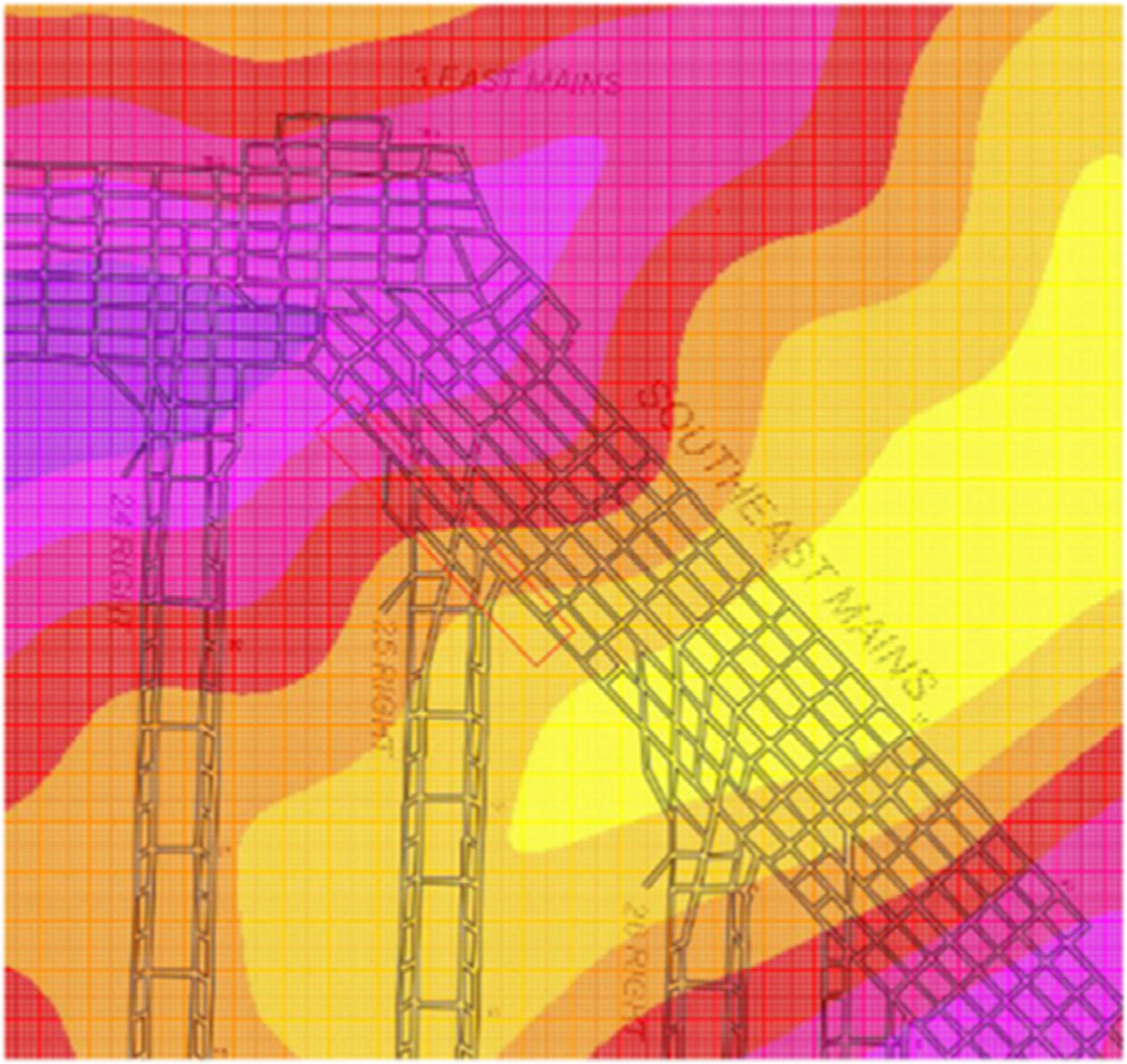


Fig. 7.
LaModel mesh for overburden stress.

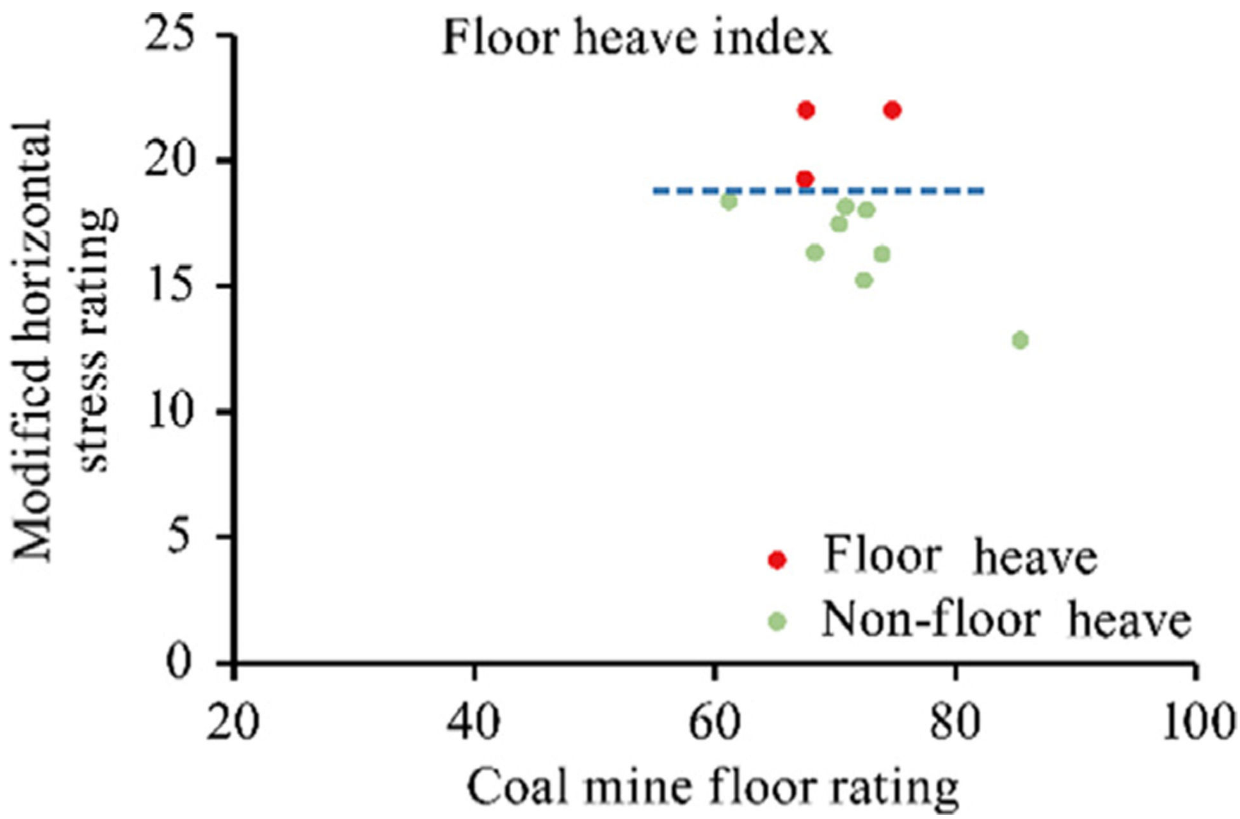


Fig. 8.
Floor heave index using the modified horizontal stress rating.

Table 1

CMFR unit ratings for UCS tests.

UCS (MPa)	Rating
<10	10
12–20	2 × UCS-10
20–30	UCS + 10
30–80	0.3 × UCS + 31
80–160	0.125 × UCS + 45
>160	65

Table 2

CMFR unit rating for discontinuity spacing.

Discontinuity spacing (mm)	Discontinuity Spacing rating
<20 (lamination)	0
20–60	5
60–200	15
200–600	25
>600	35

Table 3

Calculation procedure of unit rating and the CMFR.

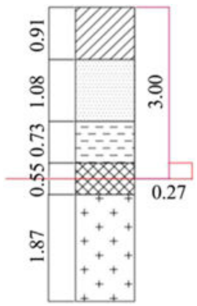
Stratigraphic column	Thickness (m)	Discontinuity spacing (mm)	Rating	UCS (MPa)	Rating	Unit rating	Thickness-weighted average rating
	0.91	53.4	5	79.3	54.8	59.8	59.8 × 0.91 = 54.4
	1.08	90.2	15	117.2	59.7	74.7	74.7 × 1.08 = 80.7
	0.73	146.3	15	110.3	58.8	73.8	73.8 × 0.73 = 53.9
	0.55	182.9	15	149.6	63.7	78.7	78.7 × 0.27 = 22.1
	1.87	187.5	15	173.1	65.0	80.0	CMFR = 70.3

Table 4

CMFR horizontal stress rating.

Stress notch angle (°)	Angle rating
>30	5
20–30	3
10–20	1
<10	0

Table 5

Calculation of the horizontal stress rating for the Central Appalachian study mine.

Borehole name	Failure/non-failure (F/NF)	Depth of cover (m)	Depth rating	Stress notch angle (°)	Angle rating	Horizontal stress rating	CMFR
BH 1	F	672.02	67.2	90	5	72.2	67.58
BH 2	F	595.40	59.5	90	5	64.5	67.49
BH 3	F	731.63	73.2	90	5	78.2	74.75
BH 4	NF	669.90	67.0	45	5	72.0	70.87
BH 5	NF	562.80	56.3	45	5	61.3	73.88
BH 6	NF	451.44	45.1	45	5	50.1	85.38
BH 7	NF	650.07	65.0	45	5	70.0	70.32
BH 8	NF	614.53	61.5	45	5	66.5	68.30
BH 9	NF	578.42	57.8	45	5	62.8	72.38
BH 10	NF	678.51	67.9	45	5	72.9	72.59
BH 11	NF	683.90	68.4	45	5	73.4	61.16

Table 6

Calculation of modified horizontal stress rating.

Borehole code	Failure/non-failure (F/N)	New horizontal stress coefficient	In-situ vertical stress (MPa)	Modified horizontal stress rating	CMFR
BH 1	F	1.23	17.94	22.02	67.58
BH 2	F	1.23	15.69	19.26	67.49
BH 3	F	1.23	17.94	22.02	74.75
BH 4	N	1.02	16.64	17.02	70.87
BH 5	N	1.02	14.92	15.27	73.88
BH 6	N	1.02	11.77	12.04	85.38
BH 7	N	1.02	16.01	16.38	70.32
BH 8	N	1.02	14.97	15.32	68.30
BH 9	N	1.02	13.96	14.29	72.38
BH 10	N	1.02	16.52	16.90	72.59
BH 11	N	1.02	16.84	17.23	61.16