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Influence of varying bedding thickness of underclay on floor stability

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ABSTRACT

The variation in bedding thickness of the weak immediate floor has long been a challenge in the Illinois basin coal mines when it comes to floor stability. The vertical thickness of the immediate floor is not constant throughout the mines and can vary over short horizontal distances. The biggest misconception from a design standpoint is to use the maximum or average thickness found from core logs taken from various locations on the mine property. The result of this practice is oversized pillars in the areas where the weak immediate floor has thinned vertically. This over-design leaves coal in situ which could have otherwise been extracted. This paper presents a plane strain numerical model to illustrate the effect of a change in bedding thickness of a weak immediate floor across one or two coal pillars. The floor bearing capacity of the variable floor below each pillar where then compared to the consistent floor. The results show that the varying bedding thickness of weak underclay has an impact on the bearing capacity of the floor. Geometrically with the decrease in bedding thickness for constant pillar width, the B/H ratio increases exponentially. The influence of varying bedding thickness on the floor bearing capacity is apparent at higher B/H ratios. The floor bearing capacity under a single pillar is in variable floor model if the average thickness remains constant. For single pillar, the average of the bedding thickness can be considered and for pillars in a panel, and a safety factor has been proposed to take into account this change in bedding thickness.

1. Introduction

In Illinois basin coal mines, the coal seam is often underlined by an immediate floor bed composed of weak underclay (fireclay), which can cause operational and stability issues due to the low strength characteristics of the weak floor. This is amplified in the presence of water. In the short term, the weak floor can undergo bearing capacity failure and develop floor heave which may cause complete abandonment of the panel or the part of the panel [1]. Further, if the bedding thickness varies over short horizontal distances (i.e. between the adjacent pillars) the differential settlement of the pillars can cause roof stability issues.

Geologically, underclay is classified as a gray, argillaceous rock and often, occurs beneath the beds of coal in the Illinois Basin [1]. The origin of the underclay has been speculated, but has been thought to be the decayed root system of the lush vegetation which now comprises the overlying coal bed. Depending on the composition of the clay (i.e. percentage of illite, kaolinite, montmorillonite, etc.) the clay has a tendency to swell in the presence of water.

The bedding thickness of the underclay can vary from less than 0.5 m, to 6 m at different locations in the Illinois Basin. The contact between the underclay and the older underlying bed is gradational whereas it is sharp with the contacts of the coal pillar [2]. The case studies across the Illinois Basin coal mines indicate that the weak floor thickness can vary about 0.3–1.0 m over a distance of two pillars and 2.0–2.5 m in the mine area [1]. In addition to the case studies, the core logs in Fig. 1, indicate that the thickness of the underclay can change dramatically at different locations. The punching failure in the West Kentucky coal mine in the No. 11 seam was observed due to the increase in floor thickness from 0.6 to 1.5 m [3].

2. Problem illustration

One of the problems the mine engineer faces when conducting the floor stability analysis is determining the thickness of the weak floor which can be representative of the mine as a whole. This would not be a significant issue if the thickness was constant

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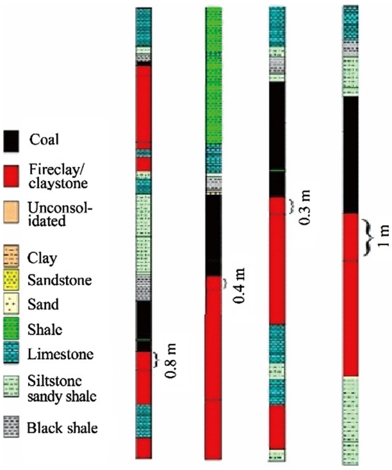


Fig. 1. Drill core logs representing varying weak floor thickness at different locations [2].

throughout the entire mine; but this is often not the case. The issue using the maximum floor thickness is that the pillars will be oversized. The issue using the average floor thickness is that the floor failure can initiate when a higher thickness is encountered as the pillars will be undersized. Often the more conservative approach is taken (average thickness of the underclay bed). In the author's opinion, the most practical method to account for the varying thickness is to estimate the floor bearing capacity by numerical modelling. This is because empirical equations cannot account for this variability.

The problem is illustrated in Fig. 2 which represents a coal pillar of width *B*, entry width *S* and the immediate weak floor with thickness *H*. The terms "consistent floor", which is represented by a constant (unchanging) floor thickness under each pillar, as well as the term "graded floor", which is characterized by the vertical thinning or thickening of the immediate floor by thickness *t*, will be used throughout this paper.

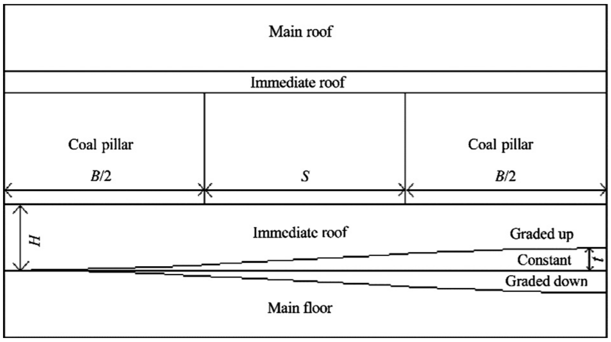


Fig. 2. Illustration of the problem.

A decrease in thickness of the underclay bed is represented by $H - t$ and will be characterized as "graded up" and an increase will be represented by $H + t$ and is characterized as "graded down". So that reference to the pillars is not confused, the term "base floor" will be used in reference to the left pillar and the term "graded floor" will be used for the right pillar unless otherwise noted.

The bearing capacity of immediate floor at varying thicknesses will be compared. Bearing capacities of the floor graded up, graded down at the left pillar and the base floor thickness at the right pillar will be compared to the bearing capacity of the consistent floor. The results will be presented in the form of increase or decrease in the percentage of the floor bearing capacity. For example, if a decrease in bearing capacity of 20% is observed under the graded down thickness, this means the bearing capacity is 20% lower under the right pillar relative to the bearing capacity of the consistent floor.

3. Model characteristics and properties

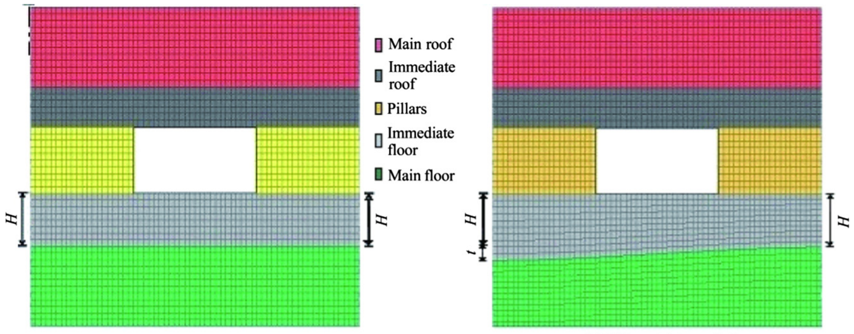
Numerical modelling was conducted using the finite difference method with FLAC3D, which has the ability to simulate the geotechnical problems associated with soil and rock. The problem was modelled in plane strain. Fig. 3 illustrates the two-dimensional numerical model consisting of a roof, a room, and two half-width coal pillars, with a consistent immediate floor (Fig. 3a) and a graded up immediate floor (Fig. 3b).

Plane strain can be modelling in FLAC3D when the element size in the out-of-plane direction is small compared to the elements of the in-plane direction (i.e. large aspect ratio of the in-plane element size relative to the out-of-plane element size).

Displacements and velocities were restricted normal to the plane *X* by creating the roller boundaries around the entire model grid. The farthest coordinate direction in the *Z* plane (bottom of the model) was pinned so that the displacements and the velocities are restricted both in normal and parallel direction. At the base of the model, zero displacements were set and at the top of the model, a constant compressive velocity was applied in the negative *Z* direction to compress the model grid.

The Mohr-Coulomb failure criteria were selected for all the materials. The material properties of the main roof, immediate roof, pillars, immediate weak floor, and the main floor are shown in Table 1.

This model was calibrated to an equation for bearing capacity design. This was the only avenue to calibrate to a known solution since field data on this type of problem is not readily available. The



(a) With consistent weak floor

(b) With variable weak floor

Fig. 3. Two-dimensional model.

Table 1
Strata material properties [4,5].

Material	Young's modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (°)	Dilation angle (°)
Limestone (main roof and floor)	20.00	0.25	7.70	20.00	30	10
Shale (immediate roof)	4.00	0.25	0.60	20.00	23	10
Coal (pillars)	2.48	0.34	0.20	1.62	35	10
Underclay (immediate floor)	3.86	0.42	0.45	0.84	0	10

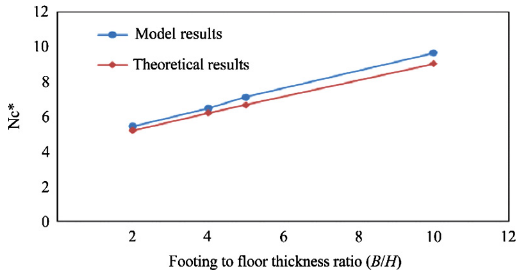


Fig. 4. Validation plot comparing the model results to the theoretical results.

Table 2
Ratio of model strength to theoretical strength.

B/*H* ratio	Ratio of model strength to theoretical strength
2	1.04
4	1.04
5	1.06
10	1.06

procedure was also conducted by Gadde and Kostecki & Spearing [1,6].

One of the earliest theoretical approximations on foundation design is by Prandtl's approximation for a continuous footing resting on the semi-infinite homogeneous soil [7]. While this may be only valid when the floor is semi-infinite while the floors are finite in nature in the field scenarios. The Mandel and Salencon's analysis is similar to Prandtl's approximation considering continuous footings supported by a soil with a rigid base at a shallow depth that is represented in Fig. 2 [8]. The equation can be expressed as:

$$q_{c\text{-strip}} = cN_c^* \tag{1}$$

Where $q_{c\text{-strip}}$ is the load bearing capacity of the strip foundation; *c* the cohesion; and N_C^* the normalized bearing capacity factor for cohesion which is based on the effective friction angle of the soil.

To validate the model to that of the theoretical results, the model was run with four different footing to floor thickness (*B*/*H*) ratios of 2, 4, 5 and 10. This was conducted at zero-degree friction angle. The model results were compared to the theoretical results as shown in Fig. 4. Table 2 shows a 4%–6% difference in the calculated and modelled results. It can be seen that a reasonably good match is made between the modelled and calculated results.

4. Results and discussion

4.1. Geometrical representation of gradational floor on B/H ratio

The fundamental parameter affecting the floor bearing capacity is pillar width to floor thickness ratio (*B*/*H*) which significantly gets effected due to the variation in the immediate floor thickness.

Geometric representation of the seven models is shown in Fig. 5. The base floor thickness is kept constant in all the models while the graded floor thickness is differed. The *B*/*H* ratios of the graded floor were compared to the base floor and represented in the form of percentage increase in the *B*/*H* ratio in Fig. 5. It clearly shows that *B*/*H* ratio of the floor grading upwards is increasing exponentially while the floor grading downwards decreases linearly. Therefore, it can be assumed that the floor bearing capacity can increase substantially with the upward gradation of the weak floor while the downward gradation can have a little effect on the floor bearing capacity. The thickness of the consistent immediate weak floor is also an important factor in determining the effect on the deviation of the *B*/*H* ratio. Thin weak immediate floors have the tendency to increase deviation while the thick floors have the tendency to decrease the deviation in the percentage change of *B*/*H* ratio.

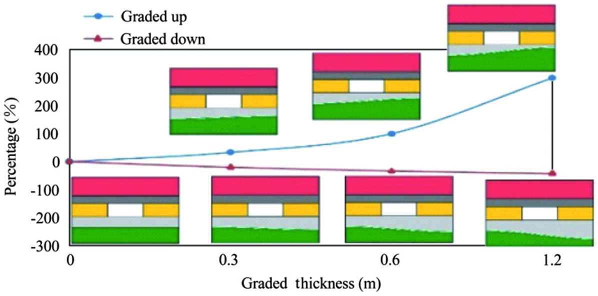


Fig. 5. Geometrical effect on *B*/*H* ratio with the grading weak floor.

As noted in Fig. 5, *B*/*H* ratio under right pillar compared to *B*/*H* ratio under left pillar.

4.2. Effect of a varying underclay thickness on floor bearing capacity

Three models were simulated, two "consistent-floor" models with *B*/*H* ratio of 10 and 20, respectively, and one "variable floor" model with a transition from *B*/*H* = 10 to *B*/*H* = 20. These models are shown in Fig. 6.

The "base floor" and the "graded floor" of the variable floor model are subject to change with respect to the consistent floor model. For example, when the "variable floor" model is compared with the "consistent floor" model with *B*/*H* ratio of 10, the "base floor" in the "variable floor" model is referenced to left pillar and

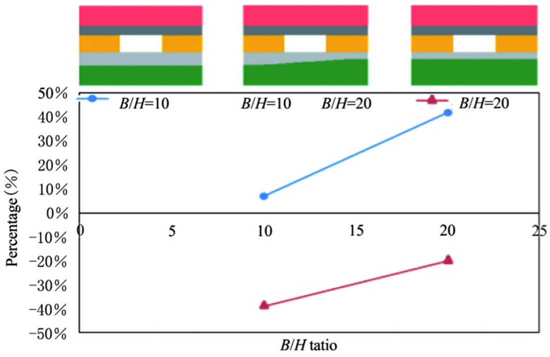


Fig. 6. Effect on the floor bearing capacity with reference to a particular *B*/*H* ratio.

the “graded floor” is referenced to right pillar and vice versa. Results of the “variable floor” model is compared to “consistent floor” model. The results of the variable floor model are presented in the form of the percent increase or decrease of the floor bearing capacity, as shown in Fig. 6.

As noted in Fig. 6, blue line is the variable weak floor compared in reference to “consistent floor” of $B/H = 10$; red line is in reference to “consistent floor’ of $B/H = 20$.

Based upon the results, an 11% increase in the floor bearing capacity was found at the “base floor” section of the model with B/H ratio of 10. Whereas a 20% decrease in bearing capacity is found at the “base floor” section of the model with B/H ratio of 20. The 11% increase and the 20% decrease in the floor bearing capacity of the two pillars can be used to design the improved pillar designs in the case of the variable floor.

However, the effect is different on the “graded floor” section of the model. In this case a 42% increase in bearing capacity was found with a B/H ratio of 10 and a 39% decrease with a B/H ratio of 20.

It can be concluded that if the pillars are designed under a B/H ratio of 20 in the case of “variable floor”, there is a substantial decrease in the floor bearing capacity of the “base floor” and the “graded floor” such that it will lead to the floor failure of the graded floor and base floor will be at the brim of floor failure.

It is also observed that if the pillars are designed according to B/H ratio of 10, then there is an increase in the floor bearing capacity of the “base floor” and “graded floor”.

4.3. Effect of varying underclay thickness on the “base floor”

The effect of a variable bedding thickness on the floor bearing capacity of the “base floor” is addressed in this section. Twenty-one models were designed: eighteen “variable floor” models and three “consistent floor” models. The “variable floor” models were modelled with a “base floor” B/H ratio of 5, 10 and 20. Each model was then “graded up” and then “graded down” by 0.3, 0.6 and 0.9 m. The three “consistent floor” models with B/H ratios of 5, 10 and 20 were also modelled.

The percent change in the floor bearing capacity at the “base floor” section of the model at different B/H ratios is shown in Fig. 7.

Although, the overall effect on the floor bearing capacity at the “base floor” is minimal (i.e. less than 10%), it is found that the “graded up” scenario is less pronounced than the “graded down” scenario at all B/H ratios. Additionally, it can also be concluded that the effect is more apparent at higher pillar width to floor thickness (B/H) ratios.

4.4. Effect of varying underclay thickness on the “graded floor”

In the previous section, results relative to the “base floor” *x-y* was discussed. This section will address the effect of a variable bedding thickness on the “graded floor”. The results are shown in Fig. 8.

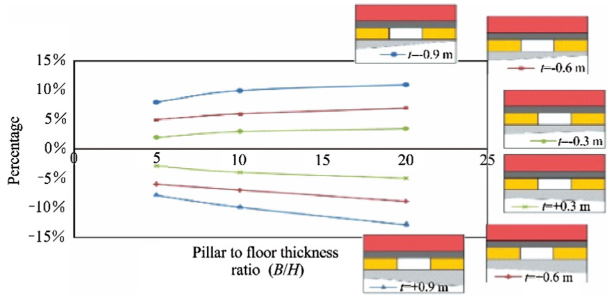


Fig. 7. Effects of a varying bedding thickness on the floor bearing capacity of the “base floor”.

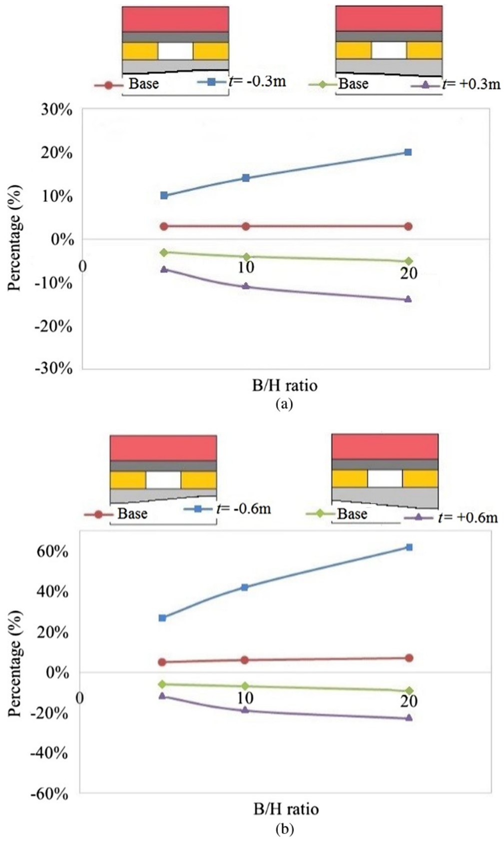


Fig. 8. Effects of a variable bedding thickness on the floor bearing capacity of the “base floor” and “graded floor” at ±0.3 m thickness and ±0.6 m thickness.

The results show that when the model is “graded up” by 0.3 m, the bearing capacity of the “graded floor” section increases 21% in the case of a B/H ratio of 20, and when the model is “graded up” by 0.6 m, the bearing capacity increases to nearly 63%.

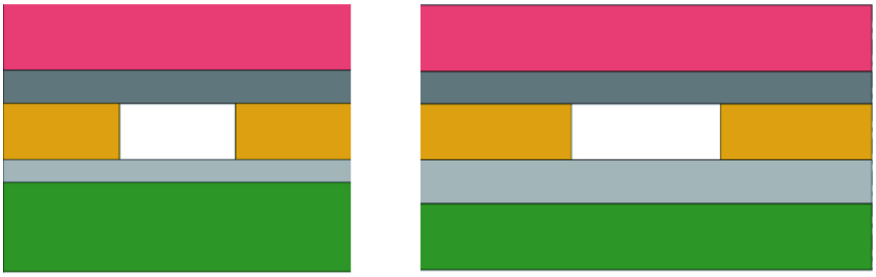
Under the “graded down” scenario of 0.3 and 0.6 m, a 15%–20% decrease in the floor bearing capacity was found. This is even true at higher B/H ratios.

Overall, a “graded down” scenario has a significantly less effect on the “graded floor” section at any B/H ratio. It is also important to note that the 0.6 m “graded up” scenario increases the bearing capacity nearly three times to that of the 0.3 m “graded up” scenario when the B/H is large (i.e. $B/H = 20$).

4.5. Effect of varying underclay thickness for thick and thin floors

Floor thickness itself is a major factor in determining the floor bearing capacity. For example, at two different mine depths, the B/H ratio developed can be same. The bearing capacity will be equal while the thickness variation will result in different load bearing capacities.

Two “consistent floor” models were modelled with a B/H ratio of 20, with thick and thin floor thickness relatively as shown in Fig. 9. Another four “variable floor” models with the “base floor” set at $B/H = 20$ with a thick and thin floor thickness and a “graded floor” which is “graded up” by 0.3 m and also “graded down” by 0.3 m. Fig. 10 shows that the thin floor has a double the large effect on the floor bearing capacity than the thick floor at the “base floor” location.


(a) With thin floor thickness

(b) With thick floor thickness

Fig. 9. Pillar width to floor thickness (*B*/*H*) ratio of 20.

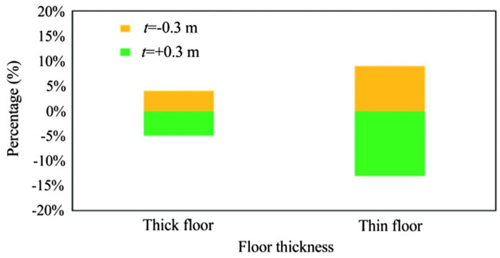


Fig. 10. Effect of floor thickness on the floor bearing capacity of the base floor in the graded model.

4.6. Effect of varying underclay thickness across a single pillar

Variation of the weak floor can also occur across the width of a single pillar. An example of this is shown in Fig. 11. Fifteen models were simulated to understand the effects of a varying floor thickness at different *B*/*H* ratios. Material properties, failure criteria, boundary, and loading conditions were the same as in the previous numerical models.

A similar presentation of results was carried out and is shown in Fig. 12. Based upon the results a "graded up" scenario has a higher effect on the floor bearing capacity than the "graded down" scenario. It was also observed that at higher *B*/*H* ratios, there is a greater effect on the floor bearing capacity. It can also be observed that when "graded up" by 0.3 m, the increase in load bearing capacity is 5%-11%, depending on the *B*/*H* ratios.

4.7. Average floor thickness as an metric for pillar design

Six models with half pillars and a "consistent floor" and "variable floor" were simulated; both models were simulated at *B*/*H* ratios of 5 and 10, as shown in Fig. 13. In the "variable floor" model, the difference between the load bearing capacities of the floors is around 8% in the case of *B*/*H* ratio of 5. When "variable floor" model is compared to the "consistent floor" model as shown in Fig. 13, the load bearing capacity of the "base floor" was 4% more and "graded floor" was 4% less. As the floor thickness increases in the "variable floor" model, the difference between the floor bearing capacity increases and is not the same to that of the "consistent floor" model as shown in Fig. 14.

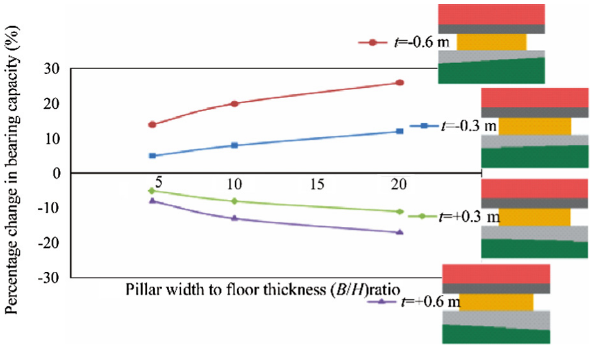
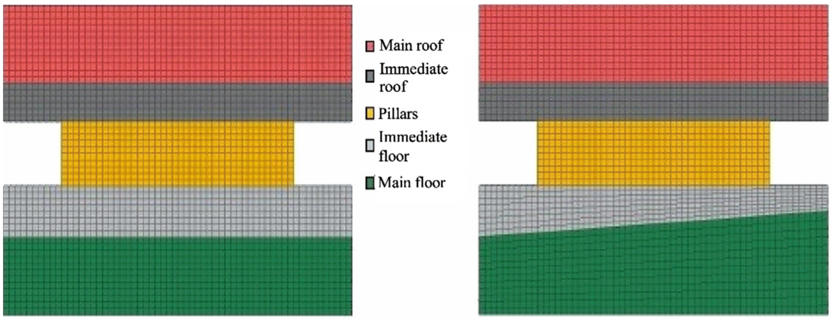


Fig. 12. Effect of varying underclay thickness on the floor bearing capacity at different *B*/*H* ratios.

Similarly, six single pillar models with the "consistent floor" and the "variable floor" scenario, were simulated. Variable floor model had an average thickness equal to that of the consistent floor model as shown in Fig. 15.

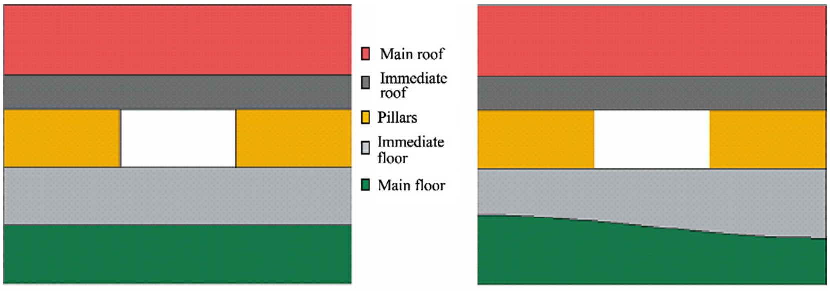
The "consistent floor" model and the "variable floor" model both had a *B*/*H* ratio of 5 and 10. The load bearing capacities of the immediate floor are exactly the same as shown in Fig. 16. This shows that an average floor thickness can be utilized for design in the case of a variable underclay thickness across a single pillar.



(a) "Consistent follr" thickness

(b) "Variable floor" thickness across the pillar

Fig. 11. Two-dimensional model with "consistent floor" thickness and "variable floor" thickness across the pillar.



(a) "Consistent floor" thickness

(b) "Variable floor" thickness

Fig. 13. Pillar width to average floor thickness of 5 across two pillars.

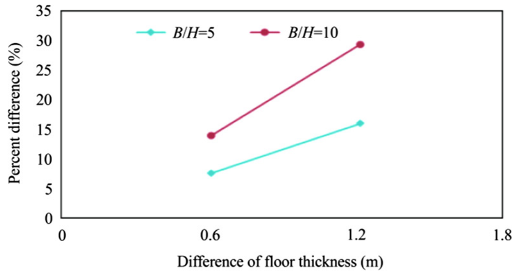


Fig. 14. Floor bearing capacities of the "variable floor" model with average floor thickness to that of the "consistent floor" thickness.

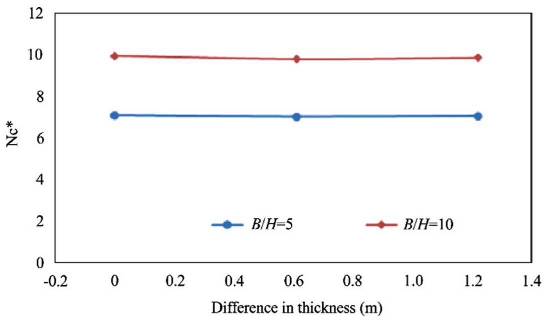
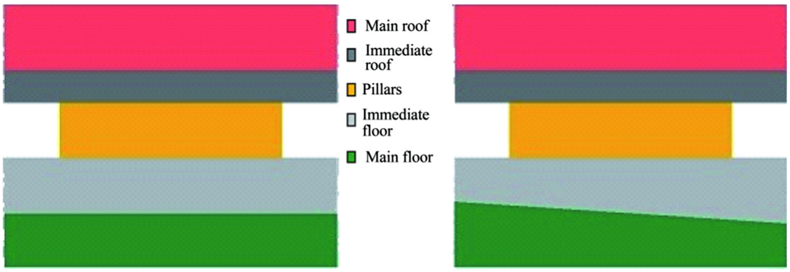


Fig. 16. Floor bearing capacities of "consistent floor" model and "varying floor" model with average floor thickness.



(a) "Consistent floor" thickness

(b) "Variable floor" thicknes

Fig. 15. Pillar width to average floor thickness of 5 across single pillar.

4.8. Effect when underclay bedding thickness varies on both sides

As the pillars are not excavated in two-dimensional space, it is possible that the varying underclay thickness can occur in more than one horizontal direction. Obviously there are a myriad of factors affecting the floor bearing capacity when considering this scenario. Therefore, further work is recommended to study this problem.

4.9. Design recommendations

The following design recommendations can be made:

(1) Confirm the variation of the underclay bed thickness in the area of the panel.
(2) The floor bearing capacity across a single pillar under a "variable floor" scenario can be estimated using the average immediate floor thickness.
(3) Since the panel consists of several pillars, the pillars can be designed according to the safety factor of 1.1 in the case of varying thickness throughout the panel.

5. Conclusions

A study of the underclay floor behavior in the Illinois Basin coal mines, with a variation of the bedding thickness, has been addressed. The following main conclusions can be drawn:

(1) The floor bearing capacity of the immediate floor depends on the bedding thickness; i.e. thick bedding thickness corresponds to lower floor bearing capacity and thin bedding thickness leads to high floor bearing capacity. The variation in the bedding thickness largely affects the floor bearing capacity of thin beds. The 0.3 m variation in bedding thickness of a thin bed affects the floor bearing capacity by 10%–15% while for the thick beds, it is less than 5%.
(2) The variation of the bedding thickness under a single pillar does not affect the floor bearing capacity if the average bedding thickness is constant. Similar floor bearing capacity is observed with constant bedding thickness and bedding thickness with variation of 0.6 and 1.2 m.
(3) Pillar width to immediate floor thickness ratio (B/H) is major factor for determining the floor bearing capacity. The

variation in the bedding thickness largely affects at higher B/H ratios. At high B/H ratios with 0.3 m variation in bedding thickness can result in 10% difference in floor bearing capacity.

(4) Floor safety factor has been proposed which takes into consideration the variation in the immediate weak floor. This can be used in the coal mines with weak immediate floor followed by strong main floor in the Illinois Coal Basin. Further studies need to be conducted on the variable weak floor and need to calibrate it with the in situ conditions.

References

[1] Gadde MM. Weak floor stability in the Illinois Basin underground coal mine. Morgantown: University of West Virginia; 2009.

[2] Grim RE, Allen VT. Petrology of the Pennsylvanian underclays of Illinois. Geol Soc Am Bull 1938;49(3):1485–513.

[3] Perry K, Bradley J, Unrug K, Klimek M. Mitigation of floor heave in West Kentucky Coal Mine. Int J Min Sci Technol 2016;26(3):521–5.

[4] Lu J, Ray A, Morsey K, Peng S. Effects of rock/coal interface property on coal pillar strength. In: Proceedings of the 27th international conference on ground control in mining. Morgantown, WV; 2008. p. 262–267.

[5] Spearing AJS, Hirschi J. The conceptual design and financial implications of a room and pillar mine using paste fill. Illinois Clean Coal Institute Project Report. Carbondale, IL; 2012:12/3A-1.

[6] Kostecki T, Spearing AJS. Influence of backfill on coal pillar strength and floor bearing capacity in weak floor conditions in the Illinois Basin. Int J Rock Mech Min Sci 2015;76:55–67.

[7] Terzaghi K, Peck RB. Soil mechanics in engineering practice. New York: John Wiley and Sons; 1967.

[8] Mandel J, Salencon J. Strength of a ground on a rigid foundation (theoretical study). Geotechnique 1972;22(1):79–93.