

Article

Critical Evaluation of the Current Design of Coal Room and Pillar Panels as Input for Changes to the Future Design Methodology

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Abstract

The design of coal room and pillar panels has traditionally focused primarily on pillar behaviour. However, if the design process were approached from first principles, one would start with the design of the rooms and first look at the redistribution of the stresses around the rooms. Numerical simulations (elastic and elasto-plastic behaviour) clearly demonstrate the development of relaxed zones in both the roof and floor strata, as well as along the sidewalls in the pillars. The extent of these relaxed zones is governed by factors such as excavation geometry and the ratio of vertical-to-horizontal in situ stresses. A second concern is the widespread tendency to approximate in situ pillar behaviour through vertically loading experiments, such as uniaxial compression tests. These experiments would only be representative if pillars were constructed structures. More complex stress paths develop within the coal pillars during mining, and the load is far from uniform. The current design practices are based on the average pillar load, while the rock behaviour is not determined by average stresses but by local stresses. This paper concludes by proposing directions for future research and by identifying opportunities to improve current understanding and design methodologies for coal room and pillar workings.

Keywords: strata control; ground control; coal mining; room and pillar design; in situ stress paths; pillar strength

1. Introduction

The design of pillars, and more specifically the design of coal pillars, is a topic that has been researched extensively in the past, and it is still studied extensively (e.g., [1–11]). The list of references includes a number of papers published during the last few years to illustrate the last point (e.g., [12–18]). All this means that there is not only a large interest in this topic, but there also is a need to understand the behaviour of pillars better. The ultimate goal is to optimise the room and pillar parameters without jeopardising the short-term and long-term safety. A change in the geometry (pillar and/or room width) has a direct effect on the extraction ratio. When no pillar extraction is planned (i.e., retreat mining), the coal in the pillars is lost forever. Note that this paper is focused only on coal room and pillar panels and not on retreat mining, pillar extraction, or pillars adjacent to longwall panels.

At first glance, one would not expect that a lot of research is still needed at this time since the geotechnical design of room and pillar panels seems simple. The behaviour of the rock is relatively straightforward, at least in comparison to other mining methods and certainly in comparison to total extraction mining methods. For example, when applying



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the longwall method, the roof collapses, the fracturing is extensive around the panel, and meter-scale displacements occur in the strata until they reach the Earth's surface.

The aim of this paper is not to summarise past research. Also, the aim is not to drastically change the current design method. Rather, some complementary suggestions to the ongoing research are formulated and presented here. The two main elements in this paper are (i) the relatively small focus on the local stress redistribution around the rooms in comparison to the average load over the pillar area and (ii) the use of uniaxial compression experiments as proxies for the in situ pillar behaviour. Both elements are discussed in detail in the next paragraphs. The purpose of the numerical simulations performed is primarily aimed at supporting these two main elements in this paper. Therefore, no specific case study is modelled in this paper, nor is it intended to investigate all parameters that directly or indirectly influence the behaviour of the rock in a coal room and pillar panel. A typical example of the latter is the use of support in the roof and sidewalls. At the end of this paper, suggestions are formulated for future work and for improvements to our knowledge of coal room and pillar design.

2. Local Stress Redistribution Around the Excavations

2.1. Elastic Simulations

When looking from a certain distance at the past and current design practice of coal room and pillar workings, one must conclude that the focus primarily is on the pillars, i.e., the load on the pillar vs. the strength of the pillar. One could argue that this is logic, as major incidents in the past involved the collapse of several pillars, even complete panels [19–21]. However, if one were to start a room and pillar design from a blank piece of paper (without any prior knowledge of pillar design practice), one would start most likely with the design of the rooms and the local redistribution of the stresses around the rooms.

First, results are discussed for an elastic and continuum 2D model. A depth of 250 m is applied, corresponding to a vertical stress of 6.25 MPa. Vertical symmetry planes are introduced in the model mid-way through the room and mid-way through the pillar. On the top and bottom boundary, vertical stresses are applied. Both the vertical and horizontal stresses are initiated in all elements of the model prior to the excavation. The standard 6 m width for the rooms is modelled, and pillar widths of 34 m are assumed in the first group of simulations. The total height of the model is 60 m, and the seam elements are situated in the middle. For example, for a 3 m high excavation, 28.5 m of roof material and 28.5 m of floor material are part of the model. This means that the average pillar stress in the 2D approach is 7.35 MPa for a pillar that is 34 m wide. Three different values are applied for two parameters, i.e., the height of the pillar is taken to be equal to 1.5 m, 3.0 m (reference), and 4.5 m. So, 3 m, plus and minus 50%. The horizontal stress is for the reference case equal to the vertical stress, i.e., an initial isotropic stress state of 6.25 MPa. The two alternatives for the horizontal stress also are plus and minus 50%, i.e., 3.125 and 9.375 MPa. Note that the chosen range of horizontal stress for a depth of 250 m is far from extreme, as a ratio of horizontal-to-vertical stress can be equal to 2 or even larger [22,23]. When one wants to focus on the local stress redistribution around an excavation, a sufficiently small mesh is needed. The model is composed of 10 cm square elements in the area surrounding the excavation. The same material is used for the floor, the seam, and the roof, and no interfaces are introduced above or below the seam. The reason for these simplifications is to be able to concentrate on the main goal of the simulations presented, i.e., the illustration of the impact of the geometry and of the initial stress state on the stress distribution after mining. The chosen characteristics for the coal are based on earlier research [24,25], i.e., a Young's modulus equal to 3 GPa and a Poisson's ratio of 0.2. Some of the models correspond to relatively high factors of safety based on the basic formula developed by Salamon and

Munro [5]. E.g., for a mining height of 1.5 m, 3.0 m, and 4.5 m (and a pillar width of 34 m), the factor of safety is 3.2, 2.0, and 1.6, respectively.

In Figure 1, the locations of the stress peaks are shown in the roof (halfway the room width of 6 m) and in the pillar (halfway the mining height). The three mining heights are presented in Figures 1a, 1b, and 1c, respectively. In each subfigure, the results for the three different initial horizontal stresses are presented. An ellipse representing the peak stress arches around the excavations are drawn. Inside these arches, there is a zone of stress relaxation in both the roof (and floor) and along the sidewalls inside the coal pillars. Such a relaxation is one of the reasons that roof support is required because the bedding planes open or fractures are introduced. This mechanism is well known for the roof layers. For the sidewalls, this aspect generally is not considered in the design process. Note that the size of the relaxed zone is determined here for an elastic and continuum model, and this model is independent of fracturing, contacts opening, or spalling. However, note that, for some displacement discontinuity codes, the relaxed zones at the edges of the pillars are not modelled, and the peak stress occurs at the sidewall. This is not a major problem if the aim of the modelling is to learn more about the average loading of the pillars, but it is a drawback when one investigates the behaviour of a pillar. In Table 1, the data are provided for the peak stresses in the pillar, i.e., the peak vertical stress, the corresponding horizontal stress, and the distance of the peak to the sidewall. The overall observation is that the larger the pillar height and the larger the initial horizontal-to-vertical stress ratio, the deeper into the sidewall the stress peak is situated. Or, in other words, the larger the relaxed zone is at the sidewall. If the initial ratio is larger than 1.5, the relaxed zone would also be extended further into the pillar. If the height of a pillar is small, the width of the relaxed zone is also small, i.e., 0.3 to 0.4 m for the cases modelled.

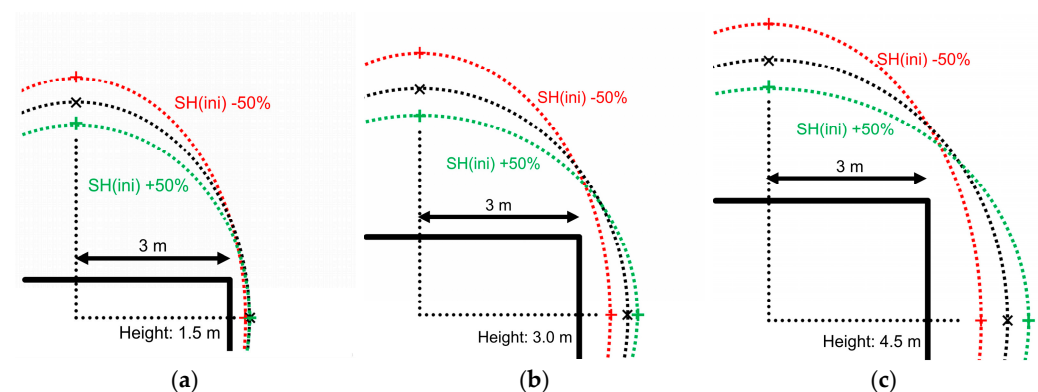


Figure 1. Locations of the stress peaks in an elastic model for three different initial horizontal stresses (pillar width of 34 m): (a) mining height of 1.5 m; (b) mining height of 3.0 m; (c) mining height of 4.5 m.

Table 1. Data for the peak stresses in the pillar for different mining heights in an elastic model for three different initial horizontal stresses (pillar width of 34 m), i.e., the peak vertical stress, the corresponding horizontal stress, and the distance of the peak to the sidewall: (a) 1.5 m; (b) 3.0 m; (c) 4.5 m.

	SH(ini) – 50%	SH(ini) = SV(ini)	SH(ini) +50%
(a)			
SYy-peak (MPa)	14.93	13.98	13.43
SXX at peak (MPa)	0.64	1.64	1.95
Distance from wall (m)	0.3	0.4	0.4
(b)			
SYy-peak (MPa)	11.32	10.65	10.37
SXX at peak (MPa)	0.58	1.54	2.69
Distance from wall (m)	0.6	0.9	1.1

Table 1. Cont.

	SH(ini) −50%	SH(ini) = SV(ini)	SH(ini) +50%
(c)			
SYY-peak (MPa)	9.85	9.38	9.26
SXX at peak (MPa)	0.6	1.64	3.09
Distance from wall (m)	1.0	1.5	1.9

In Figure 2, the stress redistribution in the pillar (at mid-height) is presented for the reference mining height of 3 m. Both the variation of the vertical stress (Figure 2a) and the horizontal stress (Figure 2b) are presented for the three initial horizontal-to-vertical stress ratios. A comparison of both figures shows that the horizontal stresses are low in the zone of larger vertical stresses. Or, in other words, the risk for weakening is larger. Note that introducing interfaces in the model between the seam and the surrounding layers most likely results in lower horizontal stresses, while stiffer roof layers could have the opposite effect. In Figure 3, a zoom-in on the vertical stresses for the first 5 m into the pillar is presented for nine combinations, i.e., three stress ratios and three mining heights. These graphs also illustrate what was observed in the data of Table 1. When the width of the relaxed zone is smaller, i.e., for smaller mining heights (Figure 3a), the stress peaks are larger and are more concentrated over a smaller area. Also, the opposite is true for wider relaxed zones (Figure 3c).

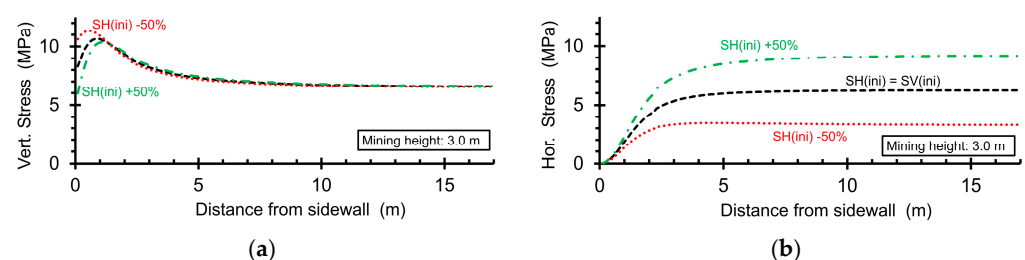


Figure 2. Stress redistribution in the pillar (at mid-height) in an elastic model for three different initial horizontal stresses (reference mining height of 3 m and pillar width of 34 m): (a) variation of the vertical stress; (b) variation of the horizontal stress.

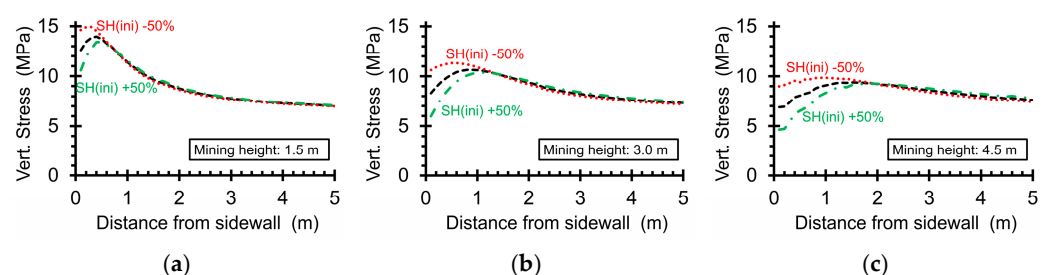


Figure 3. Variation of the vertical stress in an elastic model over the first 5 m into the pillar for three different initial horizontal stresses (pillar width of 34 m): (a) mining height of 1.5 m; (b) mining height of 3.0 m; (c) mining height of 4.5 m.

The previous simulations were for a relatively large pillar. In Figure 4, the width of the pillar is reduced significantly, i.e., to a width of 14 m. The height is the same as in the reference case, i.e., 3 m. The average vertical load is larger, i.e., 8.65 MPa for a 14 m wide pillar at a depth of 250 m in comparison to an average load of 7.35 MPa for a 34 m wide pillar. The width-to-height ratio in the new model is equal to 4.7, resulting in a factor of safety equal to 0.92 (basic formula by Salamon and Munro [5]). This is less than half the factor of safety for a pillar that is 34 m wide. The vertical stress in the middle of the pillar is

6.6 MPa and 7.7 MPa for a pillar that is 34 m and 14 m, respectively. In Table 2, the same information is presented that was presented in Table 1, but now it is for a pillar that is 3 m high and has three different pillar widths, i.e., 24 m, 14 m, and 6 m. Looking at the geometrical parameters, the data clearly show that the width of the relaxed zone is mainly determined by the dimensions of the room rather than by the width of the pillar. The peak vertical stress increases for smaller pillar widths, as the average stress is also larger. This influences the behaviour of the various pillars.

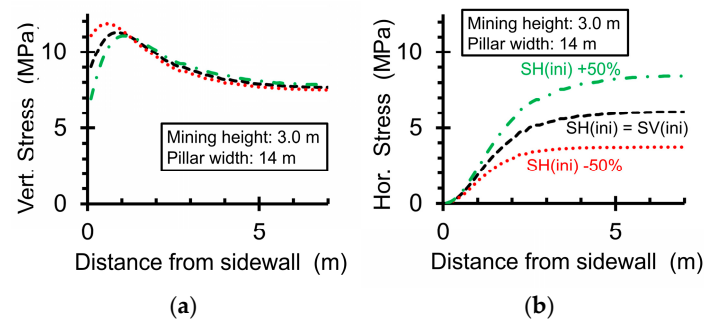


Figure 4. Stress redistribution in the pillar (at mid-height) in an elastic model for three different initial horizontal stresses (reference mining height of 3 m and pillar width of 14 m): (a) variation of the vertical stress; (b) variation of the horizontal stress.

Table 2. Data for the peak stresses for different pillar widths (24 m, 14 m, 6 m) in an elastic model for three different initial horizontal stresses (mining height of 3.0 m), i.e., the peak vertical stress, the corresponding horizontal stress, and the distance of the peak to the sidewall: (a) 24 m pillar width; (b) 14 m pillar width; (c) 6 m pillar width.

	SH(ini) – 50%	SH(ini) = SV(ini)	SH(ini) +50%
(a)			
SYY-peak (MPa)	11.44	10.8	10.54
SXX at peak (MPa)	0.59	1.54	2.69
Distance from wall (m)	0.6	0.9	1.1
(b)			
SYY-peak (MPa)	11.86	11.3	11.08
SXX at peak (MPa)	0.61	1.58	2.7
Distance from wall (m)	0.6	0.9	1.1
(c)			
SYY-peak (MPa)	13.84	13.58	13.54
SXX at peak (MPa)	0.71	1.36	2.53
Distance from wall (m)	0.6	0.8	1.0

In conclusion, the local stress redistribution around the excavation in a room and pillar panel shows a zone of stress relaxation in the outer part of the pillar. And this zone is larger for a higher initial horizontal-to-vertical stress ratio and for larger pillar heights. For the various cases modelled, the vertical stress peak can be situated up to nearly 2 m into the pillar, i.e., for a stress ratio of 1.5 and a mining height of 4.5 m. This wide relaxed zone occurs even with linear elastic behaviour of the pillar. The width of the relaxed zone, defined by the distance between the sidewall and the vertical stress peak, is not really affected by the width of the pillar, even over large intervals. In other words, the stress redistribution around the excavations is mainly influenced by the geometry of the rooms. The impact of the width of the relaxed zone is not directly integrated in the current design formula, nor is the impact of the initial horizontal-to-vertical stress ratio. The general conclusion so far, and probably the most relevant, is that the vertical load is

far from uniform. Current design practices only take into account the average load on the pillar and not the non-uniform load distribution. Working with an average load must be called into question.

2.2. *Elasto-Plastic Simulations Based on a Mohr–Coulomb Constitutive Model*

In earlier research [24,25], a finite difference continuum model was calibrated using data of in situ fracture depths in coal pillars [26]. The in situ fracture depths were compared to the width of the zone with plastic deformation. A sensitivity analysis of the most critical parameters was also conducted. A good correlation was observed for a Mohr–Coulomb criterium with cohesion values between 1.5 and 4.5 MPa, a friction angle of 27° , and a tensile strength of 0.5 MPa. The maximum in situ depths of fracturing observed for the three case studies varied between 1.5 and 2.6 m [24]. In the current model, the same friction angle and tensile strength are chosen, and the cohesion is equal to 1.5 MPa. As will be shown below, these values give satisfactory results for the zone of plastic deformation. The mesh and other input characteristics are the same as for the elastic model. Note that for many panels, i.e., at shallow depths, no damage is induced by the stress redistribution, and, consequently, elastic simulations well represent the pillar behaviour.

For the reference case, i.e., a mining height of 3 m and a pillar width of 34 m, the vertical and horizontal stress redistribution through half of the pillar at mid-height is presented in Figure 5 for the simulations with elasto-plastic behaviour. The vertical stress in the first 5 m is plotted in a larger window (Figure 5c). A comparison to the elastic simulations (Figure 2) shows that the peak has moved further into the pillar. In Table 3, the same data are provided for the peak stresses in the pillar as in Tables 1 and 2, i.e., the peak vertical stress, the corresponding horizontal stress, and the distance of the peak to the sidewall. The data for the elastic model of a 3 m high pillar is duplicated, allowing an easier comparison. Due to the possibility of plastic deformation, the peak has moved further into the pillar, enlarging the zone of stress relaxation. The largest increase is observed for the low initial horizontal-to-vertical stress ratio, i.e., an increase from 0.6 m to 1.9 m. For the three ratios, the ratio of 0.5 (i.e., -50%) results in the largest distance between the peak and the sidewall. This was the opposite for the elastic simulations, where the ratio of 1.5 resulted in the largest distance, i.e., 1.1 m. However, the vertical peak stress remains largest for the small initial stress ratio. The peak of the vertical stress is situated just beyond the plastic deformation zone. Another significant difference between the curves for the elasto-plastic simulations in comparison to the elastic behaviour is that due to the plastic deformation, the vertical and horizontal stresses are lower. Note that a perfect linear elasto-plastic constitutive model is applied. Over a width of 1 m, the horizontal stresses are nearly zero (see Figure 5b). For an initial stress ratio of 0.5, a maximum is also observed in the graph of the horizontal stress. For the conditions and geometry of the model, it is clear that there is failure in part of the pillar, but, on the other hand, there is a very large portion of this 34 m wide pillar that is still fully in the elastic domain. The distance between the vertical stress peak and the sidewall is, for the elasto-plastic simulations, larger than for the elastic simulations, which is logical. However, the increase in this distance remains relatively small for this geometry (Table 3), i.e., between 0.5 m (from 1.1 m to 1.6 m for a stress ratio of 1.5) and 1.3 m (from 0.6 m to 1.9 m for a stress ratio of 0.5). The reason for it is that the elastic stress redistribution around the excavation leads to a non-negligible width for the zone of stress relaxation. As mentioned above, the factor of safety for this model is equal to 2, based on the original formula of Salamon and Munro [5].

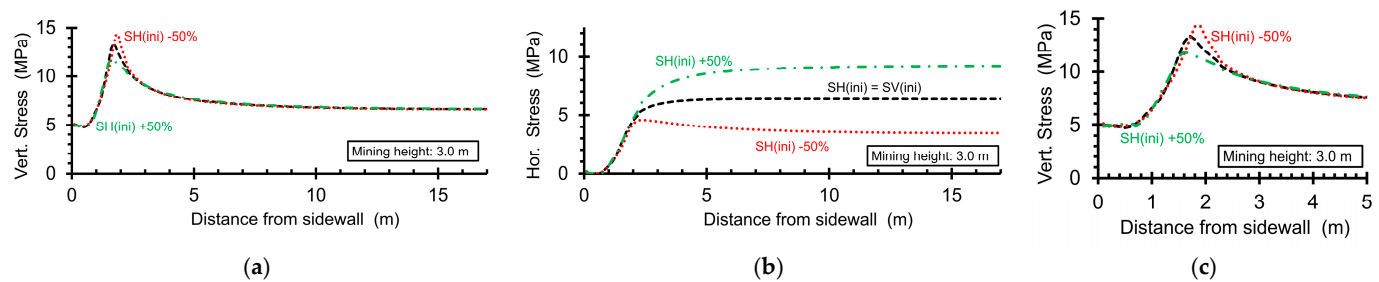


Figure 5. Stress redistribution in the pillar (at mid-height) in an elasto-plastic model for three different initial horizontal stresses (reference mining height of 3 m and pillar width of 34 m): (a) variation of the vertical stress; (b) variation of the horizontal stress; (c) vertical stress over the first 5 m into the pillar.

Table 3. Data for the peak stresses in the model of the reference pillar (width of 34 m and mining height of 3.0 m) for three different initial horizontal stresses, i.e., the peak vertical stress, the corresponding horizontal stress, and the distance of the peak to the sidewall: (a) elastic behaviour, Table 1(b); (b) elasto-plastic behaviour.

	SH(ini) − 50%	SH(ini) = SV(ini)	SH(ini) + 50%
(a)			
SYX-peak (MPa)	11.32	10.65	10.37
SXX at peak (MPa)	0.58	1.54	2.69
Distance from wall (m)	0.6	0.9	1.1
(b)			
SYX-peak (MPa)	14.33	13.4	11.84
SXX at peak (MPa)	3.95	3.43	2.97
Distance from wall (m)	1.9	1.7	1.6

It is well known that a large portion of the pillar remains in the elastic domain and, even, far away from a failure criterion. The question is how to deal with this information. In other words, can one decrease this zone without jeopardising the safety? One argument to consider is that this elastic zone is part of a safety buffer and is relevant for unexpected or unknown conditions. For wide pillars, i.e., a width-to-height ratio larger than 5, the squat pillar formula was developed [26]. In [24,25], the width of the pillar in numerical models was decreased systematically until both peaks, i.e., around the left and right room, were situated in the middle of the pillar. Of course, this can only be done in a numerical model, and it is rather a theoretical exercise. For a pillar width of 6 m, the entire pillar had undergone plastic deformation. In Figure 6, the vertical stress distributions for three different pillar widths are presented, i.e., for widths of 24 m, 14 m, and 6 m. All other parameters are the same. Except for a 6 m wide pillar, the location of the vertical stress peak is situated at 1.6 m to 1.9 m from the sidewall (Figures 5a and 6a,b). For a 6 m wide pillar (Figure 6c), the maximum stress is situated in the central part of the pillar, confirming earlier simulations [24]. For this configuration, the variation of the horizontal stresses is similar to that of the vertical stresses. This is the direct consequence of the constitutive model applied and the plastic flow. Note that for the elastic simulations of a 6 m wide pillar (Table 2), the vertical stress peak is situated at a distance between 0.6 m (initial stress ratio of 0.5) and 1.0 m (initial stress ratio of 1.5).

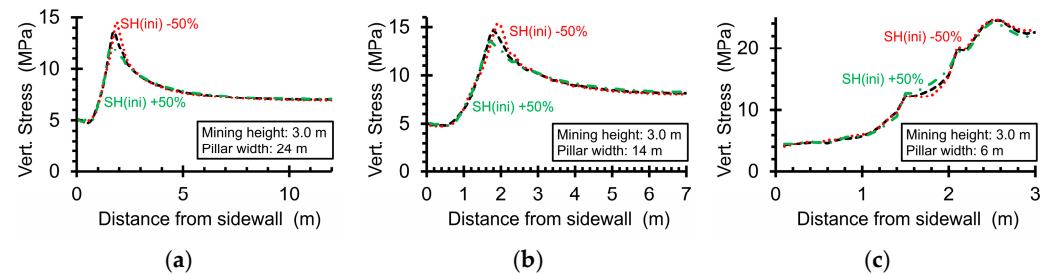


Figure 6. Variation of the vertical stress in the pillar (at mid-height) in an elasto-plastic model for three different initial horizontal stresses (mining height of 3.0 m): (a) pillar width of 24 m; (b) pillar width of 14 m; (c) pillar width of 6 m.

In conclusion, when the stresses close to the sidewall in an elastic model are situated above the failure criterion, plastic deformation occurs in an elasto-plastic model. Due to the plastic deformation, there is a further relaxation close to the sidewall, resulting in larger stresses inside the pillar and in larger peak stresses (beyond the failed or relaxed zone). In comparison to the elastic results, the additional growth of the stress relaxation zone is relatively small. Except for extremely small pillars, the zones of plastic deformation are not enlarged much when the width of the pillars is decreased. So, although the average vertical pillar stresses and the vertical stress peaks are larger for smaller pillar widths, the stress remains in a large portion of the pillars significantly below the failure criterion. As for the elastic models, the general conclusion remains the same, i.e., the vertical load is far from uniformly distributed across a real pillar. Again, using an average load in the current design processes must be called into question.

3. Typical Stress Paths in Real Coal Pillars

When discussing pillar behaviour, often an association is made with the uniaxial compression tests. A specimen free of any stress is loaded in one direction until failure occurs. If classic UCS tests are conducted on core specimens, the axial stresses are clearly the major principal stresses and, apart from the influence zone in the vicinity of the platens, the other stress components are small or zero. Therefore, the classic UCS tests are not a good representation or proxy for the behaviour of pillars, i.e., for pillars with a width equal to or larger than their height [4,27]. UCS values are useful to compare the strengths of different types of rock. As an alternative to the classic UCS tests, researchers study specimens with shapes more like the shapes of in situ pillars. The shape effect, like the size effect, is well known, and it has been well investigated from the early days of rock mechanical studies [28]. However, for these specimens, the tests also start from specimens that are free of any stress.

In Figure 7, stress paths are presented for various elements in the elastic numerical model along the horizontal plane at mid-height. The information is for the reference case of a 3 m high and 34 m wide pillar. The stress paths are presented for the three different initial stress ratios (see Figure 2). The results for the initial isotropic stress state are presented in Figure 7b, while the other two subfigures, i.e., Figure 7a,c, contain the results for the two initial anisotropic stress states. Since the data are for the mid-height plane, the vertical and horizontal normal stresses that are calculated are principal stresses. For a horizontal-to-vertical stress ratio of 0.5 and 1.0, the vertical principal stress is for all elements the major principal stress (and the horizontal principal stress is the minor principal stress). For a ratio of 1.5, the initial horizontal stress is the major principal stress, but the horizontal stress component evolves towards the minor principal stress for some elements. The stress path that corresponds to the stress of the vertical peak is plotted using a ticker line. Not all elements along the central plane are represented, but a selection has been made to

the left and to the right of the peak stress so that one gets a good overall picture without overloading the graphs.

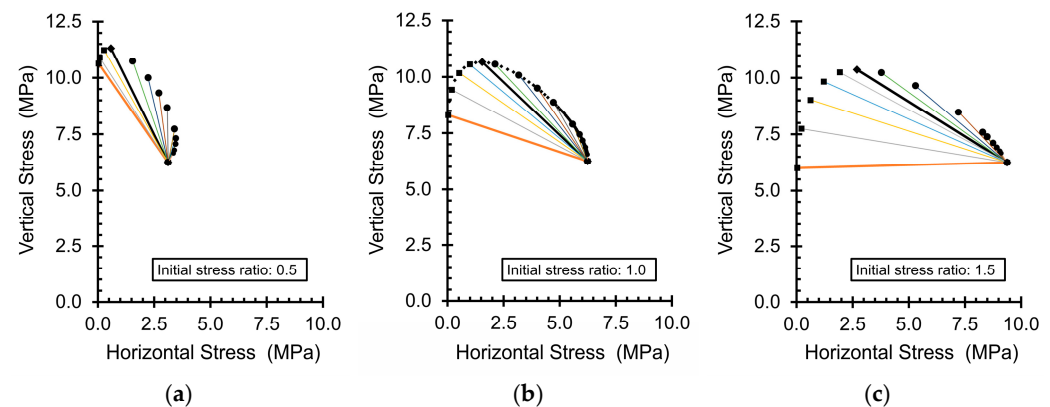


Figure 7. Stress paths in the elastic model along the horizontal plane at mid-height (reference case of a 3 m high and a 34 m wide pillar) and for initial horizontal-to-vertical stress ratios of: (a) 0.5, (b) 1.0, and (c) 1.5.

As in a real in situ pillar, the starting points of the stress paths for all elements are the homogeneous stress states. The end points correspond to the calculated stress redistribution in the elastic model. In the central part of the pillar, the horizontal stresses do not change a lot. For the initial stress ratio of 0.5, there is a small increase in the horizontal stress. For the ratios of 1.0 and 1.5, there are small decreases. The vertical stresses in the central part increase slightly, and the average vertical stresses over the pillar area also increase due to the excavation. It is more important to look at the stress paths around the vertical stress peak and close to the sidewall, i.e., the thick black line in the graphs and the points to the left of it, respectively. For the stress paths corresponding to the vertical stress peaks, the vertical stresses logically increase, but there is a significant decrease in the horizontal stress (see Table 1b for the specific values). For the stress paths that correspond to the elements that are situated to the left of the stress peak (towards the sidewall), the horizontal stresses are decreasing significantly following the excavation. For the elements that are adjacent to the sidewall, the final horizontal stresses are zero. So, the stress state corresponds to a uniaxial compressive state (in 2D) only for these elements. When the initial stress state is isotropic, some elements undergo only a small increase in the vertical stress. When the initial horizontal-to-vertical stress ratio is equal to 1.5, even a decrease in the vertical stress is observed adjacent to the sidewall.

In conclusion, stress paths that occur in uniaxial compression tests do not occur in the pillars during the mining of the rooms. For a classic UCS test, the stress path starts at (0, 0) MPa, and the vertical or axial stress increases until it reaches the UCS value. When specimens with shapes similar to in situ pillars are tested, the horizontal stresses in the central part of the specimen also increase during testing. The influence of stress paths on rock failure criteria has been highlighted in recent studies [29–31]. As discussed above, most laboratory experiments begin with stress-free specimens, after which the applied load is gradually increased. Around underground excavations, however, the stress path is fundamentally different. The rock mass is initially in equilibrium under a triaxial in situ stress state, and the excavation causes at least one principal stress component to decrease while another may increase.

The aforementioned research [29,30] employed two-dimensional distinct element modelling to simulate the micro-fracturing processes that govern rock failure. These studies demonstrated that the micro-fracturing associated with loading rock from an unstressed or low-stress condition differs significantly from the micro-fracturing that develops during

unloading from the in situ stress state. Consequently, the associated weakening mechanisms differ, resulting in substantially different failure envelopes. Conventional loading paths produced the highest apparent rock strength and therefore overestimated the in situ strength of the rock mass, where failure is typically associated with partial unloading rather than continuous loading. These findings were obtained by investigating three sets of stress paths, all of which started from an isotropic stress state (including a zero-stress condition for the conventional loading). The first set of stress paths involved a stepwise increase in the major principal stress while maintaining a constant minor principal stress, corresponding to a conventional compression test. In the second set, the major principal stress remained constant while the minor principal stress was progressively reduced until failure occurred, thereby representing an unloading path. The third set combined loading and unloading by simultaneously increasing the major principal stress and decreasing the minor principal stress using equal stress increments. Compared with the first two sets of stress paths, this combined loading–unloading path resulted in a greater increase in deviatoric stress. These observations warrant further investigation in the context of coal room and pillar mining, where stress redistributions during mining are governed by combinations of loading and unloading.

4. Distribution of Vertical Load in In Situ Compression Experiments

Following the evaluation presented above, it is interesting to have a new look at the in situ experiments conducted in South Africa around 1970 [8,9,32,33]. There is no discussion that enormous efforts were involved in these in situ tests but, more importantly, that they provided a tremendous insight concerning in situ coal pillars and a better understanding of their behaviour. The impact of these tests on the knowledge of pillars cannot be overestimated. A brief description of the tests conducted by Wagner is as follows [8,9]: first, a narrow corridor was excavated around the to-be-tested pillars (with a horizontal square section of 1 m^2); second, a horizontal slot was cut at mid-height in which 5×5 hydraulic cells were placed; and third, the test pillars were loaded in uniform increments of displacement, and the required pressures were recorded. This resulted in an average load–displacement curve per test pillar, and data on the variation of the load in each hydraulic cell. More details are available in the publications mentioned above.

Referring to the earlier discussion of the different stress paths between compression tests and the pillar behaviour during the excavation of the rooms, the in situ compression of test coal pillars also starts from a zero-stress state. Hence, the variation of the vertical stresses along the central horizontal slot is different from the variation due to the stress redistribution induced by the mining. In Figure 8, the vertical stress is presented along a line in the middle of a test pillar, i.e., for a series of five hydraulic cells. These graphs are based on the published results of the in situ tests [8,9], and the data are reconstructed in a relatively simple way. The reason for limiting Figure 8 to a single line of five hydraulic cells is that it facilitates the comparison with the results of the 2D models. Note that each cell represents a width of 20 cm, or a fifth of the test pillar width. Figure 8a represents the data for the point on the curve with an average load, which is significantly lower than the average peak load of 10.8 MPa. For this example, it is at 67% of the peak value prior to reaching the peak in the curve. The section in Figure 8b is for the point just before reaching the peak, and the section in Figure 8c clearly is situated in the post-peak part of the average load vs. displacement curve. The average load for the latter point is still 75% of the peak value.

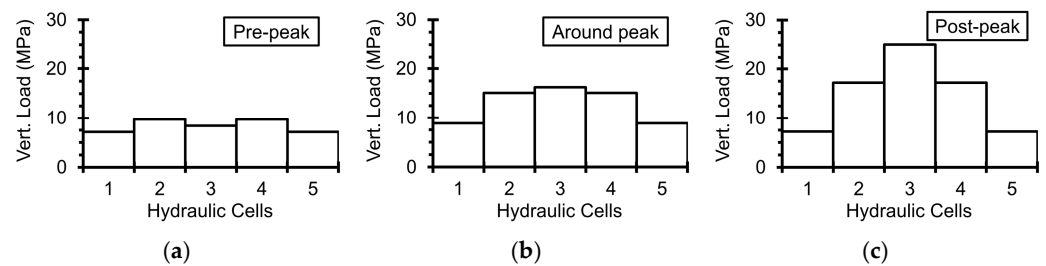


Figure 8. Variation of the vertical load along a line in the middle of the test pillar for a series of five hydraulic cells (based on published results [8,9]): (a) pre-peak at 67% of the peak value; (b) at or around the peak value; (c) post-peak at 75% of the peak value.

The load distribution in Figure 8c, and to a lesser extent in Figure 8b, shows the influence of confinement on the larger load in the central cell(s). Note that the applied vertical displacements by all hydraulic cells are uniform. It is concluded that the central zone of the test pillar is capable of withstanding extremely high stresses, even after failure of the pillar circumference [33]. For loading till nearly 70% of the average peak load (Figure 8a), the distribution of the load is still relatively uniform. The conclusion that the central zone is strong due to the confinement is without doubt correct. For a real in situ pillar with a larger width than the 1 m wide test pillar, the impact of the confinement must be even larger. The question is whether this finding is relevant or useful in coal pillar design in room and pillar panels without pillar extraction. First, it is not a good idea to design a pillar that is situated in the post-peak zone. In other applications, e.g., yielding pillars adjacent to a longwall panel, the aim could be to enter the post-peak zone, but in a basic room and pillar panel, one should stay away from the average peak strength. Second, and this argument is more relevant, the loading due to the stress redistribution following the mining of the rooms around a pillar is not uniform, and, to a certain extent, the stress redistribution is the opposite of the strength variation determined by the uniform compression of a pillar. The stress redistribution is well illustrated in Figures 2–6. When no damage occurs around the sidewalls, there is a zone around the room that is characterised by stress relaxation, followed, away from the sidewall, by larger stresses around the vertical stress peak and a large central zone with stress states far below the failure criterion. The reasons why there are low stresses around the sidewalls due to the stress redistribution (Figures 2–4) are different from the reasons the strength variation is low along the circumference, i.e., due to the absence of confinement, but with the same vertical compression as in the rest of the test pillar (Figure 8c). When damage occurs around the sidewalls due to the stress redistribution, there is still a large central zone with stress states far below the failure criterion (Figures 5 and 6). The latter zone only disappears when the width of the pillar is very small (Figure 6c) and the entire pillar volume has failed (or, in the model terminology, has undergone plastic deformation).

In conclusion, the stress paths of the pillar material during excavation of the rooms significantly differ from the stress paths during in situ compression experiments. The local mechanisms behind these stress paths are also different. One might therefore question whether the two situations are comparable at all. A comparison between strength and load based on average stress across the entire pillar is incorrect as the load (stress paths) differs so significantly.

5. Discussion

When considering the theme of this Special Issue of *Applied Sciences*, i.e., Advances and Challenges in Rock Mechanics and Rock Engineering, attention should extend beyond cutting-edge research, novel methodologies, and advanced analytical and experimental

techniques. Equally important for advancing our understanding of rock behaviour is the willingness of researchers to critically re-examine established findings, conventional approaches, and both past and current engineering practices. Often, this is a real challenge. In this context, the present paper critically evaluates the past and current practice of designing coal room and pillar panels. And this is done by questioning the various steps in the design process and by going back to the fundamentals of rock mechanics and rock engineering. It is hoped that the present paper will be viewed by other researchers who have worked or are still working in this field as part of progressive insight into the behaviour of coal pillars. This paper therefore aims to provide a clear direction for future improvements in design methodology, which should lead to safer environments.

In the past, statistical analyses of failed and stable pillars in South Africa by Salamon and Munro have led to a widely and successfully applied formula for the factor of safety of coal pillars [5]. The methodology which was applied in the sixties of last century can be seen as an AI exercise *avant la lettre*, i.e., the data for real in situ behaviour of a large number of room and pillar panels is used to determine the various coefficients in the strength formula. This requires our respect, considering the tools available at that time. Considering two parameters (i.e., the height and width of the pillars) and three coefficients seems limited today when taking the current mathematical and computer power into account. As shown in the first part of the present paper, the initial horizontal-to-vertical stress ratio is a parameter that has a significant effect on the stress redistribution and thus on the variation of loading along the horizontal central plane in a pillar. In more recent years, further fine-tuning of the Salamon and Munro formula has been implemented, taking, for example, local conditions into account [2,7,12,26]. As the value of the coefficients in a statistical strength formula are based on the final criteria of safe vs. unstable pillars, such formulas have the advantage that unknown characteristics or conditions are indirectly part of the statistical analysis and thus are indirectly integrated into the formulas. On the other hand, not knowing them is a disadvantage, e.g., if one would like to apply the formula in different environments. For future advances in the design methodology, one could ask the question if further finetuning the original statistical formula by Salamon and Munro is the most appropriate way for improving the safe design of room and pillar workings.

This thought leads to the question concerning how the strength of a coal pillar should be defined. And this question goes beyond the choice to raise the mining height to, e.g., a power of -0.66 or -0.75 in the formula by Salamon and Munro [5]. The results presented earlier show a significant and relevant discrepancy between the stress redistribution during the development of room and pillar panels (i.e., the actual load on a pillar in a real mining environment) and the stress variation within test specimens, being lab specimens or underground test pillars, during uniaxial compression tests. Note that the stress variations in test specimens are strongly dependent on the moment within the full loading experiment, whereby the maximum average stress is seen as potentially the maximum strength of a pillar. However, the observed discrepancy in stress variations needs further attention, and one cannot just compare the average load on an in situ pillar with the average (maximum) strength in a pillar compression test. In a simplified way, one can describe the variation of the vertical stress in a real pillar as (i) being low at the sides (due to the zone of stress relaxation in the elastic domain and due to possible damage zones), (ii) the stress peak, and (iii) a large central zone with relatively constant and only slightly increased vertical stresses. During uniaxial compression tests of wide lab specimens or of the in situ test pillars, the stress variation is (i) low stresses at the sides, due to the absence of confinement and the failure of the material and (ii) larger vertical stresses towards the centre of the test specimens or the centre of the test pillars. The increase in vertical stresses is due to the effect of the confinement, i.e., more load is needed to compress the rock with the same

displacement increments. How much larger the vertical stress is depends on the position along the stress–strain curves.

Note that the horizontal stress variations inside real pillars vs. the variations in test specimens or test pillars also are different. In a large central zone of a real pillar, the horizontal stresses are relatively constant and are only slightly increased in comparison to the initial stress state due to the small increase in vertical stresses. On the other hand, in test specimens or test pillars, the horizontal stresses increase systematically towards the centre due to the confinement effect.

One could say that the large discrepancy in stress variations between mined pillars and test specimens or test pillars is caused by the fact that “one does not build a pillar, but one excavates a room”. And this should be combined with the fact that strength is a non-intrinsic parameter, meaning that it is a function of a large number of parameters and conditions, among others, the stress state. In other words, the strength of each volume element in a pillar is different, as the stress state is different. Integrating this essential fact into a simple formula seems to be impossible. As learnt in each basic statistical course, and referring to the example that a person wading through a river with an average depth slightly less than the person’s height leads to drowning, considering only the average depth is a mistake. Comparing only the average load in a real pillar to the average strength is a mistake too.

The large stress values in the central part of a test pillar, close to failure, are often seen as a portion capable of withstanding extremely high stresses and a portion that helps to create safe and stable pillar conditions. The latter would only be true if the loading of a test specimen or a test pillar were similar to the loading of a real in situ pillar in mining. As both are different, the integral of the area between both curves, i.e., the curve representing the stress redistribution and the curve representing the stress variation in a uniaxial compression test, cannot define another type of safety parameter.

Even though at first glance, the geotechnical design of coal room and pillar panels seems simple, it is not. In the past, the focus has been too long on using uniaxial compression tests as a good proxy for pillar behaviour, which, in my opinion, it is not. Extensive numerical modelling of real underground cases opens new perspectives. This should become realistic in the (near) future, and the combination with new geotechnical AI methodologies currently being developed should facilitate it. The approach taken by Monsalve et al. [34] in this regard is promising. Based on discrete element models of the pillar and surrounding strata, this work presents a risk-based pillar design framework. Their initial models take the stress redistribution around the excavations (rooms) into account. Or, in other words, the stress variation across a pillar is part of the analysis instead of analysing only the average stress or load, as is applied in the classic safety formula. However, how to determine the pillar strength remains a challenge. The model is calibrated by referring to the empirical strength formula [2,35]. The vertical load increase is created by additional vertical displacements applied to the top and bottom of the model after the rooms are excavated. One should be careful with this procedure of strength determination, as it is the equivalent of transferring the pillar to larger depths, which does not happen in situ. Better alternatives are the increase in the room widths and the simultaneous decrease in the pillar widths. This also results in a larger load on the pillar and could be the equivalent of spalling and failure of the pillar sides. This is probably more realistic for the initiation of pillar failure, instead of increasing the overall load on the model.

6. Conclusions

Although the geotechnical design of coal room and pillar panels seems simple, the amount of ongoing research into pillar design shows that it is not so simple. The critical evaluation of past and current practice confirms this and leads to two main concerns.

The first concern is that the design of coal room and pillar workings focuses primarily on the pillars, i.e., the (average) load on the pillar and the (average) strength of the pillar. However, if one were to start a room and pillar design from a blank piece of paper, one would start with the design of the rooms and look first at the redistribution of the stresses around the rooms. Elastic simulations clearly show that relaxed zones occur in both the roof (and floor) and in the sidewalls of the pillars. These relaxed zones are located within the peak stress arcs. The size of these zones is influenced by the excavation dimensions and by the vertical-to-horizontal ratio of the initial stresses. For high horizontal stresses (e.g., 50% higher than the vertical stress) and for seam thicknesses of 3 and 4.5 m, for example, this width is approximately half of the mining height. For both sidewalls, this means that in 2D the width of the pillar section that really carries the vertical load is the full pillar width minus the mining height. For other initial stress states and other geometries, the reduction is different. As the relaxed zones contribute less to the total bearing capacity of the pillar, a justifiable question is whether one should rather use the distance between the relaxed zones in the design formula instead of the full pillar width, as is done in the current design. Before implementing this, further research and verification are needed.

A second concern is the common reflex to approximate the in situ pillar behaviour with a vertical loading experiment, for example, by performing uniaxial compression tests. The latter could be realistic if one were to build pillars, but that is not the case: one excavates rooms. Before mining, the coal is in equilibrium in a three-dimensional stress state, and depending on the position within the future pillar, the stress components decrease and/or increase. The typical loading path of a uniaxial compression test starts at zero stress, and the vertical or axial stress increases until it reaches the UCS value. When testing specimens that have shapes similar to in situ pillars, there is an increase in the horizontal stresses in the central part, during the loading experiments, but the stress paths are still significantly different from the paths in real in situ pillars. The local mechanisms behind these stress paths are also different.

Referring to both concerns, one might question whether the two situations are comparable at all, i.e., the real in situ stress variation across a pillar vs. the variation of load during vertical compression experiments. A direct comparison between the average load in a real pillar and the average strength is a mistake. In addition, strength is a non-intrinsic parameter, meaning that it is a function of a large number of parameters and conditions, among others, the stress state. In other words, the strength of each volume element in a pillar is different, as the stress state is different. A calculation of the integral of the area between both curves, i.e., the curve representing the stress redistribution and the curve representing the stress variation in a uniaxial compression test, cannot define another type of safety parameter (e.g., in comparison to dividing the average strength by the average load). The reason is that the conditions for both curves are different.

At the end of this paper, I would like to quote two sentences by Dr. Christopher Mark, which he wrote at the beginning and the end, respectively, of his 2007 paper [4], illustrating well the process of progressive insight in room and pillar design: “The past 25 years have seen substantial progress in the science of coal pillar design” and “Certainly, more work remains before the age-old questions of pillar design are finally solved.”

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