Design a Reasonable Width of Coal Pillar Using a Numerical Model. A case study of Khe Cham basin, Vietnam

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Abstract. Problems in surrounding rock displacement, roadway deformation and complex support are the hallmarks of the long wall mining system. Such problems seriously affect the safety and efficient production of coal mines. To control the deformation of the rocks around the roadway next to the goaf, to reduce the support pressure, in Vietnamese underground mines often leave supporting coal pillars. Identification of a reasonable design for roadway supporting pillars by a numerical simulation study was conducted under the geological and technical foundation of I-10-2 working faces at the Khe Cham coal mine, Vietnam . The characteristics of stress and pressure distribution of roof layers on coal pillars are modeled under different pillar widths. The results show a great linear increase of the vertical stress on the narrow coal pillar and as the width of the coal pillar increases, the area of the elastic core area also increases and the level of stress increase tends to be stable without any apparent uptrend. Coal pillar deformation decreases with increasing coal pillar width, but it leads to large coal loss and waste of resources. Therefore, with the current supporting solutions to increase the stability of the coal pillar, the size range of a coal pillar is determined to be 6-8 m through numerical simulation. The conclusions obtained may provide a certain reference number to choose the logical location of the furnace lines under similar geological conditions.

1 Introduction

In underground coal mining, an increase in coal recovery rate can be achieved by not leaving supporting coal pillars in the mining space or reducing its size to the minimum limit [1]. Currently, in Vietnamese underground coal mines, most of the coal seams are prepared and exploited with the long wall mining system. Therefore, the design of the coal pillar is very important for safety and efficient production in coal mines. The study of coal pillar design has been conducted by many authors, such as stress analysis and pillar design method proposed in [2-4]. The formation of pillars in a long-wall logging system is

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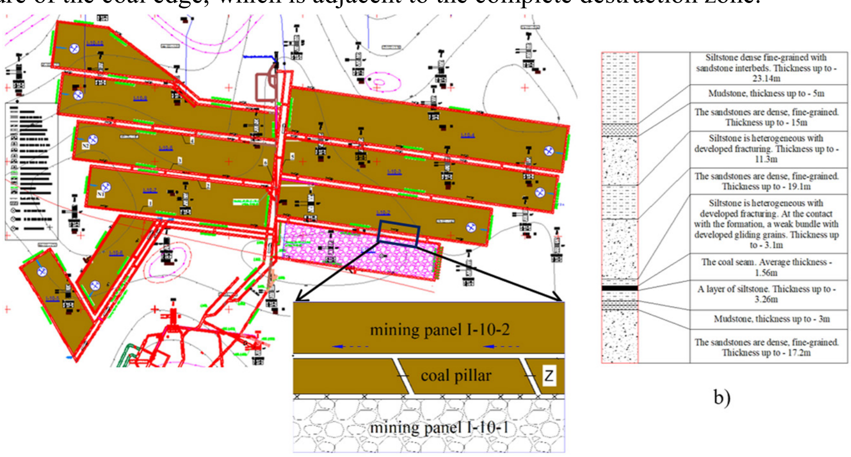
necessary for the purpose of: (1) isolating the exploited panel, (2) supporting the roadway. Different methods are used for the design of coal pillars for different situations or functions.

In this paper, we examine the protective coal pillars along the goaf area of an earlier adjacent mining panel. Coal pillars used for the support of the roadway and the extraction panel exists only along one side. Sheorey [4] proposed three methods for pillar analysis and design: (i) select the strength of the pillar from the formula, determine the average load (depending on one-sided or two-sided goaf, caving or stowing) and the width of pillar with a suitable safety factor; (ii) choose the width of the pillar so that the roadway is not much affected by the previous mining panel; and (iii) perform a numerical model to analyze stresses with different coal pillar sizes according to coal seam conditions. When the first and the second methods are selected, Wilson's formula [5] and Sheorey formula [6] may be used, and they are taken from the analytical method of pressure pillar with respect to dimensions of coal pillars. When the third method is selected, it is not necessary to select the strength or give the formula as an estimate of the pillar load and the required strength, but it is important to simulate the actual structure of the model using the properties in accordance with the application of a corresponding failure criterion for the coal seams. A numerical model for stress analysis of this problem was performed in [7-13].

Although the use of design formulas is more common in the chain of design and analysis of pillars, but the use of numerical models is necessary for some complex situations. From numerical simulations, Wei and Cheng [14] showed that the distance of the roadway from goaf has some effect on the distribution of stress in the roof of the coal seam, which cannot be calculated using design formula. Based on the simulated two-dimensional number model, Wei and Cheng [14] show that an intermediate value of the pillar width is not good for roadway stability. Wilson says [5] that a line placed in the position of a high stress area on the side will be destroyed. In the study [15] the authors analyzed and demonstrated that the roadway should be placed in the plastic flow zone of the abutment pressure of the coal edge, which is adjacent to the complete destruction zone.



a) b)

Fig. 1. Layout and roof lithology of the working faces of the coal seam 10: a) layout of the working faces; b) lithological profile.

Here, the pillar of coal in a coal mining panel with gently sloping coal seam and average thickness was analyzed using a 2D model. In this model, stress distribution and failure regions are analyzed in detail. The present analysis is based on the mining conditions of I-10-2 mining panel at seam No. 10 in Khe Cham coal mine, Quang Ninh coal basin, Vietnam. The I-10-2 Mining panel is a long wall mining face, and in the south of this mining panel is an I-10-1 mining panel, where coal has been extracted (Figure 1). The height of the ground is from +58 to + 78 m and the height of the working face is from -250 to -286 m. The mining face is 445 m along the strike and 140 m along the dip. The average thickness of coal seam is 1.56m and the dip angle is 80. The main roof is sandstone or fine sandstone with an average thickness of 19.1 m. The Immediate roof is siltstone with a thickness of 3.1 m. The Immediate floor is a siltstone and mudstone with a thickness of up to 6.26 m. The main floor is sandstone with a thickness of 17.2 m. The properties of the rocks are given in Table 1. In this analysis, eight different coal pillar widths were considered: 4, 6, 8, 10, 12, 14, 16 and 20 m.

Table 1. Mechanical properties of rock massused in numerical modelling.

Rock properties	**Rock name**			
		Roof and floor strata		
	Coal	**Mudstone**	**Siltstone**	**Sandstone**
Elastic modulus (MPa)	4300	13900	16500	21100
Poisson ratio	0.35	0.3	0.28	0.28
Cohesion (MPa)	0.9	3	2.1	3.2
Friction angle (deg)	19	26	30	38
Tensile strength (MPa)	0,4	1,2	0.9	1.6
Density (MN/m3)	0.0125	0.0225	0.0225	0.0278

2 Research method

The different width of the coal pillar has a different distribution of internal stresses. To study this problem, the finite element methodology is used with the Phase2 program of the Canadian company Rocscience [16]. The Phase2 program has the advantage of investigating stress distribution and stress variation in mining. In this article, the Phase2 program will be used to study the effect of different widths of a coal pillar on the distribution of stresses in surrounding rocks on the whole.

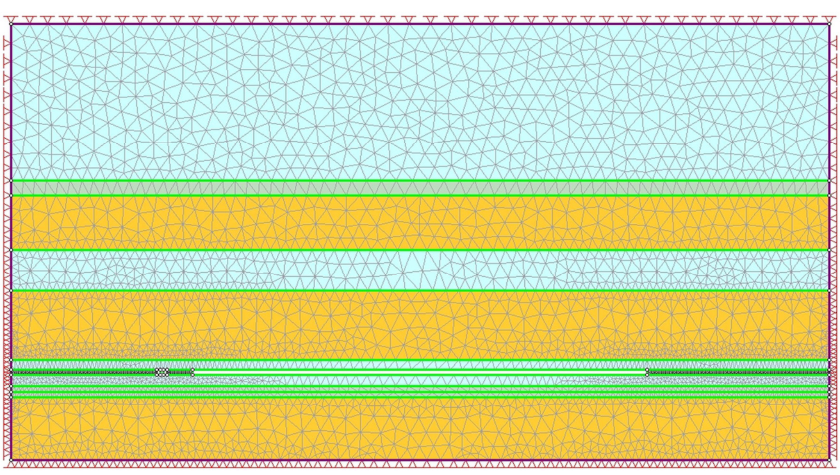


Fig. 2. Plot of the two-dimensional model.

Under the background of I-10-2 working face, eight different 2D models were modeled by Phase2 models with coal pillar widths of 4, 6, 8, 10, 12, 14, 16 and 20 m . All digital models use a width of 400 m and a height of 150 m (Figure 2). At the top of the models, a vertical load (p = γH = 0.0238 x 300 = 7.14 MPa) was applied to simulate uniformly distributed load. The Mohr - Coulomb model of elastomeric plastic with the rule of

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discontinuous flow is used for roofs and floors. The roadways in these models are rectangular with dimensions of 3.0m wide and 2.5m high. The ratio of horizontal and vertical pressure is taken respectively at 0.6 and 0.6. Horizontal displacements are fixed at the internal boundary while vertical displacements are fixed at the bottom boundary. The modeling processes are as follows: (1) calculating the initial state caused by gravity; (2) modeling the layout of the roadway located near the extracted I-10-1 mining panel with different coal pillar sizes.

Figure 2 shows a 2D view that simulates the working state of the working face area. The mining panel adopts the long wall mining system. The coal pillar between mining faces I-10-1 and I-10-2 is the focus of this investigation.

3 Research results

3.1 Formatting Vertical stress distribution on coal pillars

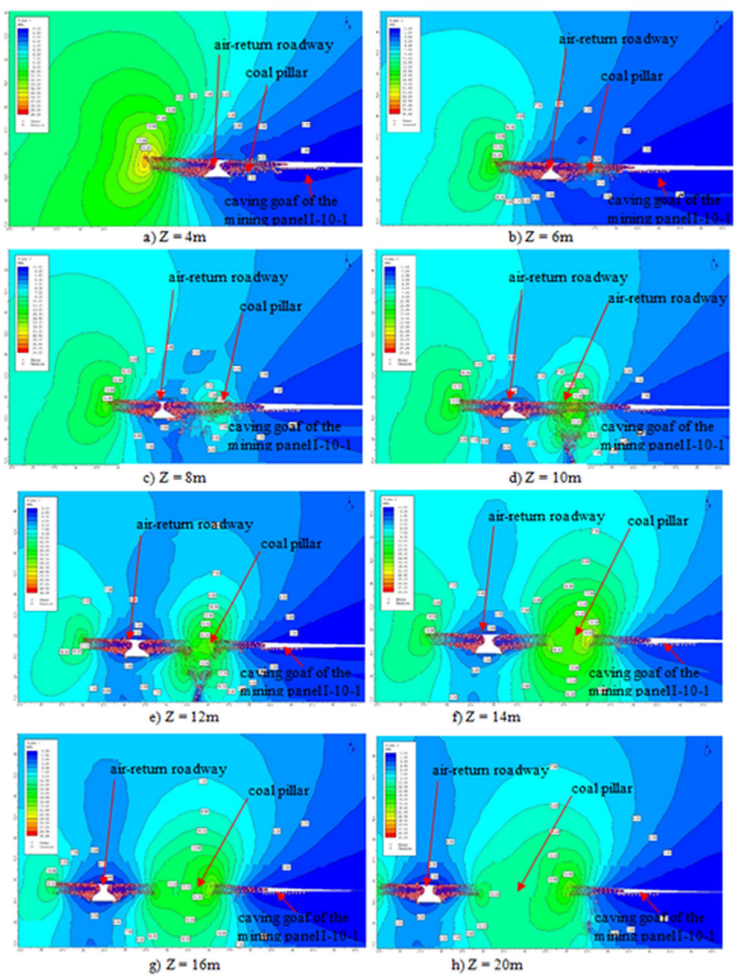

Fig. 3. Vertical stress distribution of roadway surrounding rock and of the coal pillar.

The vertical stress distribution of surrounding rock under different coal pillar widths is shown in Figure 3. The state of the vertical stress distribution of the surrounding rock on the roadway and at the coal pillar changes as width of different coal pillars changes. The vertical stresses on the roof and floor of the roadway are in a state of low stress, and the basic stresses are maintained. The stress concentration is on the wall of the road, and they are slightly different under different coal pillar widths. Significant differences exist in the effects of different coal pillar widths. As the width of the coal pillar increases continuously, the elasticity of the stable area in the coal pillar is expanded, along with improving its bearing capacity.

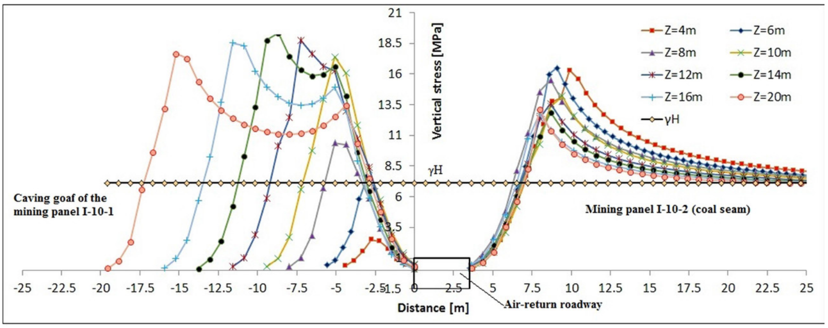

Fig. 4. Chart of vertical stress distribution on coal pillar of different sizes and in the coal seam.

The vertical stress distribution amplitude on coal pillars of different widths is shown in Figure 4. With an increasing width of the coal pillars, a region of maximum stresses appears gradually in the corresponding coal pillars such as in the coal seam. When the width of the coal pillar is 4 m, the vertical stress at the coal pillar is relatively low and only one stress peak exists. The coal pillar is in a state of plastic failure with the failure zone running through the coal pillar, the stress peak is 2.51 MPa less than the natural stress; elastic core area does not exist inside the coal pillar, and weak bearing capacity. When the width of coal pillars is from 6-8m, vertical stress increases and maximum stresses reach 7.67 MPa and 10.37 MPa, higher than natural stresses but smaller than the stress peak on the coal seam. An increase in the width of the coal pillar result in increase enhanced bearing capacity of that particular pillar to bear the load from the roof rock layers. Elastic core area begins to form and expand within the coal pillar. When the coal pillar is 10m, the stress peak on the coal pillar reaches 17.42 MPa and is higher than the stress peak on the coal seam. This can be explained that the maximum stress has been transferred from the coal seam to the coal pillar and at this time the coal pillar plays the main bearing role from the roof rock pressure.

As the width of the coal pillar is increased from 12 to 20 m, the maximum stress peak value gradually forms 2 stress peaks on either side of the coal pillar. If the width of the coal pillar continues to be increased, these peak stresses are not significantly reduced and then remain unchanged. The elastic area at the core of the coal pillar is expanded and the coal pillar is enhanced for stability.

Thus, with the increase in width of the coal pillar, the maximum vertical stress of the coal pillar increases and when its width is greater than 12 m, there will be two stress peaks on the coal pillar and then stress peak values do not change much. In contrast, the maximum stress on the coal seam decreases with increasing width of the coal pillar. When the pillar width is less than 8 m, the maximum vertical stress of the coal pillar is smaller than the coal seam, so the coal seam will bear the main force from the pressure of the roof rock layers. When the width of the coal pillar is greater than 10 m, the maximum stress of the coal pillar is greater than that of the coal seam. At this time, the maximum stress is

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transferred from the coal seam to the coal pillar, so the coal pillar now plays the main bearing force from the pressure of the roof rock layers.

3.2 Formatting Vertical stress distribution on coal pillars

The law of deformation of the coal pillars and the roadway when different widths of the coal pillars are shown in Figures 5 and 6 (in the model only instantaneous displacement can be determined).

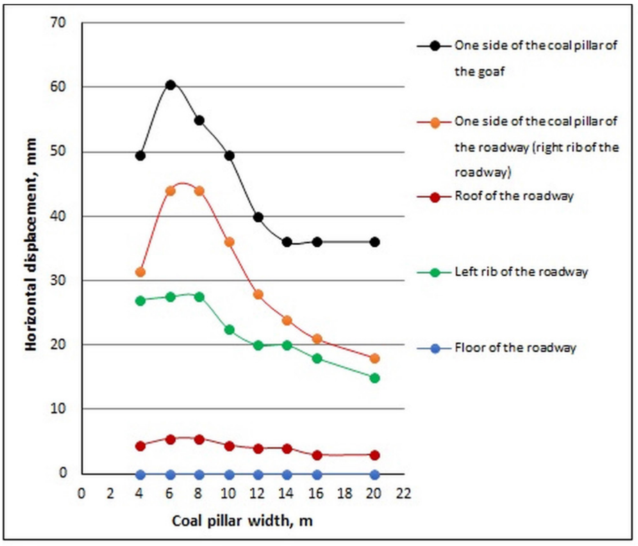

Fig. 5. Horizontal displacement of the coal pillar and roadway under different coal pillar widths.

As shown in Figure 5, when the width of the coal pillar is 4-6 m, the peak of the horizontal displacement value of the coal pillar toward the goaf increases from 49.5 mm to 60.5 mm, with 22% amplitude increases. When the width of the coal pillar is 6-8 m, the horizontal displacement value of the coal pillar toward the goaf decreases significantly from 60.5 mm to 55 mm, with the amplitude decreasing by 10%. When the width of the coal pillar was greater than 8 m, the horizontal displacement decreased slowly and decreased to 36 mm at the condition of the coal pillar width of 14 m, and then it almost did not decrease as the width of the coal pillar increased.

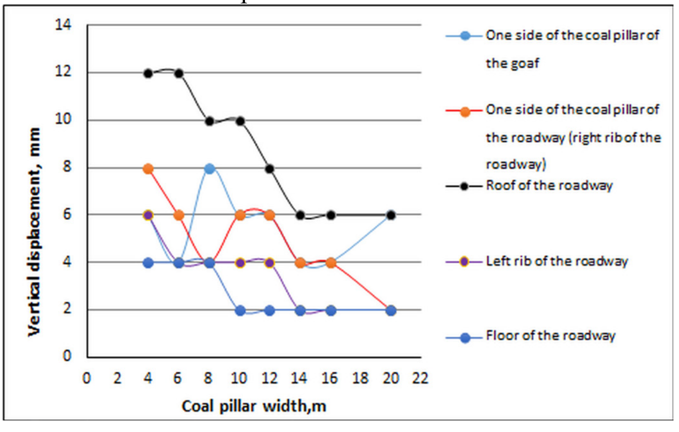

Fig. 6. Vertical displacement of the coal pillar and roadway under different coal pillar widths.

The peak value of the horizontal displacement of the coal pillar toward the roadway also increased within the width of the coal pillar from 4-6 m and then gradually decreased in proportion to the increase in the width of the coal pillar. The horizontal displacement peak value shows a rapid linear increase from 31.5 mm to 44 mm (40% increase amplitude) when the width of the coal pillar is within 4-6 m range; meanwhile, it is almost unchanged within the width of the coal pillar at about 6-8 m. When the width of the coal pillar is greater than 8 m, the horizontal displacement peak value decreases.

For the roof of the roadway, when the width of the pillar is 4-6 m, the roof sinkage is larger within 12 mm; When the width of the pillar is 6-8 m, the roof sinkage decreases from 12 mm to 10 mm. As the width of the coal pillar increases, the roof sinkage continued to decrease and reached a steady state of 6 mm when the width of the coal pillar was greater than 14 m.

Coal pillar width has a small effect on roadway floor because it remains unchanged with the increase of coal pillar width.

The amount of displacement of the roadway wall on the coal seam side also varies with the width of the coal pillar. When the coal pillar is 4-6 m wide, the amount of horizontal displacement is virtually unchanged at 27 mm, while the vertical displacement decreases from 8 mm to 4 mm. When the coal pillar was 6-8 m wide, the horizontal and vertical displacement values were almost unchanged. When the coal pillar was wider than 8 m, the horizontal displacement values gradually decreased while the vertical displacement values did not change significantly, and it only decreased gradually when the coal pillar was wider than 12 m.

In summary, the width of the coal pillar has a great influence on the horizontal displacement of the coal pillar, roof sink age and roadway wall; but the effect is relatively small on the floor. Based on the analysis of the deformation of the coal pillar and the rock surrounding the roadway, a reasonable width of coal pillar should be considered at 6 - 8 m.

3.2 Formatting Vertical stress distribution on coal pillars

The stability of the roadway can be judged from the distribution of stress and failure areas as follows: When the width of the coal pillar is very large, such as 20 m, there are two vertical stress peaks shown on the coal pillar, there is a plastic flow zone on both sides of the coal pillar and there is a large elastic area in the center of the pillar. In this situation, the pillar is able to handle high loads and maintains good pillar stability. However, in this case coal loss is large. When the width of the coal pillar is very small, such as 4 m, the largest vertical displacement is located at the edge of the pillar and the horizontal displacement is very large; Coal pillars are crushed and cannot be maintained in a stable condition.

When the width of the coal pillar was 6 to 8 m, a small elastic area began to form within the pillar core and the stress distribution was shaped like a large arc, but the largest vertical displacement was located on the roadway roof and Coal pillars are not crushed. Moreover, the maximum peak of vertical stress is distributed in the coal seam, not at the coal pillar, so the place where the bearing is mainly the coal seam. Therefore, for cases where the width of the coal pillar is 6 -8 m, the pressure on the coal pillar is not large, and if the integrity can be maintained by some supporting measures, the coal pillar may be maintained in a stable condition by relying on supportive strength.

When the width of the coal pillar is 10-12 m, it is in a productive state, and the elastic state is not large enough in the center. At the same time, the maximum stress is on the coal pillar and cannot be transferred to the coal seam (Figure 4) so the main bearing place is the coal pillar. Therefore, a medium-sized coal pillar is not conducive to the stability of the roadway.

According to the Mohr–Coulomb principle, the rock compressive strength can be stated as:

$$\sigma_1 = \sigma_3 \tan 2\theta + \sigma_c \qquad (1)$$

Where: σ1 is the compressive strength, MPa; σ3 is the confining pressure, MPa; θ is the shearing angle (θ=(π/4)+(φ/2)), deg; φ is the friction angle, deg; σ_c is the uniaxial compressive strength (σ_3=0), (σ_c=2c cos φ/(1-sin φ)), MPa and c is the cohesion.

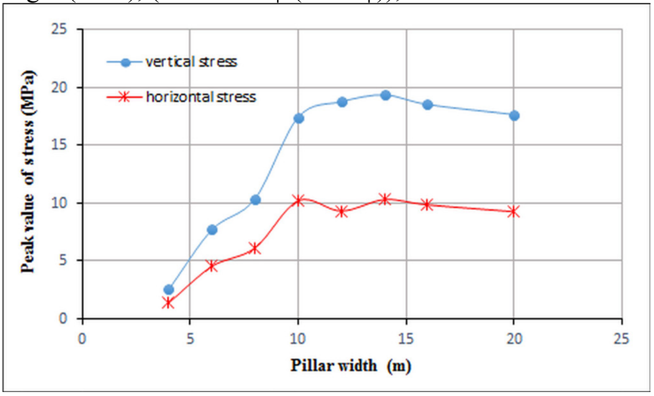

Fig.7. The peak value of vertical and horizontal stress with respect to different pillar widths.

From equation (1), it can be seen that the compressive strength increases with an increase in lateral pressure (horizontal pressure). As shown in Figure 7, with an increase in the width of the coal pillar, both the increase in the horizontal and vertical peak stress, except that a coal pillar of 12 -20 m width is subject to little stress changes. If the effect of parameter σ_c is ignored, equation (1) shows that the ratio of vertical stress to horizontal stress has a great influence on the failure of the pillar and roadway stability. The greater the ratio, the more likely failure of the coal pillar. The ratio of maximum vertical stress to maximum horizontal stress according to the width of coal pillars is shown in Figure 8. The ratio has a maximum value at 12 m of coal pillar width, so this width is not sufficient for roadway stabilization.

When the width of the coal pillar is less than 10m, the maximum horizontal stress in the column increases rapidly. When the width of the coal pillar is greater than 10 m, the maximum horizontal stress increases very slowly (Figure 8).

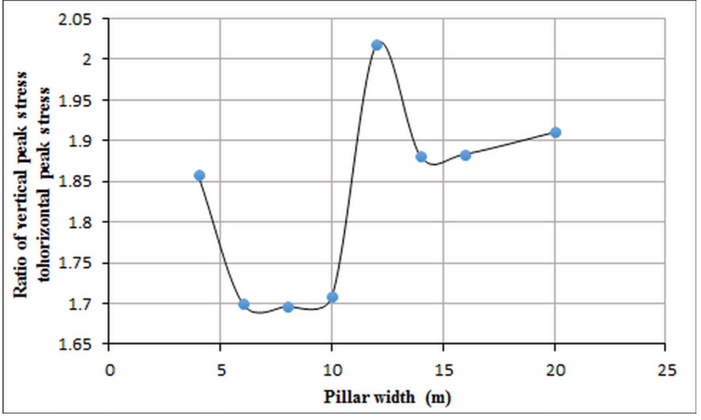

Fig.8. The ratio of vertical peak stress to horizontal peak stress with respect to different pillar widths.

From the above discussions, the reasonable width of the coal pillar should be considered within 6-8 m, because in this condition, the coal seam is the locale the main bearing from the pressure of the roof layers and therefore the roadway can be maintained stability with supportive.

4 Conclusions and Discussion

The present study has therefore deduced the relational effects that arise between the width of the coal pillars and the stresses exerted on the coal seams. It was deduced that with the increase in the width of the coal pillar, the stress in the coal seam always decreases, while the stress in the coal pillars increases. When the width of the coal pillar is 12m, the stress in the coal pillar reaches its maximum value and then decreases significantly to a constant value with a further increase of the coal pillar width. The two stress peaks on both - sides of the coal pillar began to form when the width of the coal pillar was greater than 12 m; an elastic area in the center of the pillar was widely developed and it was able to maintain stability of coal pillars but there was big loss of coal in pillars. When the width of the coal pillar is less than 8 m, the maximum stress is in the coal seam and when the width is greater than 8 m, the maximum stress is in the coal pillar. This indicates that with the increase in the width of the coal pillar, the mine pressure is initially applied to the coal seam and then gradually transferred to the coal pillar. Therefore, when the width of the pillar is in the range of 8 - 12 m, there is only one stress peak on the pillar and by then the coal pillar is the main bearing place so it is not favorable to stress environment and the entire coal pillar will be broken. In this situation, the stability of the roadway is worse and the roadway will undergo great deformation. When the width of the coal pillar is less than 6 m, this leads to the failure zone of the entire coal pillar. In particular, when the width of the coal pillar is not more than 4 meters, the coal pillar will be crushed and the stabilized road will be worse. When the width of the coal pillar is between 6 and 8 m, the maximum vertical stress distributed on coal seam and applied pressure up the coal pillar is not high. However, in this case the horizontal stress in the coal pillar is not high, the coal pillar is weakened, and the deformation of the roadway will be slightly larger but acceptable. The roadway will still be in good condition in this case and the integrity of the coal pillar can be stably maintained by appropriate support.

Therefore, for designing a reasonable pillar width for mining panels along the roadway, there are four points to keep in mind. Firstly, the width of the coal pillar should not be near to the critical width (at this width, the maximum stress is transferred from the coal seam to the coal pillar), because the roadway will be in a bad stress environment and the width of the coal pillar is not large enough to resist the maximum stress. Second, the width of the coal pillar should not be too small, because in this situation, the bearing capacity of the coal pillar will be small and the coal pillar will be crushed. Third, when the width of the coal pillar is too large (such as 20 m in this study), the coal pillar will stabilize with an elastic area large enough in the center of the coal pillar. Fourth, when the width of the coal pillar is small (less than the critical width but not too small), the roadway will have relatively large deformation because the horizontal stress is not high. The first two will cause serious problems for the roadway system. The third helps stabilize the sugar, but the coal loss is large and unsuitable for reducing the loss of resources. The final problem will not be too troublesome, because deformation will only be released when the highest pressure is applied on it. When the coal pillar is in a relatively low stress state, the deformation of the roadway will not be large and the integrity can be maintained with appropriate support.

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