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Analysis of Stress and Pillar Strength in Underground Coal Mines

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ABSTRACT

Underground coal mining is located in Tanah Kuning, Batu Tanjung Village, Talawi Sub-district, Sawahlunto City, where some constraints arose in a CV BMK is the existence of several mining fronts on mining blocks that have started to become critical and fail. It can be seen from the condition of the supports in some places that they have started to crook and break. This indicates a significant change in strain around the coal pits and pillars. The research was carried out by testing In-situ stresses using Flat-jack, observing the condition of the rock mass, and testing the physical and mechanical properties of the rock. The purpose of this study was to find out the magnitude of the strength and stress on the pillar based on the theory of tributary area loading, to provide safe and economical pillar geometry recommendations, and to discover the causes of rock mass movements. Based on the results of the analysis using the Tributary Area theory, the Safety factor Pillar 1 obtained was categorized as unsafe based on the reference value of the safety factor. The most ideal pillar size recommendation based on previous geotechnical studies was 9 m x 9 m with a maximum recovery of 38% and a safety factor of 1.7. Based on the results of the calculation of strength and loading on the pillars, the value of Pillar 1 strength is 6.0 MPa, Pillar 2 strength was 9.57 MPa, and Pillar 3 was 10.9 MPa with the value of Pillar load for Pillar 1=5.1 MPa, Pillar 2=4.47 MPa and Pillar 3=5.58 Mpa.

KeyWords: Watershed Management, Inhibiting Factors, Sustainable Development.

INTRODUCTION

The room and pillar coal mining method is extracted by leaving a pillar that functions as a support for the space (room) in the coal seam in the ground. The size of the pillars is determined by calculating the strength of the roof rock, the floor, and the characteristics of the coal seam (Genis & Aydan, 2008). Cheng *et al* (2013) add, that the rock mass at a deep location will experience In-situ stress generated by the weight of the soil/rock above it gravitational stress, stress due to tectonic events, and residual stress. Based on the Tributary Area method (Aly, 2013), each pillar will support the load above it so that there is an equilibrium for all structural components.

Various empirical equations have been developed in recent decades to discover the actual strength of the pillars in the field. The Hydraulic Fracturing Technique is an in-situ stress measurement technique that is effective in measuring stress for deep areas. Mainly used for in-situ stress measurement in hydropower engineering, road engineering, subway, and others (Serdyukov *et al*., 2016). Meanwhile, according to Lulić *et al* (2023), the flat jack test technique is a direct, in-situ testing method that requires only slotting into the wall. It is considered non-destructive because the damage is temporary and easy to repair after testing. Parivallal *et al* (2011) adds flat jack testing can be used for engineering problems to evaluate structures where this method is also used to find out In-situ stress and compressive strength.

LITERATURE REVIEW

2.1 Load of Pillars (Tributary Area)

Tributary Area loading theory is derived from a simple analysis of static equilibrium. Fig 1 showed a cross-section of a horizontal coal structure with uniform thickness mined using several long rooms and pillars, with the same room and pillar lengths. The width of the room and pillars are *Wo* and *Wp* (Cano Nunez *et al*., 2012).

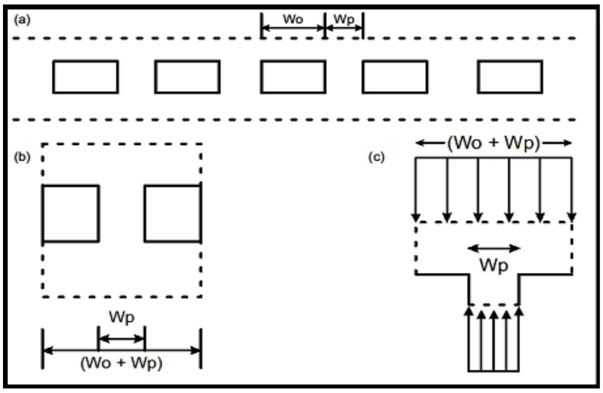

Figure 1. The basis of the Tributary Area method for determining the mean axial stress of the pillars

According to the Tributary Area method, each pillar will support the weight above it and half the distance from the surrounding pillars (*Wo*+*Wp*). For pillars with width and length *Wp* and *Lp* as well as room width *Wo* can be used similarly. The area supported by the pillars is an area measuring (*Wo*+*Wp*) and (*Lp*+*Wo*) so the equation that can overcome this in the vertical direction is.

$$\sigma_p = \sigma_v \left[\frac{(W_p + W_o)(L_p + W_p)}{W_p L_p}\right]$$

For pillars located on an inclined layer, Trumachev & Melkinov (1964) in Das *et al* (2019) proposed an equation for the normal stresses on the pillars, namely.

$$\sigma_p = [\sigma_v(cos^2\alpha + m\, sin^2\alpha)][\frac{(W_p + W_0)}{W_p}]^2$$

2.2 Causes of Pillar Collapse in Underground Mines

The mechanism of pillar collapse must be understood to adequately assess the strength of the pillar. Pillar collapse in rocks is influenced by several factors including rock type, geological structure, pillar size, and In-situ stress conditions (Brady *et al*., 1985). The collapse of a pillar is caused due to the stress on the pillar exceeding the strength of the pillar. To obtain stable pillar conditions, the same values of stress and pillar strength are required. Brady *et al* (1985) have provided a model of pillar failure in rock masses. Fig 2[a] showed a failure model that depicts the erosion of pillar walls into the mine pit, the type of failure is progressive. Next, Fig 2[b] depicted a model of pillar failure along the failure plane that develops within the pillar core. Then, Fig 2c illustrated the fracture failure model in the pillar in the soft parting zone (Clay) above and below the pillar. Fig 2 (d & e) of the structure was oriented along the vertical axis of the pillar, as a result, the possibility of a buckling failure model occurs. However, the pillar was oriented by the inclined structure, and the possibility of a shear failure model occurs.

2.3 Flat Jack Technique

The flat jack test is a direct, in-situ testing method that requires only slotting into the wall. It is considered non-destructive because the damage is temporary and easy to repair after testing. Flat jack testing can be used for engineering problems to evaluate structures, where this method is also used to determine In-situ stress and compressive strength (Parivallal *et al.*, 2011). Therefore flat jack measurement is a measurement technique that is In-situ test or directly in the field which aims to determine the stress and deformation of rock structures in tunnels and mines.

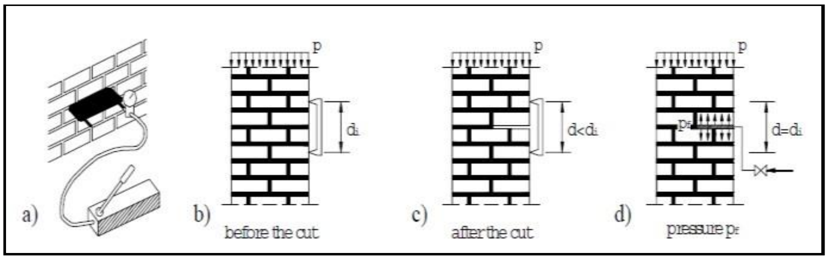

Figure 3. Pillar Collapse Model (Brady *et al.*, 1985)

The first displacement was determined by measuring the distance between the specified measuring points on the wall surface. Then, the slot was cut in the normal direction according to the direction of the pressure being measured. This allows deformation after slot creation. The descent distance between the measuring points is smaller than the initial distance. Cutting the slots causes partial stress on the above and below the relief. After that, a thin flat jack was inserted into the slot. With the he*Lp* of hydraulic devices, pressure is applied to the walls. This results in a return to the initial displacement plane, which they reached i.e. the previously measured value, before displacement. The pressure exerted by the hydraulic pump can be measured using a pressure gauge, within a range equal to the maximum operating pressure of the flat jack. The system must be able to maintain constant pressure for a time of at least 5 minutes. The maximum operating pressure for the flat jack is 6.9 MPa (1000 psi). Stitch drilling is only suitable for weak rocks. The use of a hammer is not recommended because there will be disturbances that may occur in the vicinity of the rock. In the case of strong rock, the rock is irregular, and thick, requiring a rock saw to cut. Saws are usually equipped with water-cooling blades.

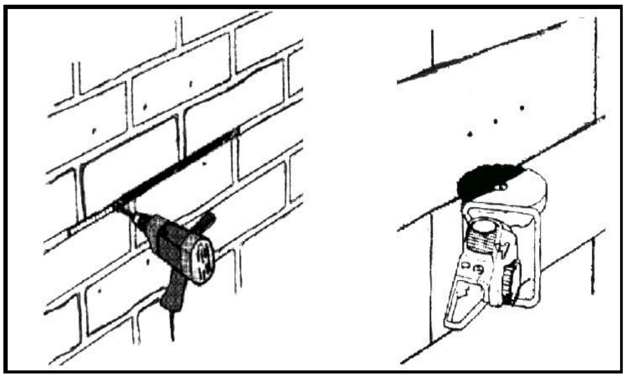
Figure 4. Slot Drilling and Sawing Method (Gregorczyk & Lourenco, 2000)

RESULTS

3.1 Pillar Tension and Strength (In-situ Stress)

From the results of measurements in March 2022 at a depth of 110.1 m with a flat jack, an average stress of 29.75 kg/cm² was obtained, at a depth of 113.9 m the stress was 33.03 kg/cm², while at a depth of 120.24 m obtained a stress of 33.58 kg/cm². For more details can be seen in Table 1 below.

Table 1. Measurement of stress values in underground mine

Location	Depth (m)	Stress σv (kg/cm²)	Average
Pillar	110,1 m	29.50 kg/cm² 30,00 kg/cm² 29.75 kg/cm²	29.75 kg/cm²
Pillar	113,94 m	33.20 kg/cm² 33.00 kg/cm² 32.90 kg/cm² 33.75 kg/cm²	33.03 kg/cm²
Pillar	120,24 m	33.50 kg/cm² 33.50 kg/cm²	33.58 kg/cm²

This research was conducted at different depths. The results of vertical stress measurements using a flat jack showed that the deeper you are in, the higher the stress produced, as a result of the stress value increases during excavation. The cause of the increase in stress occurs because the load that was originally borne evenly was shifted and redistributed. More details can be seen in Fig 5 below.

Figure 5. In-situ stress measurement using Flat-jack a) Determination of reference point; and b) Insertion of the plate into the hole that was made.

Based on the results of the analysis, the vertical stress value was greater than the horizontal stress value because vertical stress is the stress from the surface to the depth point in meters multiplied by the density of the rock at that depth, while the horizontal stress is empirically influenced by the K value (Sheorey (1994). Based on the results of the analysis, the K values range from vulnerable (0.92-1.06) after that, the K value was multiplied by the vertical stress. Therefore, the horizontal stress value was relatively smaller than the vertical stress. As can be seen in Fig 5 showed the value of vertical and horizontal stresses increases the deeper the excavation is carried out, the increase in stress occurred because the load that was originally borne evenly shifted, and was redistributed.

3.2 Pillar Tension and Strength (Load on Pillar)

Determination of the load received by the pillars is determined based on the theory of tributary area loading with the formulation proposed by Trumbachev & Melkinov (1964) for sloping coal seams for calculations. The value of is the ratio between the horizontal stress and the vertical stress After the m value is obtained then it's used to find the value of the load on the pillars as in the following formula.

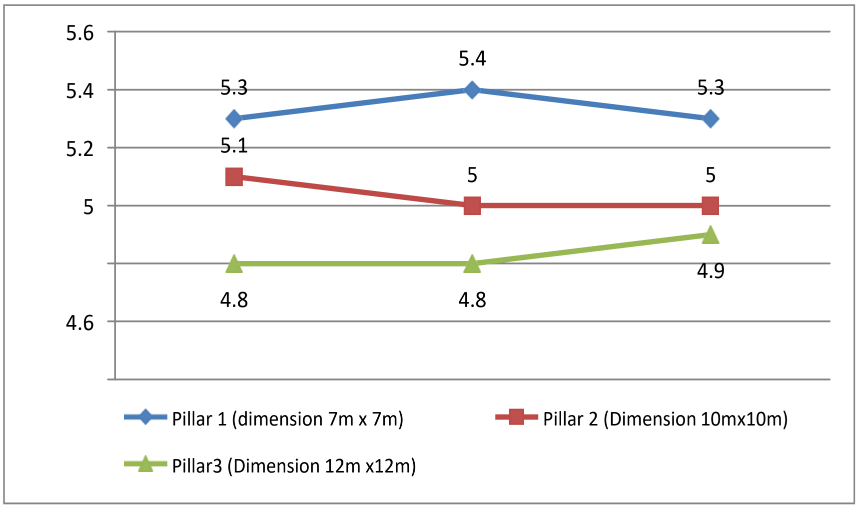

Figure 6. Load on Pillar

Based on the calculation results of the loading on the pillars using the equations of Trumbachev & Melkinov (1964), the results of the loading on pillar 1 were highest compared to pillar 2 and pillar 3, which were strongly influenced by the size of the dimensions of the pillars used in branch one of 7 m x 7 m, as a result, the smaller the pillar area, the greater the load. Apart from the pillar dimensions, the vertical stress value and the value of m (vertical and horizontal stress ratio) as well as the dimensions of the hole openings were also very influential on the calculation of the load value on the pillar but the values obtained do not experience significant differences between Pillar 1, Pillar 2 and Pillar 3. Thereby, it looks very influential was the size of its dimensions.

3.2 Pillar Tension and Strength (Pillar Strength)

The strength of the coal pillars is obtained by using the empirical equations of Potvin *et al* (1989) for calculations using equation (9), with the pillar size (W) and height (h) excavation (coal layer thickness 2.5 m) and c is the compressive strength test value of each pillar sample. From the calculation of the strength of the pillars, the results of the pillar strength in Pillar 1 have the smallest strength value of 6 MPa, Pillar 2 of 9.57 MPa, and pillar 3 got the largest value of 10.9 MPa. There is a contrast in value which is strongly influenced by the value of rock strength (σc) and pillar dimensions. Based on laboratory testing in Pillar 1, the lowest compressive strength value was 5.2 MPa, it was the smallest compared to Pillar 2 which obtained a compressive strength value of 5.75 MPa, and Pillar 3 of 5.5 Mpa. In addition, the dimensions used in the branch the smallest one measuring 7 x 7 m compared to the pillars of the second branch of 10 m x 10 m and the third branch of 12 x 12 m. Based on the above analysis, the strength of the pillar increases in direct proportion to the compressive strength of the rock and the dimensions of the pillar. To conclude, the larger the dimensions of the pillar, the greater the resisting force on the pillar.

3.3 Pillar Tension and Strength (Coal Pillar Safety Factor)

Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018 concerning "Guidelines for the Implementation of Good Mining Engineering Rules", mine openings must be planned by and follow the established regulations. Based on these regulations, the evaluation of the collapsed openings and analysis of the stability of the pillars must be able to meet the requirements of the applicable regulations, namely the safety value for a minimum value of 1.5. The pillar safety factor is obtained from the comparison between the pillar strength (σps) with the load on the pillar (σp) equation.

Location	Pillar Dimension (m)	Load on pillar (σp)(MPa)	Pillar Strength Safety factor (σps) (MPa)	Safety factor
1	7 x7	5,36	6,05	1,12
		5,4	6,05	1,12
		5,46	6,05	1,11
2	10 x 10	5,1	9,57	1,87
		5,05	9,57	1,89
		5,06	9,57	1,9
3	12 x12	4,81	10.93	2,27
		4,81	10.93	2,27
		4,84	10.93	2,25

From the results of the analysis above, it can be concluded that the pillar in branch one was in a vulnerable or unstable condition (FK < 1.5). In addition, the three test points stated that the value of the safety factor obtained means it's unsafe.

3.4 Pillar Tension and Strength (Pillar Geometry Recommendations)

In evaluating and determining the pillar design recommendations, take into account factors such as geotechnical, economic, and safety factors. In the calculation of the value of the safety factor in the previous discussion, it was found that Location One was categorized as unsafe because the Safety Factor obtained from the three points of FK testing was <1.5, therefore an analysis was carried out to get a safety factor value > 1.5, then a simulation was carried out on the dimensions.

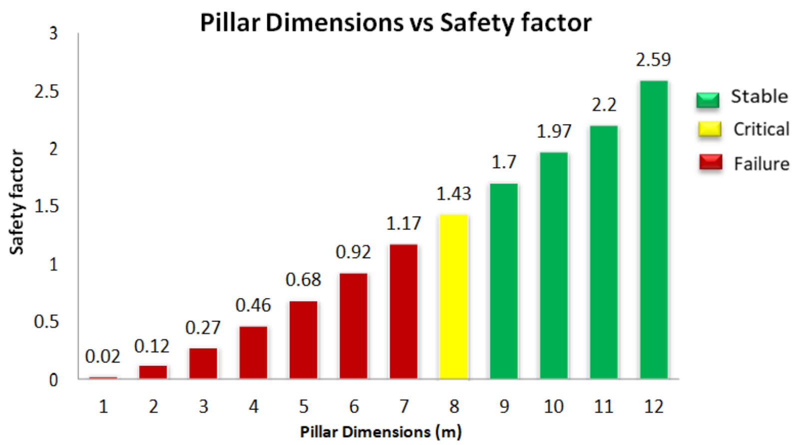

Figure 7. Variation of Safety factor value for each size/dimension of coal pillar

Based on the picture above, the dimensions of pillars 1 x 1 to 7 x 7 m are not safe using in Location one because the Safety factor value was <1.5 while the Pillar size 8 x 8 m was SF 1.43, which means in a critical condition. However, it isn't recommended to be used if referring to the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018 FK > 1.5, the most ideal pillar size recommendation based on geotechnical studies is a pillar with dimensions of 9 x 9 m, the FK value is 1.7 so it is safe to apply to Pillar 1. The pillar dimensions are related to the Extraction ratio value which is the ratio between the mined area and the total ore body. Mining pillars with larger dimensions are relatively more stable but the effect is more coal to be left behind. Whereas if the pillar dimensions are too small, it has a relatively greater potential for instability. After calculating the safety factor, the results of the pillar dimensions 9 x 9 m, 10 x10 m, 11 x 11 m, and 12 x 12 m displayed the value of the safety factor which was in stable condition FK > 1.5 so it is necessary to calculate the extraction ratio value of the dimensions of the pillar as a result the coal can be taken optimally.

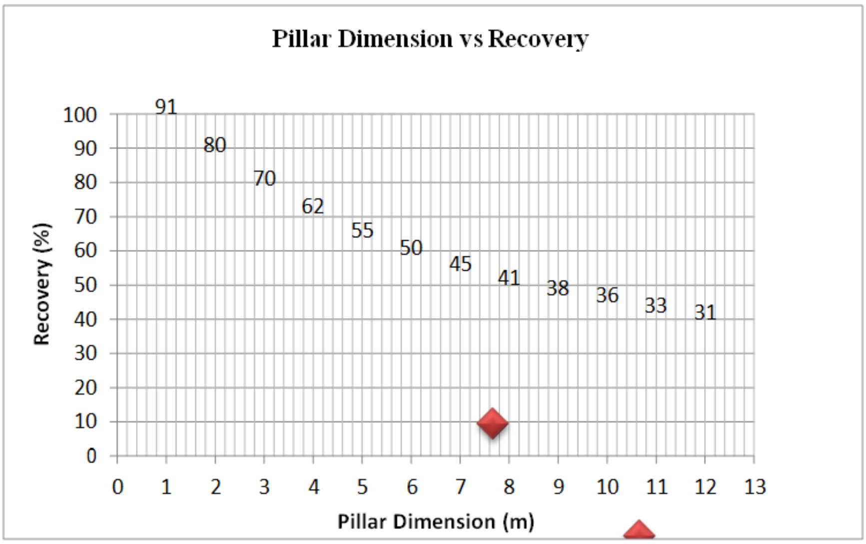

Figure 8. Pillar Dimension vs Recovery

Based on Fig 8, explained that the smallest pillar dimension, namely 1 x 1m, got the largest recovery value, which is 91%, while the largest pillar dimension 12 x 12 m got the smallest recovery value of 31%. It means that if the size of the pillar is the smallest dimension we use in recovery, it will be bigger but in terms of safety factors it is not safe and if the dimension of the largest pillar is used for a safety factor it is very safe, but the coal cannot be taken to its full potential because the pillar can still be reduced to a smaller size. Therefore, in obtaining an ideal pillar geometry that is geotechnically safe and economically recoverable, it is necessary to link the value of the safety factor and the recovery value that has been obtained from the previous analysis, so that coal can be extracted optimally, and the safety factor is maintained.

In this case, it was found that the most ideal pillar geometry to use was a pillar with dimensions of 9 x 9 m with an estimated recovery of 38%. This statement is reinforced by the results of research (Ratih *et al*, 2021) entitled "Determining the Design of Chain Pillars in Coal Mining Shortwall Mining" in his writings discussing the effect of pillar dimensions on the safety factor. The recommended pillar was rectangular with dimensions of 9 meters wide. then obtained an extraction ratio of 43.75% at one mining level. In conclusion, the value of the safety factor will increase along with the increase in the size of the pillar dimensions.

CONCLUSION

Based on the results of the calculation of strength and loading on the pillars, the value of Pillar one strength was 6.0 MPa, Pillar t*Wo* strength was 9.57 MPa, and pillar three was 10.9 MPa with the value of Pillar loading for Pillar One = 5.1 MPa, Pillar t*Wo* = 4.47 MPa and Pillar three = 5.58 Mpa. Based on the results of the analysis using the Tributary Area theory, the Safety factor Location one obtained was categorized as unsafe based on the reference value of the safety factor. The most ideal pillar size recommendation based on previous geotechnical studies was 9 m x 9 m with a maximum recovery of 38% and a safety factor of 1.7.

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