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Report

ROCK ENGINEERING VISIT

REPORT ON SLOPE STABILITY

Report Title: ROCK ENGINEERING REPORT MANUNGU UNDERGROUND MINE			
Report Number: MGM036_17 August 2018_Rock Engineering Report on Pillar Design and Stability			
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1. Introduction

Manungu Colliery currently mining the reserve using opencast mining method and, in the process, and planning to mine the remaining reserves with bord and pillar underground mining method. Some parts of the underground reserves are underneath a wetland, the aim of this report will be to determine the stability of workings below this area and to recommend the pillars sizes for underground mining and asses the stability of them in a long term.

Umnotho Rock Engineering was required to do a detailed geotechnical study of this area using borehole logs, the borehole logs provided information on rock types, composition, roof stability and thickness of the targeted seam, overburden thicknesses and depth below surface. Findings and recommendations from the visit are outlined below:

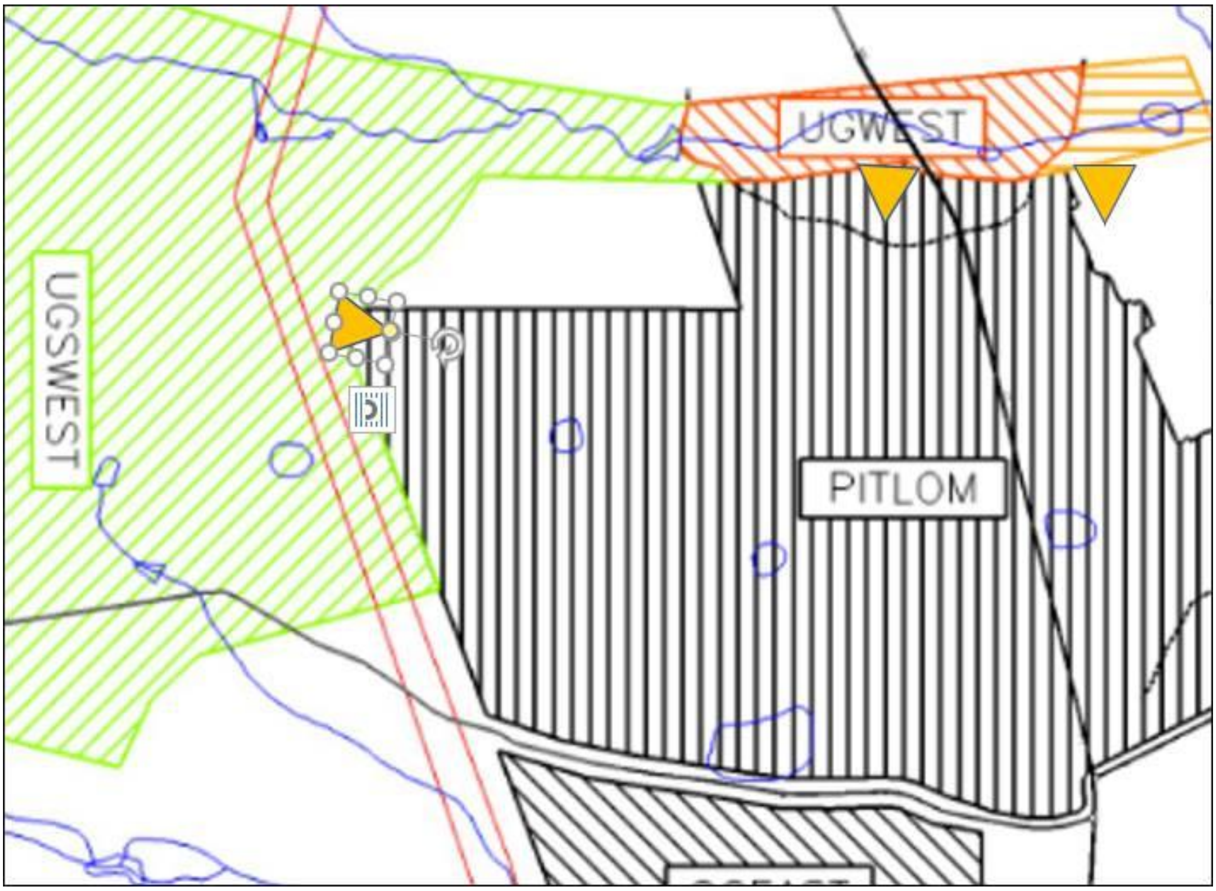


Figure 1: Plan showing the Pit Life of Mine and the planned underground areas.

2. Findings

2.1 The Geology of the Area

From the assessed borehole logs, the geology of the underground mining has 16m thick limit of weathering that comprised 12m of softs and 4m of weathered sandstone. These are underlain by the thick sandstone rock and shale rocks. These sandstone and shale rocks were underlain by the S2T and S2 coal seams.

Only 2 of the 6 assessed boreholes were intruded by a dolerite as shown in **Table 1** below. The depth of mining will be 61m in average and the planned mining height will be 5m of the S2 coal seam. The total coal seams thickness is 13.81m in average thus about 9m of coal will be left on the floor and the roof.

Table 1: Assessed boreholes information

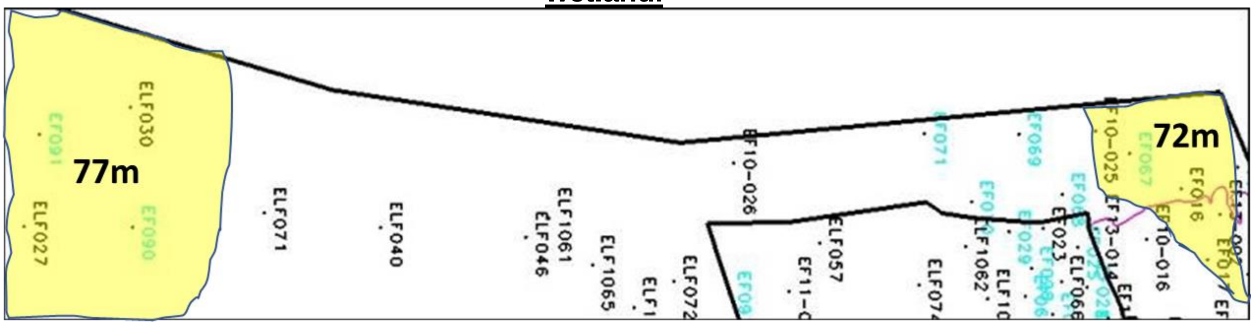
Borehole (ID)	Depth to floor (m)	S2T + S2 Seam Thickness (m)	Limit of weathering (m)	Sandstone %	Dolerite thickness (m)
EF065	54.45	3.45 + 8.75	15.62	35.71	8.4
EF067	72.09	3.42 + 9.88	16.60	23.72	18.75
EF068	58.59	3.45 + 10.66	14.80	50.00	0.00
EF069	64.32	3.31 +11.56	16.91	48.98	0.00
EF070	59.29	3.41 +10.18	16.53	53.33	0.00
EF071	62.92	3.22 + 11.65	16.57	27.08	0.00
EF090	80.73	3.26 + 9.15	9.94	50.00	4.78
EF091	74.91	3.33 + 8.77	7.96	64.52	0.00
Averages	**69.88**	**3.33 + 9.70**	**12.56**	**48.53**	

The **Table 2** below will be the basis of the stable pillar design, where a 5m mining height and 6.5m bord width were selected for a practical mining and maximum reach of the Continuous Miner (CM). The table shows key parameters which are the Safety factor, width-height ratio of 2 and the extraction ratio of 63%.

Table 2: Pillar dimensions

Borehole	Depth	W1	W2	C1	C2	h	Safety Factor CM	e	e%
EF065	54.45	10.00	10.00	16.50	16.50	6.00	**1.98**	0.63	**63.27**
EF067	72.09	12.00	12.00	18.50	18.50	6.00	**1.82**	0.58	**57.93**
EF068	58.59	10.00	10.00	16.50	16.50	6.00	**1.84**	0.63	**63.27**
EF069	64.32	10.00	10.00	16.50	16.50	6.00	**1.68**	0.63	**63.27**
EF070	59.29	10.00	10.00	16.50	16.50	6.00	**1.82**	0.63	**63.27**
EF071	62.92	10.00	10.00	16.50	16.50	6.00	**1.72**	0.63	**63.27**
EF090	80.73	12.00	12.00	18.50	18.50	6.00	**1.63**	0.58	**57.93**
EF091	74.91	12.00	12.00	18.50	18.50	6.00	**1.75**	0.58	**57.93**

Table 3: Assessed deeper boreholes (EF067, EF090, EF091) location under the wetland.



3. Discussion

The following guidelines and risk categories were used were used for the assessment:

- Shallow depth guidelines where sinkholes are common.
- The strength and the safety factor of pillars were calculated using: the Salamon and Munro's strength formula, the squat pillar formula and Tributary Area Theory
- Pillar width to mining height ratio.
- Age of pillars
- Maximum vertical subsidence guidelines.
- Damage to surface structures.
-
- Assessment of potential roof failure mechanisms,

3.1. Shallow depth guidelines

These guidelines are applicable to mining depths less than 40m as they are associated with the collapse of bord and result to sinkholes formation to surface.

Madden and Hardman investigated the problems associated with shallow depth mining using the pillar collapse cases in South Africa. They established the following guidelines for mining at depths less than 40 m below surface:

- Pillar width to mining height ratio should not be less than 2.0
- Areal percentage extraction should not be greater than 75 per cent.
- The minimum pillar width should not be less than 5.0 m
- A minimum safety factor of 1.6 should be used.

In South Africa, the pillar design formula developed by Salamon and Munro (6) has been successfully used since 1967. This formula is based on the statistical analysis of 27 collapsed and 98 intact pillar cases.

The general formula for strength was defined by Salamon and Munro (6) as:

$$\sigma_p = \frac{w^{\beta}}{h^{\alpha.}}$$

Where k, α, and β were determined by statistical analysis of collapsed and intact pillar geometries, *w* and *h* are pillar width and mining height, in metres respectively. Salamon and Munro (6) determined the values for k, α and β to be 7 176 kPa, 0.46 and 0.66 respectively.

Average pillar stress = 0.025 (HC^2/w^2), where;
H =Depth to floor of the workings and;
C = Pillar Centres

Load on Pillar= 0.025 $\frac{H.C_{1.}C_2}{W_{1.}W_2}$

Hill (1996) suggested that the following factors should be considered when considering mining at shallow depths (<40 m):

- Use of the safety factor formula alone may be misleading since other factors also influence pillar stability.
- Floor failure may occur; although more likely to occur at depth as the load is greater. Floor failure has nevertheless occurred at shallow depths.
- Bords may fail to surface, forming sinkholes.
- Workings may be subjected to surface climatic changes.
- Shallow workings result in temporary or permanent changes in the ground water table and this may lead to localized deepening of the influence of weathering.
- To all failed intersections the sandstone percentage in the overburden was less than 30%.

The problems of shallow mining were also discussed by Madden and Hardman (1992) and the following design guidelines were established:

- Pillar width to mining height ratio should not be less than 2.0.
- Areal percentage extraction should not be greater than 75 per cent.
- The minimum pillar width should not be less than 5.0 m.
- A minimum safety factor of 1.6 should be used.

However, since the development of these guidelines, there have been 34 additional pillar collapses in South African collieries. Therefore, the new pillar collapse data has been analysed to develop the new shallow depth pillar design guidelines.

There has been a total of 78 pillar collapses since 1904 in South Africa. 16 of these 78 collapses occurred at depths less than 40 m below surface in the Witbank Coalfield. The dimensions of these collapses are presented in **Table 3**

The safety factors (using Salamon and Munro, 1967), pillar width to mining height (w/h) ratios, extraction ratios and pillar widths of these collapses are summarised in **Figure 3** to **Figure 5**.

From these figures it can clearly been seen that the new shallow depth pillar design guidelines for Witbank Coalfield No 1, 2, 4 and 5 Seams should be as follows:

- Pillar width to mining height ratio should not be less than 2.2.
- Areal percentage extraction should not be greater than 75 per cent (indicates a maximum bord width of 6.5 m).
- The minimum pillar width should not be less than 6.5 m.
- A minimum safety factor of 2.1 should be used.

The shallow depth pillar design guidelines were also applied to all pillar collapses at depths less than 50m. This, however, resulted in the same set of recommended dimensions.

The average depth to floor is the underground workings will be 61m and the extraction will be 63% with 10m x 10m pillar dimensions.

Table 3. Pillar collapses that occurred at depths less than 40 m

No	Coalfield	Seam	Depth	Pillar Width	Bord width	Mining height	w/h	Safety Factor	Extraction ratio (%)
1	Springs-Witbank	Springs	36.6	6.1	7.6	4.9	1.25	1.26	80.2
2	Witbank	W 2	21.3	4.0	8.2	4.6	0.87	0.99	89.4
3	Witbank	W 5	22.0	3.5	6.5	1.6	2.19	2.09	87.8
4	Witbank	W 1	25.9	3.7	8.5	3.0	1.20	0.87	91.0
5	Witbank	W 2	27.4	3.7	7.9	2.1	1.71	1.15	90.0
6	Witbank	W 4	28.5	3.8	5.8	2.7	1.41	1.52	84.3
7	Witbank	W 2	29.6	5.2	7.0	5.5	0.94	1.22	81.9
8	Witbank	W 2	30.5	4.6	7.6	3.7	1.25	1.14	85.9
9	Witbank	W 4	30.5	3.4	6.4	2.6	1.29	1.04	88.2
10	Witbank	W 4	32.0	3.3	6.4	2.3	1.43	1.04	88.4
11	Witbank	W 4	32.5	3.2	6.5	2.1	1.52	1.01	89.1
12	Witbank	W 2	33.0	6.4	6.4	4.9	1.31	1.80	75.0
13	Witbank	W 2	33.5	6.1	6.7	5.5	1.11	1.46	77.3
14	Witbank	W 4	34.0	3.5	6.7	2.7	1.30	0.92	88.2
15	Witbank	W 4	34.0	3.5	6.7	2.7	1.30	0.92	88.2
16	Witbank	W 5	36.6	4.6	7.6	2.4	1.88	1.24	85.9

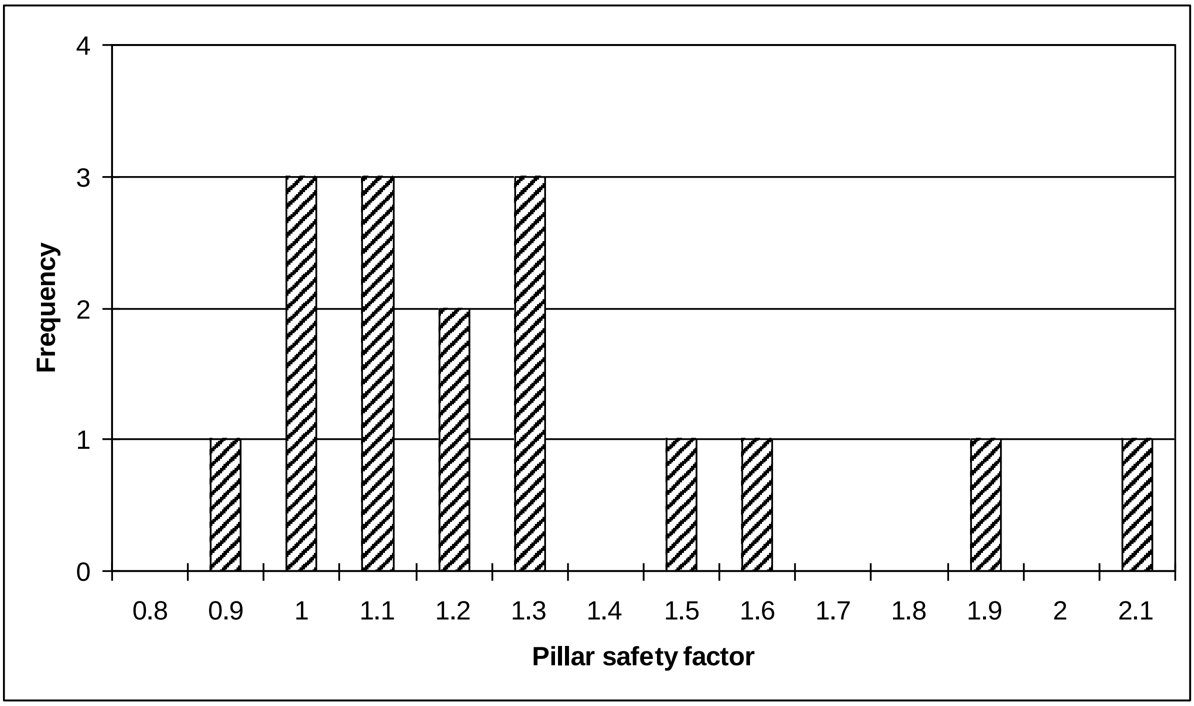


Figure 2. **The safety factor for shallow (<40 m) pillar collapses**

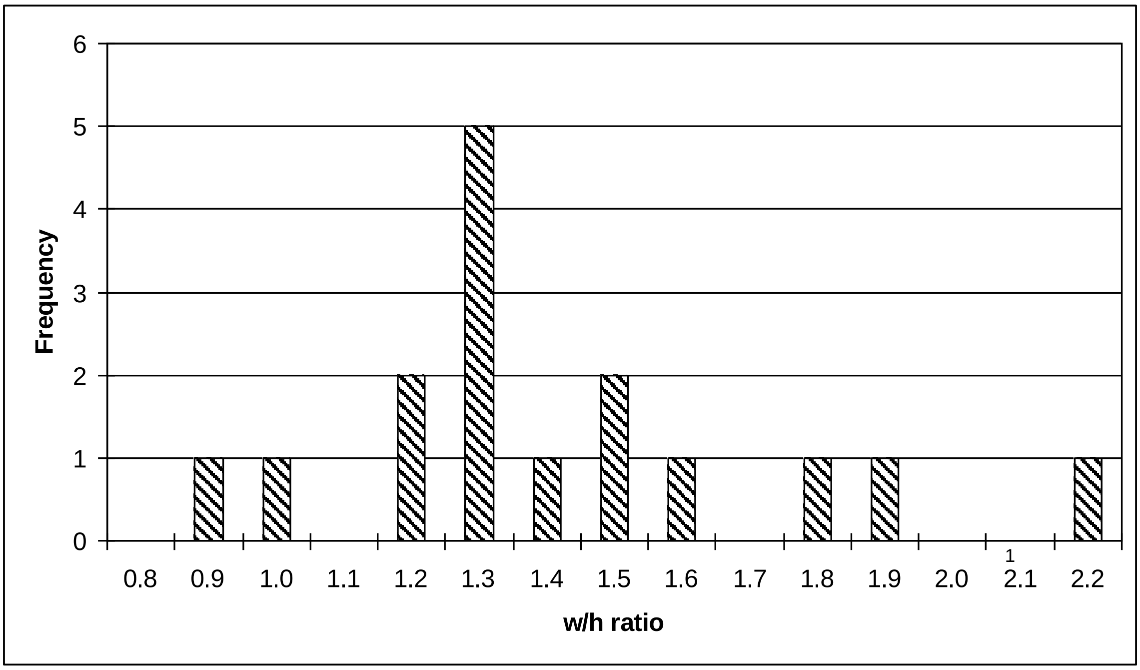


Figure 3. **The w/h ratio for shallow (<40 m) pillar collapses**

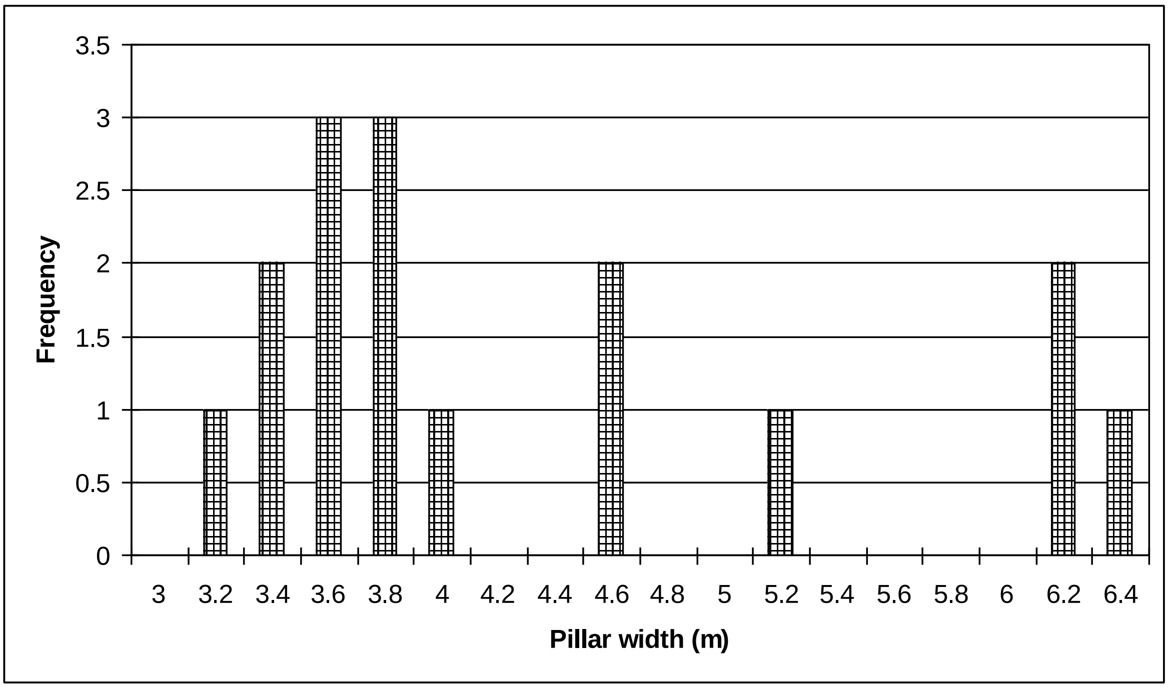


Figure 4. **<u>The pillar width for shallow (<40 m) pillar collapses</u>**

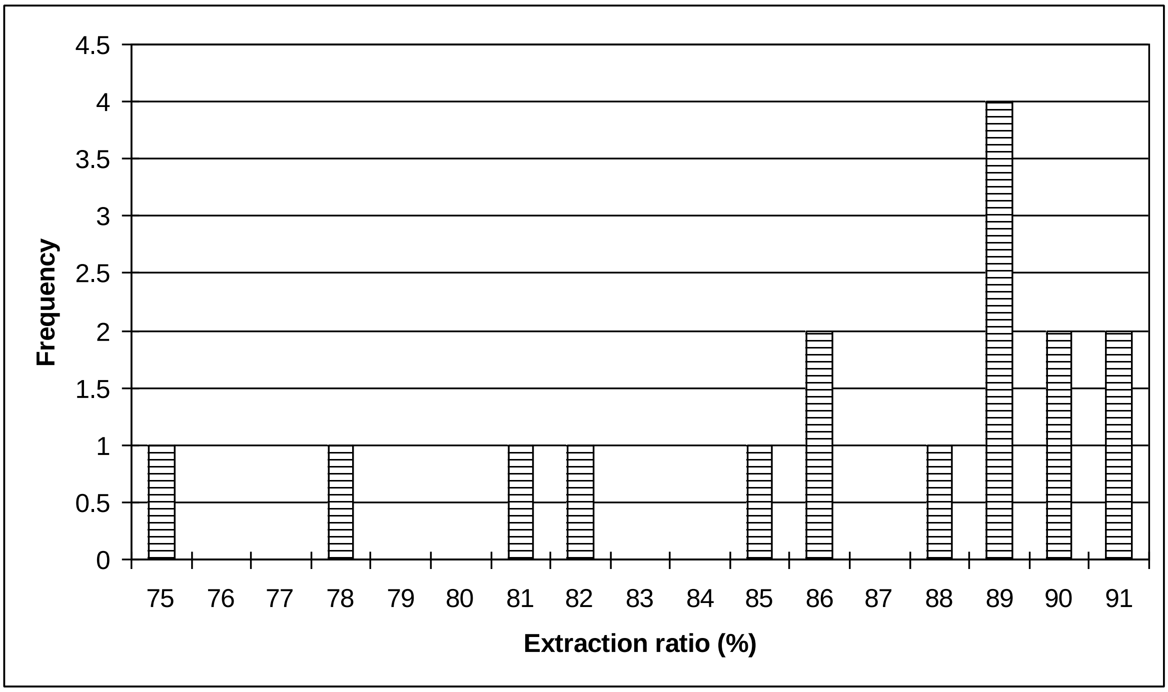


Figure 5. The extraction ratio for shallow (<40 m) pillar collapses

3.2 Pillar strength

In South Africa, the pillar design formula developed by Salamon and Munro has been successfully used since 1967. This formula is based on the statistical analysis of 27 collapsed and 98 intact pillar cases.

The general formula for strength was defined by Salamon and Munro as:

$$\sigma_p = \frac{w^{\beta}}{h^{\alpha.}}$$

where k, β and α were determined by statistical analysis of collapsed and intact pillar geometries, *w* and *h* are pillar width and mining height, in metres respectively. Salamon and Munro determined the values for k, β and α to be 7 176 kPa, 0.46 and 0.66 respectively.

Average pillar stress = 0.025 (HC^2/w^2), where;
H =Depth to floor of the workings and;
C = Pillar Centres

Effective pillar width= $\frac{\text{4Area of the pillar}}{\text{Circumference of pillar}}$

Load on Pillar= 0.025 $\frac{H.C_1.C_2}{W_1.W_2}$

From the calculations and design for the mine, the average **pillar load is 4Mpa** and the **pillar strength is 7Mpa**

3.3 Pillar width to mining height ratio

The pillar width to height ratio is 2 which is the required standard for pillar stability, so pillar failure is least expected. Percentage extraction will be less than 75% and effective pillar widths will be 10m.

3.3 Age of pillars

The pillars will be new, and the design is such that the pillars won't fail due to size and the pillar load of 4Mpa is less that the pillar strength of 7Mpa.

3.4 Maximum vertical subsidence

MacCourt et al. investigated the maximum vertical subsidence due to pillar failures. Their investigation was based on actually subsidence measurements of pillar collapses. They stated that at greater depth, the amount of subsidence is significantly less.

The reason for this arrested subsidence was not clearly understood but was believed to be due to the effects of frictional resistance to sliding of the overburden blocks as the ratio of the weight of the overburden to the magnitude of the confining horizontal stress decreases with increasing depth (van der Merwe and Madden).

MacCourt et al. suggested the following equations to calculate the maximum expected subsidences in the case of pillar failures:

$$S_m = 0.8\ h_e \text{ for mining depth less than 100 m}$$
$$S_m = 0.5\ h_e \text{ to } 0.1\ h_e \text{ for mining depth greater than 100 m}$$

where $h_e = eh$ and h and e are the mining height and extraction ratio, h = 6m, the mining height and e = 0.63 the percentage extraction under the wetland. The calculated value for S_m is 3.03m to surface.

Due to mining depth and large size pillars left, the possibility of pillar failure is very low. The risk of sinkhole formation due to bord collapse is also low due to the overburden composition that comprise more than 30% sandstone. There will be also 7m thick coal beam left in the roof which will also add more stable beam.

3.5 Roof failure mechanisms

The immediate roof failure can result from one or a combination of the following failure mechanisms:

- Bending or flexural;
- Shear;
- Guttering (Buckling);

The failure mechanisms are discussed briefly to gain an understanding on how they influence sinkholes.

3.5.1 Bending or flexural failure;

When a roadway is cut some layers in the immediate roof tends to detach from the overlying rockmass forming a stack of layers that are gravity loaded. The thickness of the detached layer (beam) is generally small as compared to the intersection span and hence the layers experience beam behaviour.

The beam was assumed to be continuous and only supported by pillars. Figure 6 illustrates the beam behaviour where tensile stress is expected to develop at the centre of the beam of the intersection and at the rib roof contacts.
At the centre of the intersection tensile stress will develop at the bottom and at the top of the contacts. The change in stress orientation within the beam is due to the change in direction of the bending moments along the length of the beam.

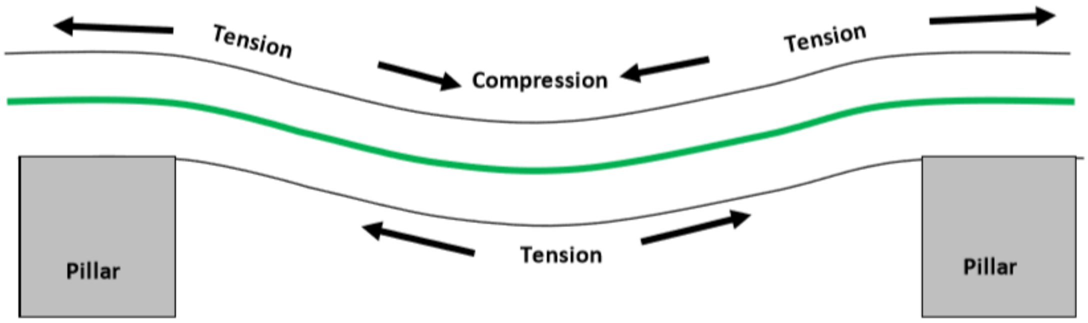


Figure 6: <u>Conceptual pillar supported beam</u>

Assuming a circular beam exist at the centre of the intersection and supported by the corners of each pillar moment per unit length is given by the following equation:

$$M_{demand} = \frac{wb^2}{48}$$

Where: Mdemand = Moment demand at failure,
w: load per unit area at failure w= kp. *K* is the factor of safety and *p* actual load per unit area acting on the beam,
b, a: bord width and diagonal length (m) respectively

Moment capacity is derived from the tensile strength using the equation from elastic theory for flat and constant thickness plates:

$$M_{capacity} = \frac{\sigma_t\, I}{d}$$

Where Mcapacity : moment capacity
t: tensile strength (MPa)
I: moment of inertia per unit length I = t3/12 t: thickness of the solid beam (m)
d: distance from edge to beam centre (d=t/2) The Safety Factor (SF) is given by:

$$Safety\ Factor\ (SF) = \frac{M_{capacity}}{M_{demand}} = \frac{8\sigma_t t^2}{pb^2}$$

The load (*p*) in the formula includes the self-weight of the solid beam, the surcharge load (dead weight of the weathered material) and hydrostatic pressure. The SF is directly proportional to the thickness and tensile strength of the solid beam and inversely proportional to the bord width. The tensile strength of the rock was taken to be 2 MPa which is typical of the Witbank sedimentary rocks.

The results indicate that the potential for collapse is low. However, the empirical assessment does not take into consideration geological structures or the deterioration of the rock conditions which may potentially affect the immediate roof.

3.5.2 Shear failure

Shear failure of the immediate roof occurs when the shear strength of the layers has been exceeded. The maximum shear force of the intersection beam develops at the abutments (Figure 7). Shear force acting on the intersection is determined by dividing the load (P) by the cross-sectional area of the potential failure surface. Shear stress in given by:

$$\tau_s = \frac{p}{4tb}$$

Where,

τ_s = shear stress (demand)

t = thickness of the layer or length supported by bolts

b = bord width.

Shear strength (capacity) of the immediate roof layers is obtained from the Mohr-Coulomb failure criterion, which is defined by:

$$\tau = c + \sigma_n tan\emptyset$$

Where;

c = cohesion

ϕ = friction angle

σ_n = normal stress, where $\sigma_n = K\,\sigma_v$ and K is the field stress ratio σ_v is the vertical stress.

Cohesion and friction angle can be obtained from the intact rock properties such as uniaxial compressive strength (UCS) and direct tensile strength (DST). Cohesion and friction for siltstone/Mudstone were obtained from the literature to be 0.5 MPa and 24 degrees respectively.

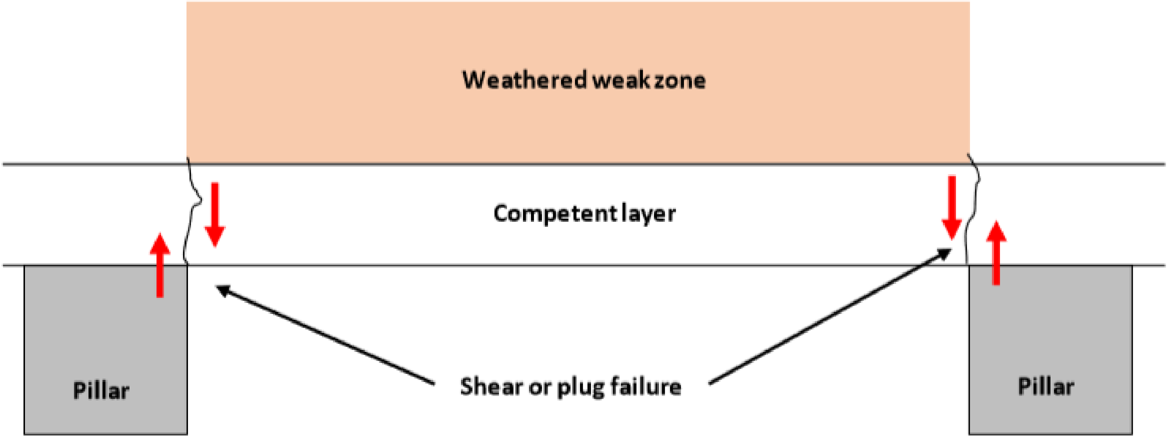


Figure 7: Illustration of shear failure

The shear factor of safety for 1.8 m roof beam and the risk of shear failure is low. The shear factor of safety taking the influence of water into considerations. The results indicate shear reduction in the factors of safety and again the risk of failure is low (minimum factor of safety 33).

3.5.3 Buckling and guttering failure

Extraction of coal in South Africa is in shallow mining depths and therefore experience high horizontal stresses. The horizontal stress is associated with tectonic plates movements, high weathering and dyke intrusions. High horizontal stresses cause delamination and buckling of laminated roof. Figure 8 illustrates roof buckling in a coal mine South Africa.

Roof collapse occurs when the horizontal stress exceeds the buckling capacity of the roof layers. Failure starts as shear and propagates into the roof in a concave shape which is known as guttering. Guttering is commonly encountered in South African mines in cases where the horizontal stress is high.

Guttering can interact with geological discontinuities in the roof and this is common in weak highly weathered roof such as mudstones and shale. In weak rocks roof guttering can manifest across multiple splits and results in massive falls of ground. The actual behaviour of guttering is generally unknown and therefore difficult to predict with confidence.

Mapping of roof guttering (Ndlovu & Stacey, 2007; Mark, et al 2010) indicates that there is generally correlation between the orientation of guttering and direction of the major horizontal principal stress on the intersections where guttering has developed.

A database of stress measurements complied by Stacey and Wesseloo (1998) indicates that in the Witbank area the major horizontal stress is often oriented in the NNW-SSE. Generally, stress damage occurs in roadways of panel developed in the E-W direction and splits oriented in the N-S.

Figure 8: Underground roof buckling as a result of high horizontal stresses.

Roof buckling in bord and pillar mining is described using Euler Beam Theory, which is given by:

$$P = \frac{EI\left(cos^{-1}\left(\frac{e}{e+u}\right)x\frac{2}{L}\right)^2}{t}$$

Where:

P = Load per unit area (MPa)

e = eccentricity (which is the initial distance of loading from the neutral axis, taken to be 0.01 m)

I = Moment of inertia = $t^3/12$

E = Young's modulus taken to be 5GPa (For Literature for Witbank Colliery) u = Displacement

L = length of the beam (L = b√2)

Figure 9 shows the load bearing capacity using Euler's Beam formula. The results show that the thickness of the competent layer has an influence on the load bearing capacity. A 1.0 m thick layer can withstand a horizontal stress that is greater than 75 MPa.

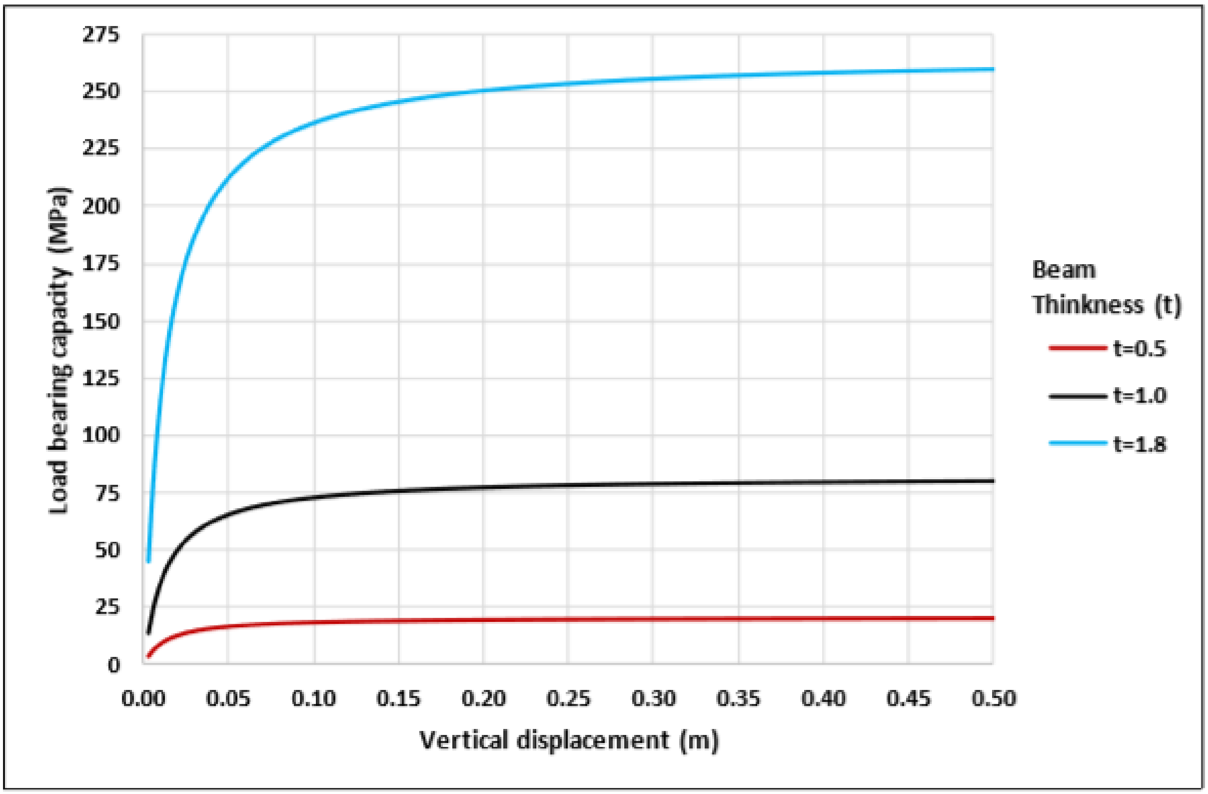


Figure 9: Load bearing capacity for various beam thicknesses using Euler Beam function

4. Conclusion and Recommendations

- From the above analysis, it is evident that the total coal seams thickness average 12m and only 6m will be mined. The roof will comprise 5m thick coal beam and another 1m of coal will be left on the floor for floor stability.

- This 5m coal beam which will also be supported will ensure that no bord failure occurs. It should be noted that the coal itself have a high tensile strength thus at this thickness it won't bend/flex.

- The overburden has at thick sandstone layer of 8m thickness and should the coal beam fail, the bulking of coal will fill the 6m void and the sandstone in the overburden will ensure that there is no effect to surface topography

- The underground mining will mine S2 seam at depths greater than 40m and comprises thick competent sandstone and coal layers thus reducing the risk of sinkhole formation to surface.

- Larger size pillars will be left below the wetland and the risk of pillar failure is very low due to high safety factor of 1.6 to 1.8. The pillar width to height ratio will be greater than 2 which will be very high thus reducing the risk of pillar failure.

- The vertical subsidence will be 3.03m to surface should the collapse takes place, however the presence of (>30%) sandstone layers in the overburden and the coal that will be left unmined will drastically decrease the risk of subsidence.

- The sandstone and coal have high tensile strength (resulting to stable beams) and they also impermeable thus reducing the risk of water flooding into workings.

- The 9 roads panel is planned to be mined, however the 5 roads panels could be planed under surface structures to further reduce the risk of subsidence.

- The Pillar dimensions will be 10m x 10m with the mining height of 6m and 6.5m bord widths. It should be noted that the 7.0m to 7.2m bord widths can also be used provided the depth is less than 60m.

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