Rock engineering method to pre-evaluate old, small coal pillars for secondary mining

by J. N. van der Merwe*

Synopsis

Due to the approaching depletion of reserves in the Witbank Coalfield, and the fact that the Waterberg Coalfield is as yet underdeveloped, there is increasing pressure to extend the lives of the operating coal mines in the Witbank Coalfield.

One potential source of coal is the old pillars, often small and at shallow depth, that were not left with secondary extraction in mind. At face value, some of these pillars appear to be suitable for secondary mining due to their high safety factors. However, it is known that over time, these pillars have scaled and the current sizes are smaller than the as-mined dimensions. It is also known that at shallow depth, the overburden is often less likely to fail during secondary mining, resulting in high abutment loads on the unmined pillars.

The paper proposes a systematic method to pre-evaluate those old pillars for the possibility of stooping. The method consists of elements of fundamental methods and newly developed technology. In essence, it revolves around using empirical methods to estimate current pillar dimensions, followed by numerical modelling to investigate the probability of progressive pillar failure and then fundamental methods to determine the limits of applicability of the numerical model.

Keywords

pillar scaling, old pillars, stooping, numerical model, overburden failure.

Introduction

As the resources in the Witbank Coalfield near depletion, there is pressure to increase extraction of the last remaining reserves in a safe manner. One potential source of additional coal is the pillars that were left several years or even decades ago, when bord and pillar mining was the only intention.

Those pillars were not designed with secondary mining (stooping) in mind. Some are small, with low safety factors, but many have relatively high safety factors and could, at face value, be considered safely mineable. However, it is known that pillars scale over time and consequently, the as-mined pillar dimensions are now smaller.

Experience has also indicated that at shallow depth, the overburden is less likely to fail than at greater depth, and therefore the abutment stresses have to be taken into account in a quantitative manner.

This paper describes a systematic method to pre-evaluate those old pillars for the possibility of stooping. The method consists of elements of fundamental methods and newly developed technology. In essence, it revolves around using empirical methods to estimate current pillar dimensions, followed by numerical modeling to investigate the probability of progressive pillar failure and then fundamental methods to determine the limits of applicability of the numerical model.

The subject matter of this paper is limited to the pre-evaluation of stooping old pillars. If the evaluation returns a positive outcome, it will be followed by detailed underground inspection and careful planning, which is beyond the scope of the paper.

Determining current pillar size

The first task is to determine the current pillar sizes. Where the old workings are accessible, pillar sizes should be measured directly. This is to be done for two purposes; firstly, for direct input into numerical models and secondly, to assist with obtaining estimates of the pillar sizes in inaccessible areas.

For the latter purpose, at least fifty road width measurements should be taken and then compared with the as-mined dimensions to determine the actual amount of pillar scaling, d_a, that has taken place. The comparison should not be done on a pillar-by-pillar manner, as experience has shown that discrepancies abound when the comparison is attempted on a one-to-one basis.

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Rather, the distributions of current and as-mined road width should be compared and d_a determined by subtracting the average as-mined road width from the average current road width. The actual amount of pillar scaling should then be compared with the predicted amount, using the equations supplied by Van der Merwe[1].

Obtaining the distributions of road widths has the added advantage that it displays the variability of the measurements. If the distributions are seen to be very wide (i.e. a high degree of variability), caution should be exercized in using just the average values. Rather, the number of simulations should then be increased to include a high, average, and low value for road width.

The ideal way to handle a situation that displays high variability is to rather base the entire analysis on probabilistic methods. That is beyond the scope of this paper, which is restricted to the core methodology that will form the backbone of the probabilistic investigation.

It is nonetheless useful to convert the distribution of pillar width into a distribution of pillar strength and then a distribution of safety factors, which often gives a more realistic view of the relative stability of a panel. This interpretation should be handled with care. If it is shown that x% of the pillars in a panel have safety factors less than 1.0, it does not follow that x% of the pillars will fail, as those smaller pillars often occur interspersed with larger ones.

From Van der Merwe (2003), the rate of pillar scaling (in m/a) for the Witbank Coalfield is given as

$$R = 0.1624\left[\frac{h}{T}\right]^{0.8135} \quad [1]$$

where h = mining height and
T = time since mining ceased in years.

The predicted amount of scaling, d_p, is then simply

$$d_p = RT \quad [2]$$

Or, by substituting Equation [1] into [2],

$$d_p = 0.1624h^{0.8135}T^{0.1865} \quad [3]$$

To estimate the amount of scaling in inaccessible areas, Equation [3] should be adapted as follows:

$$d = kh^{0.8135}T^{0.1865} \quad [4]$$

in which the constant 'k' is obtained by

$$k = 0.1624\frac{d_a}{d_p} \quad [5]$$

Equation [4] should then be used to determine the amount of scaling in the inaccessible areas. In the event that the actual amount of scaling is negative (i.e. where the as-mined roadways are wider than the current), or where none of the old workings are accessible at the time of the evaluation, Equation [3] should be used as is. Note that this not an uncommon situation and that there are several reasons why pillars can appear to have grown wider over time. Over-measurement at the time of mining is one reason, or errors may have occurred during the process of digitization of the old mine plans. In those situations, the as-mined dimensions are meaningless.

The pillar width, w, is then simply

$$w = C - (B + d_p) \quad [6]$$

where C is the pillar centre distance and B is the as-mined bord width.

Determining input into numerical model

The preferred model for this analysis is the public domain code LaModel, developed by NIOSH in the USA[3]. The reasons are that the code has been proven for this type of analysis, and is available free.

Care should be taken when selecting constitutive models for the elements making up the LaModel grid.

Non-yielding elements

For interpanel pillars and large solid areas, the linear elastic model should be used. The only characteristics required for this model are the modulus of elasticity (4 GPa for coal) and the Poisson's ratio (0.25).

Potentially yielding elements

For all other pillars, the strain softening model should be used. This requires five characteristics, namely the peak stress, peak strain, residual stress, residual strain (see Figure 1) and Poisson's ratio.

A separate set of characteristics has to be derived for each size of pillar in the area to be modelled. Even if the pillar widths are the same, pillars of different height will require unique characteristics.

Peak stress and strain

The peak stress of a pillar is calculated using the linear formula for pillar strength[1]:

$$\sigma_p = 3.5\frac{w}{h} \quad [7]$$

The linear formula is preferred for this type of analysis as it predicts lower strength for smaller pillars than the Salamon and Munro power formula[4] and is thus a more conservative approach.

Note that if element sizes less than 3 m are used, the peak stress should be adjusted as described later.

The peak strain is derived from fundamentals:

$$\varepsilon_p = \frac{\sigma_p}{E} \quad [8]$$

where E is the modulus of elasticity of coal, 4 GPa.

Residual stress and strain

The residual stress is the stress that the pillar will continue to bear after complete failure, i.e. that stress at which strain will continue to increase without any additional stress. This is not a known characteristic of coal, but in terms of the model the magnitude is not important. Selecting a residual stress, σ_r, of 0.1 MPa serves the purpose of the model.

The residual strain, however, is important because the slope of the post-failure load line (see Figure 1) determines the amount of resistance the pillars will offer once the pillar has been driven beyond failure. At failure, a pillar does not lose all load-bearing capacity totally and immediately, and

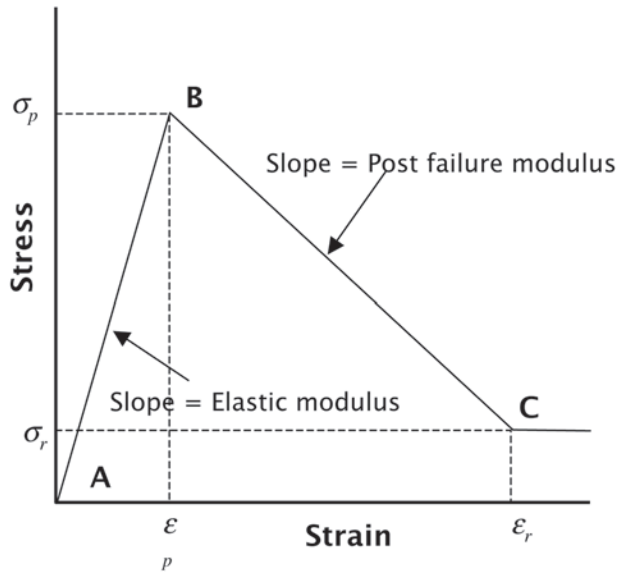

Figure 1—Stress-strain curve demonstrating the fundamental behaviour of the LaModel strain-softening constitutive model

the resistance it offers to continuing convergence has important bearing on the amount of load that is transferred to surrounding pillars.

The slope of the post-failure load line (i.e. the post-failure is modulus E_{pf}) is a function of the width-to-height ratio of the pillar. According to van der Merwe and Madden[5] it is given by

$$E_{pf} = \frac{0.562w}{h} - 2.293 \text{ GPa} \qquad [9]$$

The residual strain (see Figure 1), ε_r, is then simply

$$\varepsilon_r = \varepsilon_p + \frac{\sigma_p - \sigma_r}{E_{pf}} \qquad [10]$$

Poisson's ratio

For coal, use a Poisson's ratio of 0.25.

Selection of area and element size

The area to be modelled should be large enough for the area of interest not to be affected by edge effects of the model. The edge effects are typically constrained to around 20 elements, therefore the area should be sufficiently large to allow a margin of 20 elements around the edges.

The element size is a function of the accuracy of the model required and the size of the area to be modelled. LaModel is claimed to accommodate a maximum grid size of 1 000 by 1 000 elements, although instability has been noticed when the maximum number of elements is used. It is safer to restrict the grid to 990 by 990 elements.

When using very small elements, less than 0.5 m, it has been seen that the LaModel pillar stresses tend to be substantially less than the tributary area load, even at infinitely wide panel spans. Elements larger than 0.5 m should thus be used.

It should also be realized that the procedure described earlier allocates the average pillar stress at failure to all the individual elements making up a pillar. What this means is that when a pillar is loaded to close to the average failure load, the elements at the edge will be subjected to higher loads than those at the centre and they could then yield, resulting in higher loads on the adjacent elements, until eventually the pillar fails. This may happen even if the average pillar load is less than the failure load of the pillar.

It is thus necessary to increase the peak stress of the element as obtained with Equation [7] to that value which corresponds to the maximum stress on the edge elements when the average pillar load equals the failure load as obtained with Equation [7]. The fewer elements that are used to simulate a pillar and the larger the elements, the less marked this effect becomes. In practice, for most shallow bord and pillar coal mining situations, it has been found that at an element size of 3 m, the peak stress should be increased by 3.5%, while it should be increased by 18% if 1 m elements are used.

The greater the number of elements, especially when some are stressed beyond the peak stress and yielding occurs, the longer the run times. Read together with the remarks in the previous paragraph, the practical solution is to use the largest element size that will still result in an acceptable simulation of the mining layout.

This becomes difficult in situations where there is considerable variation in pillar sizes in a panel, but then again stooping a panel with greatly varying pillar sizes should be approached with great caution.

It may sometimes be necessary to do more than one simulation to determine the optimal element size and number of elements used. While this is time-consuming, the rewards in terms of safety and revenue obtained from stooping far outweigh the additional effort required. From a practical perspective, it is useful to do a first round simulation with large elements to determine trends, and then to refine the model with smaller elements for the final simulations.

The temptation to reduce the run times by relaxing the accuracy of the solution should be avoided. It is better to increase the maximum number of iterations allowed and be patient if the program is slow in converging to a solution.

Stooping should be simulated using mining steps, removing a line of pillars per step.

Determining the critical panel span

One of the problems sometimes encountered at shallow depth is that the panel spans are not sufficient to allow the overburden to fail, and consequently a proper goaf does not develop. This results in high pillar loads being encountered. It is therefore necessary to determine whether the existing panel width is sufficient to allow overburden failure.

In order to do this, the thickness and positions of the different layers making up the overburden have to be known. It is often difficult to get reliable information in this regard, as this type of analysis is usually performed in the older parts of the mine where borehole information is scarce. The best available data has to be used, to be confirmed by drilling new holes, especially in cases where the existing panel width is close to the calculated critical width.

Each layer in the overburden has to be evaluated individually. From the fundamental equation describing the tensile stress that develops in a clamped beam, the span at which failure of the beam will occur is seen to be:

$$L = 1.555t\sqrt{\frac{\sigma_t + \sigma_H}{q}} \qquad [11]$$

where L = critical span
t = thickness of layer under consideration
σ_t = tensile strength of layer
σ_H = horizontal stress
q = distributed load on layer.

Note that a 10% safety margin has been included in Equation [11].

Determination of distributed load, q

In the case where the layer under consideration is overlain by a thicker layer, q is simply the unit weight of the layer itself, or

$$q = \rho g t \qquad [12]$$

In the case where the layer is overlain by a thinner layer, the distributed load is greater because the thinner layer will then be partially supported by the thicker layer. Bearing in mind that the modulus of elasticity and density of sedimentary rock types are largely similar, the equation to determine the additional load for a composite layer where the bottom layer is partially loaded by the upper one can be simplified to:

$$\gamma = \left[\rho g t_b^2 \frac{t_b + t_u}{t_b^3 + t_u^3}\right] t_b \qquad [13]$$

where the subscripts u and b refer to the upper and bottom layers respectively.

Depending on whether the layer immediately above is thicker or thinner than the one underneath, Equation [12] or [13] is then used to determine the value of q to be used in Equation [11].

Note that at least some judgement is required for this part of the analysis. If successive layers are cemented, or if the transition is gradual (i.e. in the absence of a sharp contact), then the layers should be treated as a single one. Likewise, a succession of thin layers overlying a thicker one should also be treated as a single layer for the consideration of additional loading on the bottom layer.

In old areas, the core from the original boreholes will no longer be available for inspection, and a lot then depends on the description of the log.

Determination of horizontal stress, σ_H

If no horizontal stress measurement data is available, the horizontal stress can be estimated from the vertical stress, using a k-factor of 2.0. Then,

$$\sigma_H = .05H \qquad [14]$$

where H is the depth to the middle of the layer.

Determination of tensile strength, σ_t

The laboratory tensile strength of most sedimentary rock types is in the range 5 MPa to 8 MPa, which has to be downgraded to allow for discontinuities on the macro scale. In general, using 2 MPa yields reasonable results, although cases have been encountered where back analysis indicated it to be closer to the laboratory value of 8 MPa.

If there are cases where the overburden has failed in the vicinity of the area under investigation, the best results are obtained by performing back analysis, as follows:

- Assume a tensile strength of 5 MPa
- Perform the critical span calculations using Equations [11] to [14] for each layer in the sequence
- Select the layer with the largest critical span – that is, the layer least likely to fail
- Then calculate the tensile stress generated in that beam using the actual span at which failure occurred (L_a) with

$$\sigma_t = \frac{qL_a^2}{2t^2} - \sigma_H \qquad [15]$$

Note that the tensile strength obtained with Equation [15] does not incorporate an adjustment and should thus be used as obtained when used as input in Equation [11], where the necessary adjustment is made to determine critical spans for the different strata layers.

Implications of the critical span

If the panel is narrower than the critical span, then the overburden will not fail and the pillar stresses determined with LaModel will be at the maximum level for the entire length of the panel. If, however, the panel span is greater than the critical span, then the results obtained using LaModel will be valid only up until the point where the face advance is equal to the critical span.

In the latter case, if pillar yielding is not predicted with LaModel at the stage when the face advance equals 1.2 times the critical span, then it will not occur as the pillar stresses will be reduced the moment the overburden fails.

Interpretation of LaModel results

Using LaModel's post-processor, LamPlt, there are two ways in which to judge whether pillars have failed or not. Firstly, if the pillar stresses are at the value stipulated as the residual stress, failure is likely to have occurred.

The other quick method is to view the convergence. If it is not possible to distinguish individual pillars, then failure has occurred. See Figures 2 to 5 for the convergence and stress views of examples of intact and failed pillars.

Even if the pillars are indicated as stable, it is important to know whether or not they are close to the point of failure. For this evaluation, the concept of the Extraction safety factor, ESF, should be used[6]. The ESF is the safety factor calculated as the ratio between pillar strength and pillar load during the process of secondary extraction, not the tributary area load.

The pillar strength is calculated using Equation [7] and the pillar load, σ_L, is determined from the LaModel output.

$$ESF = \frac{\sigma_p}{\sigma_L} \qquad [16]$$

As long as the ESF of the line of intact pillars closest to the stooped pillars remains at a level greater than 1.2 in the situation where the overburden does not fail, there is no cause for alarm as the pillars will be at that low level for only a short period of time.

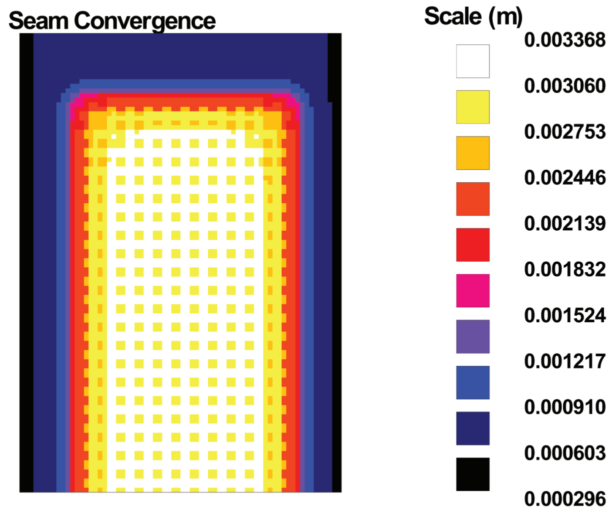

Figure 2—LaModel output diagram of convergence showing intact pillars—the individual pillars can still be clearly identified

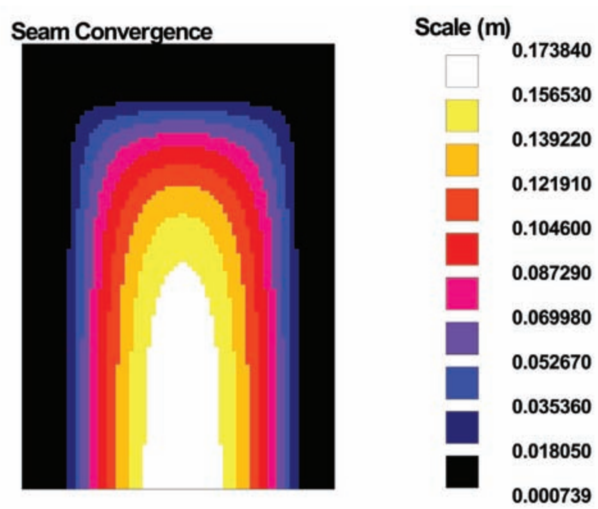

Figure 3—LaModel output diagram of convergence showing failed pillars—the individual pillars can no longer be identified. The difference is clear when this diagram is compared with Figure 2

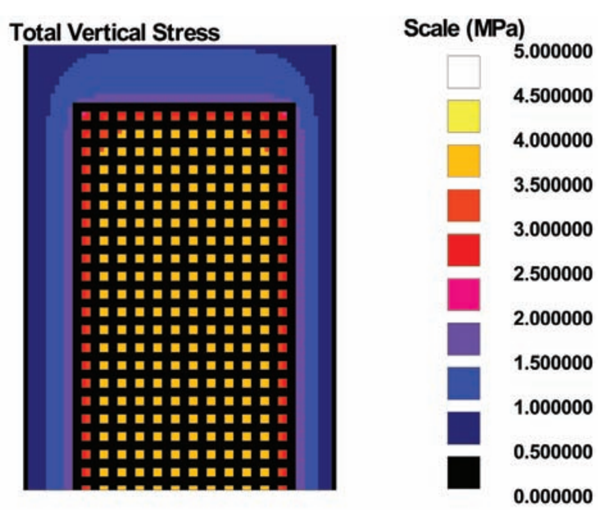

Figure 4—LaModel output diagram of vertical stress showing intact pillars—the individual pillars can still be clearly identified

The role of snooks

Pillars are very seldom extracted completely, and it is considered good practice to leave remnants or snooks of a predetermined size in predetermined positions. The NEVID system is one such method, but there are a number of others as well.

The common requirement for all these systems is that the snook sizes have to be such that they offer protection to working crews during the period when a pillar adjacent to them is in the process of being extracted, but that they have to fail very soon afterward.

When the modelling is done, it is important that the snooks are also modelled as part of the layout. It is to be expected that various configurations will have to be tested before the optimal situation is reached. Figure 6 is an example of a LaModel output page showing snooks that display the desired behaviour.

Evaluation of likely success

Supercritical panel width

In the case of a supercritical panel, there will be stress increase on the pillars in the front lineup until the stage when the critical span is reached and the overburden fails. If, at that stage, the LaModel results do not indicate failure of the pillars, and if the ESF remains above a value of 0.9, it can be expected that stooping can be done safely and that the next step, underground inspection, can be taken.

If, however, pillar failure is indicated or the ESF drops to a value less than 0.9 before the critical span is reached, then stooping has to be approached with caution.

Other options will then have to be considered, such as leaving lines of pillars intact at the stage before the ESF drops to below 0.9. LaModel should then be used to determine how many lines of pillars have to be left *in situ*.

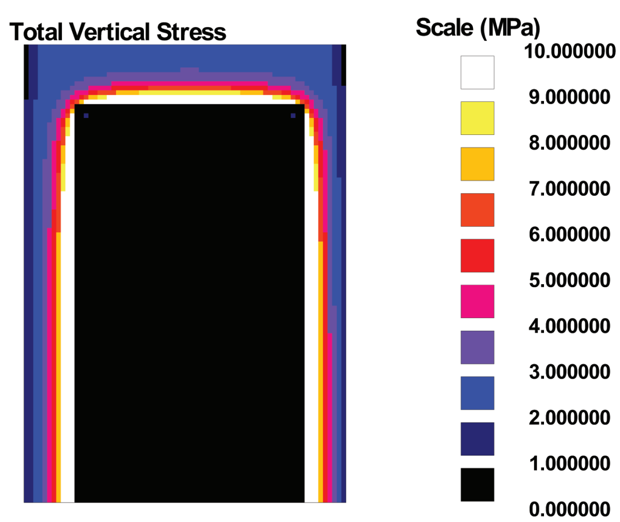

Figure 5—LaModel output diagram of total stress showing failed pillars—the individual pillars can no longer be identified. The difference is clear when this diagram is compared with Figure 4

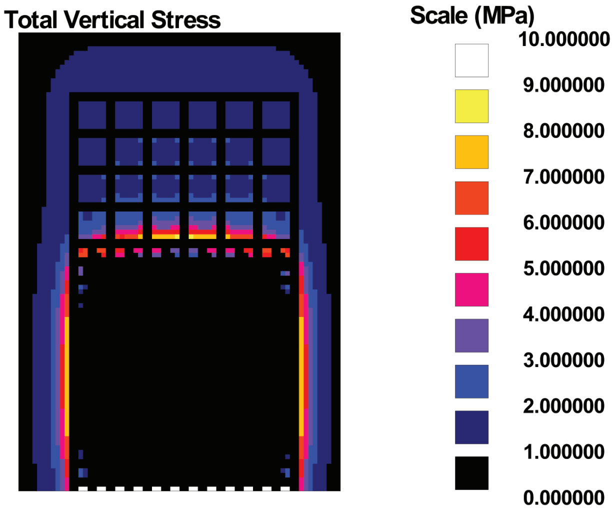

Figure 6—LaModel output diagram of vertical stress showing the desired outcome of a stooping layout. The large, unstooped pillars as well as the small snooks closest to the unstooped pillars, are intact while the snooks further away from the intact pillars have clearly failed

This option is not without disadvantages. Firstly, the possibility of overburden failure at a later stage cannot be discounted. Even though personnel will then probably not be affected directly by the collapse, as pillar stresses will then be reduced, the effects of the resultant wind blast can be serious.

Secondly, long-term surface stability is compromised in the sense that failure can still be expected at any time in the future. However, this disadvantage is also possible if no stooping is done, depending on the size of pillars.

Sub-critical panel width

Where the panel width is less than the critical width to ensure overburden failure, the stress on the pillars will increase and remain at the maximum level, which is reached when the face advance equals 1.2 times the panel width, for the duration of stooping in that panel.

If pillar failure is not indicated at that maximum stress level, and if the ESF remains greater than 1.2, then stooping is possible. If pillar failure is indicated, then alternatives such as leaving lines of pillars *in situ* before the pillars are expected to fail can be considered. LaModel should be used to determine the positions of those lines of intact pillars and also the number of lines that should be left *in situ*.

The remarks made with regard to the possibility of later overburden failure made in the previous section are applicable in this case as well.

Conclusions

There is no reason to discount the secondary mining of old, small pillars purely because they were not intended to be stooped at the time of mining. In several cases, those pillars have high safety factors and in any event, the static safety factor, as determined with the tributary area theory loading assumption, is not a reliable predictor of the likely success of stooping on its own. The concept of the extraction safety factor, using the increased pillar loads during the process of stooping, should be used instead.

The main factors that mitigate against stooping old pillars, especially at shallow depth, are that the pillars, having scaled over time, are now smaller than at the time of development and that due to the lower load on the overburden, the goaf sometimes does not develop. This results in higher pillar loads and raises the possibility of wind blasts during mining if the overburden fails suddenly.

Technology exists to evaluate these factors and to determine the likely success of a stooping operation.

The current pillar sizes can be estimated, critical spans for overburden failure can be calculated, and these can be used in numerical models to estimate the pillar loads during stooping. The numerical models can also be used to determine where and how many lines of pillars should be left intact, should that option be considered.

The methodology described in this paper is only a first step to determine whether it is worthwhile to even consider stooping. If the outcome of the evaluation is positive, the next step should be detailed underground inspection.

Acknowledgements

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