1. INTRODUCTION

With more than a decade of use, the scaled span method of analysis of surface crown pillars for active and abandoned mines has had wide application in many different mining environments. Some limitations of its applicability have however been noted with respect to the analysis of surface crowns over shallow dipping stopes. It has long been recognized that the database from which the original scaled span relationship was developed, was largely derived from steeply dipping stopes, (in fact, as indicated by Alcott, 2001, >90% of the cases were for dips, \( \theta > 40^\circ \)).

This essentially meant that the crown pillar database was very non-representative of shallow stoping geometries. Further, it had been clearly established that stability for the steep cases was largely controlled by ore zone or margin ravelling, or by shear on weakness planes at the hangingwall and footwall ore/reef zone contacts. By contrast; for the shallower cases it is evident that failure tends to be more controlled by hangingwall breakthrough, (Figure 1).

This non-representativeness of the original crown pillar database for assessing shallow dipping crowns has been previously examined by Alcott, 2001 and by others as a major limitation for use of the method for shallow cases, necessitating formulation of local site specific guidelines for addressing these shallow geometry situations. To date, however, the mechanistic differences between the two geometry extremes has not been examined in any detail. In this paper, therefore, as a basis for extending the applicability of the scaled span method to...
shallower dipping situations, a review of analysis methods commonly employed for design of flat and low dip workings has been carried out, and the original crown pillar database has been extended by an additional 114 cases, mainly from shallow dipping situations, including twenty one additional failure cases, (Figure 2).

2. SHALLOW STOPE ANALYSIS METHODS

For shallow seam or reef mining, typical methods of analysis differ significantly from the analytical and modelling assessment approaches typically used for steeply dipping workings, for which the original scaled span approach was first developed (Golder Associates, 1990, Carter, 1992). In design of flat-lying excavations in hard and soft rock conditions the traditional focus has been to concentrate on maintaining pillar stability and competence (Figure 3). Analyses have been directed more toward examination of extraction ratios, rather than to assessment of the stability of the back spans between pillars.

2.1. Pillar Assessment Methods

As failure of individual pillars oftentimes has lead to domino collapse of entire working levels, many major disasters have occurred over the years. In consequence, several well known empirical pillar design formulations have been developed in attempts to incorporate this adverse experience for allowing improved and safer designs. Arguably, the best known of these methods are those by Salamon and Munro, 1967 for coal, and by Hedley and Grant, 1972 for hard rock respectively. Both of these approaches, which are based on tributary area approximations for pillar loads and on empirical factors to define pillar strength, have had wide application in the industry. In recent years, data collected by Hudyma et al., 1994 have been incorporated together with the original Hedley and Grant, 1972 data, as a basis for formulating an improved design graph for pillar dimensioning for hard rock mining situations, (Figure 4). These empirical formulations are useful also for pillar strength estimates for application of displacement discontinuity numerical methods (eg., Nfold, Mintab etc). In combination, a wide range of mining geometries can therefore be examined, not just room and pillar layouts, but also sills and strike pillars, as well as chain and barrier pillars for longwall operations.

2.2. Extraction Influence Assessment

Because of the fact that most recent era high production coal mining is by virtually total seam extraction longwall methods, surface instability analysis has tended to become associated more with

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**Figure 2: Updated Crown Pillar Database, plotted as thickness to span ratio vs. ore/reef dip (422 Cases from 108 Mines, including 58 Failures)**

**Figure 3: Characteristic Hourglass Effect from Pillar Overstressing**

**Figure 4: Graph of Hedley and Hudyma Data for Hard Rock Pillars**
prediction of regional subsidence and surface strain effects than with the vagaries of definition of the initial likelihood of surface impact. As a consequence, numerous methods exist in the literature for definition of subsidence trough profiles, almost all of which are empirically based, and many are graphical (such as the NCB method, 1975, 1980). With the emphasis towards greater mechanized extraction in modern coal mining, only limited attention has recently been paid to room and pillar operations. Even with the need for better hazard assessments for closure studies, little new work has been done on improving analysis methods for assessing the likelihood of specific surface crown breakthroughs above over-excavated rooms or intersections. This is despite the fact that such cave-ins were a frequent occurrence in bygone years and are thought by many to have been key factors in the initiation of many of the larger domino style collapses.

Although limited analytical attention has been given to this issue, numerous rules of thumb exist for estimating the influence heights of such cave-ins. Bell et al., 1988, in reviewing causes of ground movements, suggested that ratios of 1.5 to 3 times the span of the mined opening are commonplace for cave heights, Piggot and Eynon, 1978 in their landmark work (ref. Figure 5) suggest maximum crowning heights of up to 10 times seam thickness; a value supported by the work of Whittaker and Breeds, 1977; and Garrard and Taylor, 1988. Detailed examinations by Madden and Hardman, 1992, of caving problems in South African coal mines has lead to development of a useful relationship between seam thickness and the height of caving over an intersection, consistent with the ratio of $2\frac{1}{2}$-3 times drift span width, viz:

$$t = \frac{4}{(k-1)} \pi d^2 \left[2h^2 \cot \phi + hB^2 \right]$$

where $k$ = bulking factor (1.5),

$d$ = the maximum span of the intersection (ie., $\sqrt{2B}$ where $B$ is the drift span),

$h$ = height(m) of extraction, (seam thickness),

$\phi$ = angle of repose of broken roof rock (35°), and

$B$ = bord (drift) width (m).

3. SCALED SPAN EXTRAPOLATION

As is evident, none of these approaches lends itself directly for extending applicability of the scaled span method.

Currently, though provided that controlling hangingwall rockmass characteristics, rather than seam characteristics are utilized for analysis, the scaled span approach can reasonably be used to examine crown stability on a single room basis, such as illustrated in Figure 1. The definition of the geometry of the crown for anything larger or non-flat, would however not be correct, as collapse in this sort of situation requires breaking across the hangingwall strata in order for caving to progress.

3.1. Coal Mining Analogies

Experience from examination of coal mine collapses suggests that the magnitude of subsidence-induced settlements and the extent and width of the surface expression zone is governed by the competence and rock structure of the overlying strata. Any impact of the mining is reflected through to surface only once controlling spans of the underground extraction reach some critical dimension. In Figure 6, the various stages of reaching this critical influence depth are defined. Critical subsidence is inferred to occur when the defined caving line, (which is a function of the competence of the mined roof and overlying strata) intersects with the ground surface. For sub-critical situations, such as indicated by the dotted line...
designated Case 1, low or minimal impact is seen on the surface from the mining operation at depth. For Case 2, where the cave lines just intersect the surface, in weaker rocks where high extraction has been undertaken, a distinct subsidence profile will be recorded. For hard rock covers, even at this stage minimal surface disturbance might occur. For Case 3, where a wide zone of the surface is encompassed within the cave lines, a broad band of trough subsidence occurs in weak rocks, resulting in deformation of the entire surface zone. Again, depending on conditions, in some hard rock situations, even in such cases, minimal or no surface disruption may occur.

Whether or not there is surface impact in a hard rock situation depends not only on the roof and overburden strata conditions, but whether stresses imposed on the pillars within the mined seams have reached critical values. If pillar geometry is poor (ref. Figure 3) or if pillar strengths have been exceeded, damaging pillar bursts can occur, sometimes allowing progressive domino collapse to develop, thereby leading to similar surface subsidence effects to those seen in weak rock situations, (Figure 7).

Because there has been a wealth of experience accumulated over the hundred or so years of documented European mining subsidence studies, considerable relevant information exists on subsidence effects progressing up through all types of coal mine roof rocks. Data is available from coalfields with roof rocks varying in competence from low strength Carboniferous to Triassic degradable shale sequences in many of the western European and Central US areas to relatively high strength sandstones, limestones and igneous suites in some of the South African, Canadian and Eastern European settings.

3.2. Subsidence Prediction

As with pillar and cave height assessment, there are also numerous empirical and semi-empirical approaches for estimating the extent of subsidence over total extraction zones. Few however take account of any controlling crown span developing within competent overlying strata – a commonplace situation in hard rock. This problem is analogous to dealing with inadequate caving, due to development of a stable “hang-up” in a block caving operation.

Direct relevant experience, however, exists from the Eastern Transvaal coalfield of the effects of having a competent unit overlying the coal workings (Figure 8). Here a thick dolerite sill exists within the roof zone. This restricts caving, by allowing quite wide spans to develop within the hangingwall and gob area of the longwall workings before surface breakthrough occurs. Van der Merwe (1992), based on this experience for longwall extraction, proposed the following inter-relationship between maximum subsidence and mining seam height:

\[ S_m/h = 0.39(W/H)^{0.32} \]

where \( S_m \) = maximum subsidence, and
\( h \) = mining seam height; (for a range of seam thickness from 0.5 – 2.5m), and
\( W/H \) = ratio of longwall panel width to mining depth (for a range from 1 to 3.5)

…with the critical span of the longwall panel, at which first signs of surface impact were noted, being estimated from the following semi-empirical equation….

\[ W_c = \sqrt{3.25td[1-(d-t)/2] + 2p\tan\xi} \]

where \( t \) = thickness of competent (unweathered rock sill) overlying the coal measure rocks,
\( d \) = depth below ground to the base of this competent “sill” unit,
\( p \) = thickness of “delaminating” strata between the competent “sill” and the top of the coal seam and \( \xi \) = goaf angle (ie., angle of caving, see Figure 8).
Whilst the Van de Merwe equation can be used to provide a reasonable first estimate of $W_c$, the mining extent feasible before onset of trough subsidence, the equation is really only applicable for the defined conditions (including shallow $<15^\circ$ to flat-lying strata) for which it was developed.

3.3. Inclined Seam Complications

As can be observed from Figure 9, because of geometrical effects, estimation of the extent of subsidence influence is more problematic for inclined seams. Prediction of the depth of critical influence also becomes more difficult than with flat seams. This is mainly because, with greater obliquity, the extent and shape of the subsidence influence zone becomes more asymmetric, with the zone of maximum subsidence deepening, but also moving off-centre relative to the location of the underground extraction zone. This complicates definition of the positions of the areas of maximum strain, which correspond to the points of greatest inflexion and curvature of the subsidence profile.

Analytically establishing the entire subsidence extent (broadly encompassed between the up-dip and down-dip influence angles $\psi_L$ and $\psi_H$ as shown on Figure 9) and predicting the width of the zone of observable surface disruption, (between the two zones of maximum inflexion, defined as occurring at points $X_1$ and $X_2$ on Figure 10), is complex. It depends not only on the geometry of the mined seam, but also on the competence and character of the hangingwall rockmass. As a result, a wide variety of semi-empirical techniques, many of which are graphical, have been developed for predicting site specific subsidence profiles.

For the purposes of efficiently distilling this wealth of empirical experience into the scaled span methodology, it is expedient to make use of one of the more conveniently formulated analytical subsidence profile expressions – the Russian Profile-Curve Method, (Kratsch, 1983). As defined in the sketch diagrams in Figures 9 and 10, this approach, which was developed based on experience from the Donetz Basin Coalfields, lends itself to ready spreadsheet computation. As outlined below, for generating the subsidence profile geometry, the governing expression utilizes a basic sinusoidal realationship over the half width, $L$, as defined in Figure 10. A similar cosine formulation is used for the displacement estimates, with the maximum displacement value $v_1$ based on an empirical relationship to fit results from modelling studies of trough subsidence:

**Subsidence**, $v_z = v_{z \text{ max}} \left[ 1 - \frac{x}{L} + \frac{1}{2\pi} \sin \left( \frac{2\pi x}{L} \right) \right]$

with $v_{z \text{ max}} = a M \cos \theta \sqrt{n_1 n_2}$, and

**Displacement**, $v_s = 0.2 v_{x \text{ max}} \left[ 1 - \cos \left( \frac{2\pi x}{L} \right) \right]$

with $v_{x \text{ max}} = 0.346 a M \tan(90 - \psi_L)$

where $a$, the seam closure constant, which varies from 0.3 to 0.9, depends on bulking of the roof rock and the extraction ratio of the original mining, and

$$n_1 = 0.9 \frac{1_s}{H_m} \quad \text{and} \quad n_2 = 0.9 \frac{1_d}{H_m}$$

with $l_s$ and $l_d$ respectively defining the plan geometry of the mined panel (Figure 9), with all other parameters as defined in the figure.

Definition of the central, most disturbed zone, that may develop as a true breakthrough, analogous to the zone of interest from the viewpoint of the scaled span analogy is not evaluated explicitly in the above
expressions. Its lateral extent must, however, also be predictable if these seam mining analysis methods are to be of value as a means for improving the scaled span approach.

3.4. Cave and Break-Line Definition

Key to defining the extent of the zone of probable caving is establishing appropriate and realistic break and cave angles, $\beta$ and $\xi$ respectively. This is also key to being able to define the critical influence depth, using the criteria previously illustrated on Figure 6. Defining an appropriate break angle is, however, not trivial, as it depends not only on the mining geometry but also is dependent on the rockmass characteristics of the hangingwall.

While it is clear that shear deformation is the mechanism governing the magnitude of the influence and break angles, it is evident that tensile rupture and arching effects play a significant role in governing cave angles. Longwall coal experience suggests goaf/gob cave angles to typically range in the 60° to 70° range, while block caving experience and information from silo analysis of drawpoint behaviour (Figure 11) suggests that cave angles can be quite variable as a function of block size. In readily cavable ground, cave angles are steep (often $\approx 70^\circ$) and muck flow is well represented by the ellipsoid of draw concept. In situations where cave hang-ups develop and a stable arch forms, such as shown in the lower right diagram on Figure 12, the cave geometry approximates a shallow voussoir arch with “effective” cave angles of 40° or less, matching approximately the arch thrust line.

Although accurate definition of the controlling cave angle for any given rockmass condition is obviously complex, in order to provide some reasonable approximation based on the available empirical data, it is convenient to consider the controlling stress conditions that develop as a result of seam extraction. At initiation of active shearing leading to development of the influence and break lines, and immediately prior to formation of the embryonic cave, stress conditions replicate an active/passive Rankine state. Thus, as a first approximation, it is possible for a flat seam to define the influence angles (which can be considered to represent active Rankine state shear surfaces) for a flat seam as $\psi = (45+\phi/2)^\circ$, modified as per the influence angle definition sketch included in the lower left corner of Figure 10 for dipping strata, viz:

$$\psi_{H \text{ and } L} = (45+\phi/2)\{1 \pm 0.32 \sin(20)\}$$

With these influence angles estimated for the mining seam dip and assuming some appropriate shear strength for the hangingwall rockmass, it then becomes possible to define the associated break angles, based on an empirical expression suggested by Jeremic, 1985, viz: $\tan \beta = \sqrt{2\pi \tan \psi}$

This expression, relating $\psi_L$ and $\psi_H$, the up-dip and down-dip-influence angles (which define the outermost zone of inferred shear motion) and the corresponding break angles, $\beta_L$ and $\beta_H$ (which delineate the limits, $X_1$ and $X_2$ of the zone of surface disruption if the subsidence geometry is super-critical), is based on analysis of precedent case data from longwall mining. As is evident from Figure 11, the break angles, which ultimately delimit the extent of surface caving/collapse, initially define likely positions of the two zones of maximum strain, where maximum surface curvature exists of the subsidence profile.

The two cave angles, $\xi_L$ and $\xi_H$, by analogy from the definition of the break angles and the Rankine stress state can then be defined as:

$$\xi_L \equiv \theta + \tan^{-1} \left[ \sqrt{2\pi \tan(45-\phi/2)} \right]$$

and

$$\xi_H \equiv \tan^{-1} \left[ \sqrt{2\pi \tan(45-\phi/2)} \right]$$

and the nadir angle, $\zeta$, that defines the offset of the focal point at surface relative to the centre of the extraction zone (ref. Figure 9 for definition), is, according to Kratsch, 1983, given by:

$$\zeta = 0.5(\psi_L - \psi_H)$$

With all these various angles estimated, the full subsidence profile can be defined if the geometry is super-critical. Whether or not the surface will be impacted, however, can also be readily determined by plotting the established cave lines as per Figure 11.
6, or utilizing one of the extraction influence height relationships presented earlier (eg., Piggot and Eynon, 1978). Thus, although the predicted zones of subsidence and influence are more disturbed and of wider extent in weak rock situations than in hard rock cases, because the mechanisms of failure and the method of defining the cave zone seems reasonably valid for both hard and weak rock situations, there appears to be merit in utilizing these geometrical relationships as a means to improve current scaling of crown spans for shallow dipping stope situations.

3.5. Effective Controlling Span Concept
In the light of the previous discussion and the illustration on Figures 10 and 12 of the geometry of the zones of active caving, examination of Figure 8 now provides an avenue for developing an appropriate modification to the normal definition of the controlling span for use in the crown pillar scaling relationship, viz:

\[
C_S = S \left\{ \frac{\gamma}{t(1 + S_R)(1 - 0.4\cos(\theta))} \right\}^{0.5}
\]

where:
- \(C_S\) = scaled crown span, (m)
- \(S\) = mined crown pillar span (m)
- \(\gamma\) = specific gravity of the rock mass
- \(t\) = thickness of crown pillar (m)
- \(S_R\) = span ratio = \(S / L\) (crown pillar span / crown pillar strike length), and
- \(\theta\) = dip of mined seam (degrees)

For analyzing shallow dipping stopes, it has previously been recommended to use the hangingwall length as the controlling mined span, \(S\) in the above expression. The analogies discussed above however, suggest that this assumption is over-conservative. Rather, it is proposed that the cave-line defined span width of the horizontal projection of the hangingwall length, be used as per the diagram in Figure 8. This can be taken up to some clearly defined, more competent stratal boundary, as per the illustration in Figure 8. This however, requires calculation of both upper and lower limit cave and break angles. Alternatively, and more conservatively, it can be taken as the horizontal span at the crown elevation of the stope, thereby necessitating calculation of the reduction in span length defined only by the lower cave-line.

4. EVALUATION OF CASE RECORDS
In order to verify the efficacy of the suggested refinement for determining the controlling crown span for incorporating within the \(C_S\) scaling relationship, the entire crown pillar database has been updated with over 100 additional shallow dipping examples, encompassing both hard rock cases and coal and soft rock examples. In order to acquire this extra data, specific searches for verification failure cases were made. Although extensive data regarding areal extent and trough profile depths was found, little factual data on initial collapse geometries, and timing to failure was located. Geometrical data on the limiting depth for critical breakthrough to first onset of surface deformation were also found to be sparse, although a considerable literature on mining-induced subsidence damage effects to surface infrastructure was identified (eg., Bell, 1992, Bell et al, 2002). Fortunately, the key relevant coal mine collapse data collected and synthesized by Salamon and Munro (1967) as a basis for development of their classic pillar formula is still available, tabulated in full in Madden and Hardman, 1992.

Some other relevant data on surface collapse influence from near-surface shallow dipping mining is also available from the work of Hall and Glynn, 1992, Bell et al, 2002; and Stacey and Bakker, 1992. This hard rock data for the gold reef mines in the Witwatersrand confirms earlier suggestions that in reality, as illustrated in Figure 12, rather than the smooth profile relationships previously discussed, actual subsidence effects are complex, very irregular and, in shallow dipping deposits in hard rock situations, principally related to wedge cantilevering of the hangingwall rockmass at the up-dip outcrop end of the mined zone. Based on data presented by these authors, disruption and severe surface damage appears to be restricted to a zone some 30-50m back from the outcrop of the mined slot, but tension cracks have been found extending back significantly greater distances.

![Figure 12: Tension Cracks and Cantilever Failure Effects (from Hall & Glynn, 1992)](image-url)
This type of cantilever failure behaviour, has been recognized on the margins of block caving and open pit operations, and as a result, the later stages of the mechanism of opening up of the further distance tension cracks (termed progressive hangingwall caving) has been looked at analytically as a means to determine the maximum extent of potential back-break, (Hoek, 1974 and Brown and Ferguson, 1979).

As background to the assessments included within this paper, an extension of this type of analysis was carried out to examine the potential for pillar crushing of a thin crown pillar remaining at the outcrop zone of the stope rather than the slot geometry shown on Figures 12 and 13. These assessments, which were carried out using limit equilibrium methods as well as with both PHASE² and UDEC, confirmed indications from the case records, that closure of the stope, and pillar damage (including punching up into weak hangingwalls) was more likely for flatter dips, while, with steeper dips, the stope tended to remain open without surface disruption of the hangingwall rock mass.

Assuming a worst case situation of throughgoing tension joints analogous to the geometry shown on Figures 12 and 13, loadings onto the crown pillar zone were found to be quite low (<3MPa for a 40° dipping stope geometry) assuming typical hard rock strengths equivalent to the quartzites of the S.African gold reef or the Elliot Lake mining area of Canada. The numerical analyses also suggested that crushing was unlikely. Rather, it was found that, because of stress concentrations acting onto within the crown pillar, an improvement in crown stability actually resulted, due to clamping effects.

Overall, the checks carried out of the over 100 shallow dipping workings incorporated into the updated crown pillar database (including more than a dozen shallow dipping failure cases), suggested that use of the cave angle concept as an indicator of the extent and geometry of probable hangingwall disruption, remains valid up to a mined seam (stope) dip angle within ±5 degrees of the inferred friction angle for the roof rockmass. Beyond this point, breakthrough of the hangingwall was found unlikely and sliding mechanisms within the mined reef/ore zone width and shear on the ore zone hangingwall and footwall contacts appear to dominate behaviour.

As this is the dip region for which the scaled span relationship was originally developed and for which, hitherto it was essentially most applicable, it is suggested that these refinements to the scaled span methods should not be applied for stopes steeper than about 45°.

5. REVISED SCALING APPROACH

As an illustration of the application of the suggested modification to the scaled span analysis approach, one of the shallow Sigma Mine stope discussed by Alcott, 2000 as not being adequately assessed by the existing methodology is re-analyzed using the revised crown scaling method. The actual mined stope geometry, which has stood for well over 80 years, is shown in Figure 14.
is plotted along with the suggested crown pillar thickness, \( t \), for use in analysis.

It is noteworthy that this horizontal projection of the hangingwall trace, and the cave-line together approximately delineate the boundaries of the zone of tensile relaxation predicted from detailed 2D PHASE\(^2\) analysis of such stope geometries (Figure 15). This lends further credence to the proposed graphical construction approach as a viable first order method for reasonably defining potential crown disruption influence over similar shallow dipping stopes.

Given this geometry, it is evident from the section plotted in Figure 14, that, because of the limited crown thickness, potential breakthrough to surface is possible if rock competence is poor. The convergence of the cave-lines however suggests that the geometry is only just super-critical (ref. Figure 6 for criteria).

Irrespective of the likelihood or not of possible surface impact, the first stage in assessing crown stability with the revised concept, is determining appropriate break and cave angles for the hangingwall rock mass, calculated, as follows:

\[
\beta_{\text{H}} = \tan^{-1}\left(\sqrt{2\pi \cdot \tan\left(\frac{45 + \phi}{2}\right)\left[1 - 0.32\sin(20)\right]}\right)
\]

and \( \xi_{\text{L}} = 0 + \tan^{-1}\left(\sqrt{2\pi \cdot \tan(45 - \phi/2)}\right) \)

This requires estimation of the instantaneous friction angle, \( \phi \) at an appropriate normal stress for the inferred break-line geometry. This can achieved by means of the following relationships, given an assessment of the hangingwall rockmass quality (in terms of RMR/GSI or Q) and the Hoek-Brown failure criterion parameters, (Hoek and Brown, 1980) viz:

\[
\phi = \arctan\left(\frac{1}{\sqrt{4h\cos^2\theta - 1}}\right)
\]

where; \( h = 1 + \frac{16(m\sigma_c + s\sigma_n)}{3m^2\sigma_c} \)

and, \( \theta = 1/3\left[90^\circ + \arctan\left(\frac{1}{\sqrt{h^2 - 1}}\right)\right] \)

where \( \sigma_c \) and \( m \) are respectively the uniaxial compressive strength and the Hoek-Brown material constant appropriate for the hangingwall rockmass, as estimated from Table 1

\[ m / m_i = \exp\left\{(\text{RMR} - 100)/28\right\} \]

\[ s = \exp\left\{(\text{RMR} - 100)/9\right\} \]

and \( \sigma_n \) is an estimate of the prevailing normal stress that would be acting across the break-line (this can be initially calculated using the vertical depth to the bottom of the stope and a typical minimum break-line angle of 60° ~ equivalent to the Rankine wedge failure angle 45° + φ/2), ie.,

\[ \sigma_n = \frac{\sqrt{3}}{2} \gamma H \]

Thus, with the dip angle of the stope, \( \theta \) known and the friction angle for the hangingwall rock mass defined from the above relationships, the break and cave angles for potential hangingwall failure.

For the stope geometry illustrated in Figure 14, with the appropriate properties for the hangingwall andesite rockmass i.e., UCS\( \geq 150\)MPa, \( m_i = 15 \), and rockmass quality, RMR=70, the calculations for the prescribed geometry (hangingwall dip length, \( L_h = 50\)m; stope and ore zone dip, \( \theta = 39^\circ \)) suggest a rockmass friction angle, \( \phi = 61^\circ \), and a break angle

\[
\text{Table 1: Typical Hoek-Brown m and UCS values}
\]
β_H = 72.5° and a cave angle ξ = 72°. From these data, and the geometry shown on Figure 14, the effective span is deduced as S_{Eff} = 28.6m, as compared with just over 50m for the hangingwall length.

Substituting this effective span value into the standard scaling expression along with appropriate crown thickness, t and stope strike length L_s values of 14.1m and 65m respectively, a revised scaled span, C_s value of 12.6 is calculated, compared with an original value of 19.8 computed using the hangingwall length.

The stability state of the stope can then be computed from:

\[ P_f = 1 - erf\left(\frac{2.9F_c - 1}{4}\right) \]

where \( P_f \) = Probability of failure
\( F_c \) = an approximate Factor of Safety = S/C_s, and
\( erf[ \] is the standard error function, as detailed in Carter, 2000

For this case the S/C_s ratio, (F_c) is deduced as 1.19, suggesting a probability of failure, P_f of 39%, based on a critical span estimate of S_c = 15m, using the hangingwall rock mass quality RMR=70, Q=18 in the critical span relationship, viz:

\[ S_c = 3.3 \times Q^{0.43} \times \sinh^{0.0016}(Q) \]

For correct use of the revised concept, it is critical to use the hangingwall rock mass Q/RMR values, not the ore zone characteristics. If, for example, these computations are made using the ore zone rock quality of Q=1.9, RMR=50, together with the previously calculated scaled span (C_s) value for the Hangingwall length, this would suggest S_c = 4.5m and an S_c/C_s, F_c. value of 0.2, indicating almost certain failure (P_f > 95%); values that are patently at variance with observed conditions.

The fact that many of these shallow dipping stopes have remained stable for decades (some for over 80 years) and that these revised scaled span calculations accord well with the mine-specific guideline of a minimum thickness to span ratio of 0.4 for marginal stability, based on mid-stope thickness (Alcott, 2001), provides some confidence for future use of this refinement to the scaled span method for assessing shallow dipping workings.

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