A New Approach to Surface Crown Pillar Design

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Abstract

Crown Pillar Design for most hard rock mines has in the past been arbitrary at best, purely based on precedent practise, and random at worst based simply on "leaving just one more round to surface". Logical methods of crown pillar dimensioning have long been based on Rules of Thumb. Theoretical advancements to improve on this simple design approach have met with little acceptance as the complexities of the geometry and geology of the rock masses comprising such crowns are difficult to categorize and simplify for analytical calculation or modelling purposes. A method of empirically assessing the stability and competence of surface crown pillars and of rock mass conditions above crown areas has therefore been developed based on assessment and back-analysis of over 200 case records of near-surface mine openings including 30 documented failure cases. The concept of a Critical Scaled Crown Span is introduced for sizing crown thicknesses over a given stope for a range of rock mass quality characteristics as defined by means of the NGI-Q or Geomechanics RMR classification systems.

1. Introduction

Designing for stability of surface crown pillars over mined openings involves not only an understanding of the rock mass characteristics of the ore zone and wall rocks in the vicinity of the crown, but an understanding of conditions in the near-surface weathered zone.

Detailed review of seventy mine case records encompassing over 200 thin or problematic crown pillar geometries, suggests that individual surface crown pillars fail by a wide variety of mechanisms, (Golder Associates, 1990). In blocky rock masses, failures can occur where the intersection of several adversely oriented discontinuities occur, or where a particular suite of major joints or faults provides a release mechanism for gravity collapse. Where rock quality is poor, and block size is small, failure can occur by ravelling and breakdown of the blocks comprising the crown and hangingwall. For a good quality rock mass, interlocking of blocks may create a stress arch thus improving the stability of the crown, while in cases where ubiquitous fabrics exist, uncontrollable slabbing and sloughing may lead to chimney-type failures. Often, not only is the structural fabric of the crown important, sidewall weaknesses may be critical.

2. Stability Assessment Approaches

Stability assessment for surface crown pillar design requires some evaluation of bedrock geometry and weathering effects. Traditionally, some cognizance of these effects has been incorporated into the classic *Rules of Thumb* for mining beneath crown pillars. Including empirical rules, three methods have in the past been applied to design new crown pillar layouts or evaluate the stability of old surface pillars, namely;

(i) **empirical methods** - using either *Rules of Thumb*, or more quantitatively, based on descriptive rock mass classifications,
(ii) **structural analysis and cavability assessments** .. and ...
(iii) **numerical modelling procedures.**

None of these procedures currently provides a fully adequate design approach, (Carter et al., 1990). In consequence, an attempt has been made to develop an empirical design method based on back-analysis of old failures and review of precedent experience.

3. Stability Graph Development

To embody traditional *Rule of Thumb* approaches to crown pillar dimensioning an initial design chart was prepared by plotting thickness to span, (T/S) ratios for stable and failure cases against rock quality assessed using both the Geomechanics Rock Mass Rating (Bieniawski, 1973) and NGI-Q values, (Barton, et al., 1974). The data, which are shown on Figure 1, divide reasonably well along the line:

$$T/S = 1.55\, Q^{-0.62}$$

Although this approach can be used for design, it must be appreciated that thickness to span ratios are not scale-independent, thus use of this approach as the sole basis for design, can be erroneous.

Geometrical Scaling Factors

Application of various methods of structural analysis (Bétournay, 1987), indicated that for any given rock quality, the stability of a specific crown depended principally on its geometry, In fact, from detailed evaluation it was found that the span, thickness and weight of the rock mass comprising the crown zone were the most critical characterizing parameters, (Golder Associates, 1990). Thus, by incorporating factors to account for a) the influence of foliation dip, and b) the effects of groundwater and clamping stresses, the following parameter grouping was formulated::

$$\textbf{Crown Stability} = f\,\frac{(T\sigma_h\Theta)}{SL\gamma u}$$

.. where *increased* stability for any rock mass quality would generally be reflected by an increase in ...

T, the crown pillar thickness
$\boldsymbol{\sigma_h}$, the horizontal in situ stress
and/or ..in **Θ**, the dip of the foliation or of the underlying stope walls

.. and where *decreased* stability would result from an increase in ...

S, the crown pillar span
L, the overall strike length of the crown
γ, the mass of the crown pillar
and/or ..in **u**, the groundwater pressure

In this expression *all* the parameters except σ_h and u are related solely with the geometry of the crown pillar. Thus, so that a crown geometry number could be developed that would be only geometry and weight dependent, these stress and groundwater terms are suggested to be included within the determination of rock mass quality. For current purposes this is expedient, as both the Geomechanics RMR and NGI-Q systems take into consideration the effects of in situ stresses and groundwater conditions. With refinement of the proposed empirical procedure, however, these factors may ultimately need to be considered separately and explicitly.

Crown Geometry Number

Rearranging the previous expression to reflect dependency solely on basic geometrical factors leads to an overall *Crown Geometry Number* expressed in terms of the following functional relationships; where each is given equal ranking; ie.,

$$C_g = f\,(F_{ST} \times F_{SR} \times F_W \div F_\Theta)$$

where

F_{ST}=span / thickness ratio = S/T
F_Θ =stope inclination factor
= $(1 - 0.4\cos\Theta)$
F_{SR}=span ratio factor = $\dfrac{S}{(1+S_R)}$
and F_W=weight factor = γ

By regrouping these parameters and noting firstly that the expression is of the same form as that for induced bending stress of a simply supported beam under self weight, and secondly that bending stresses

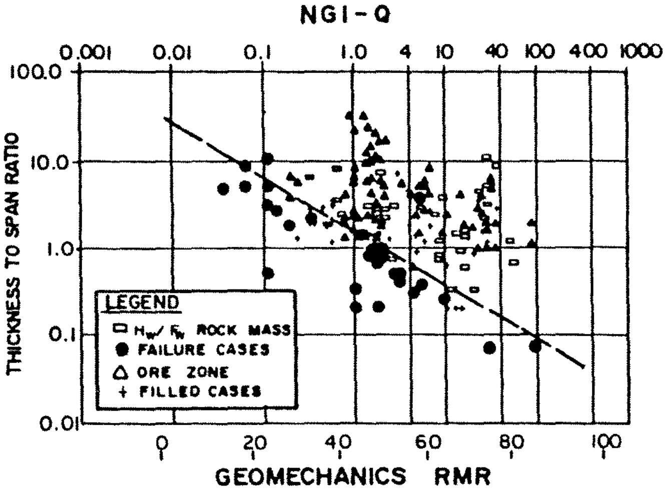

Figure 1 : Summary of Crown Pillar Case Records plotted as Thickness to Span Ratios versus Rock Mass Quality of Weakest Zone of Crown Geometry

scale approximately with the square of the span, a final empirical expression, (C_S) termed the *Scaled Crown Span* for a particular crown pillar was defined by taking the square root of C_g, ie.;

$$C_S = S\,[\gamma/(T\{1+S_R\}\{1-0.4\cos\Theta\})]^{0.5} \quad \text{(metres)}$$

where: S = crown pillar span (m)
γ = rock mass unit weight (T/m^3)
T = thickness of crown pillar (m)
Θ = orebody/foliation dip,
and S_R = span ratio
= S/L (crown pillar span ÷ crown pillar strike length)

It should be noted that the foliation dip expression reflects the span controlling hangingwall dip. Thus as the dip of the foliation and hence the stope sidewalls shallows from 90° to past 45° the effective span of the stope is no longer the ore zone width but rather the hangingwall length. Detailed discussion of the full development of this expression is beyond the scope of this current paper. For more complete information, the interested reader is referred to Carter et al. (1992) or to the original Golder Associates' (1990) report to Canmet.

Figure 2 has been prepared using the C_S scaling relationship by plotting all of the case records in the Golder-Canmet database against Rock Quality on an RMR/Q scale (where the two classification scales have been positioned relative to each other based on Bieniawski's widely published correlation relationship): $\mathbf{RMR = 9 \log_e Q + 44}$

If the straight line, power curve expression proposed by Barton in 1974 for defining the maximum span of unsupported openings (Critical Span = $2Q^{0.66}$) and the average power curve expression proposed by Carter, 1989 to fit the mean trend to the various civil engineering and deep stope classifications (Critical Span = $4.4Q^{0.32}$) are plotted on Figure 2

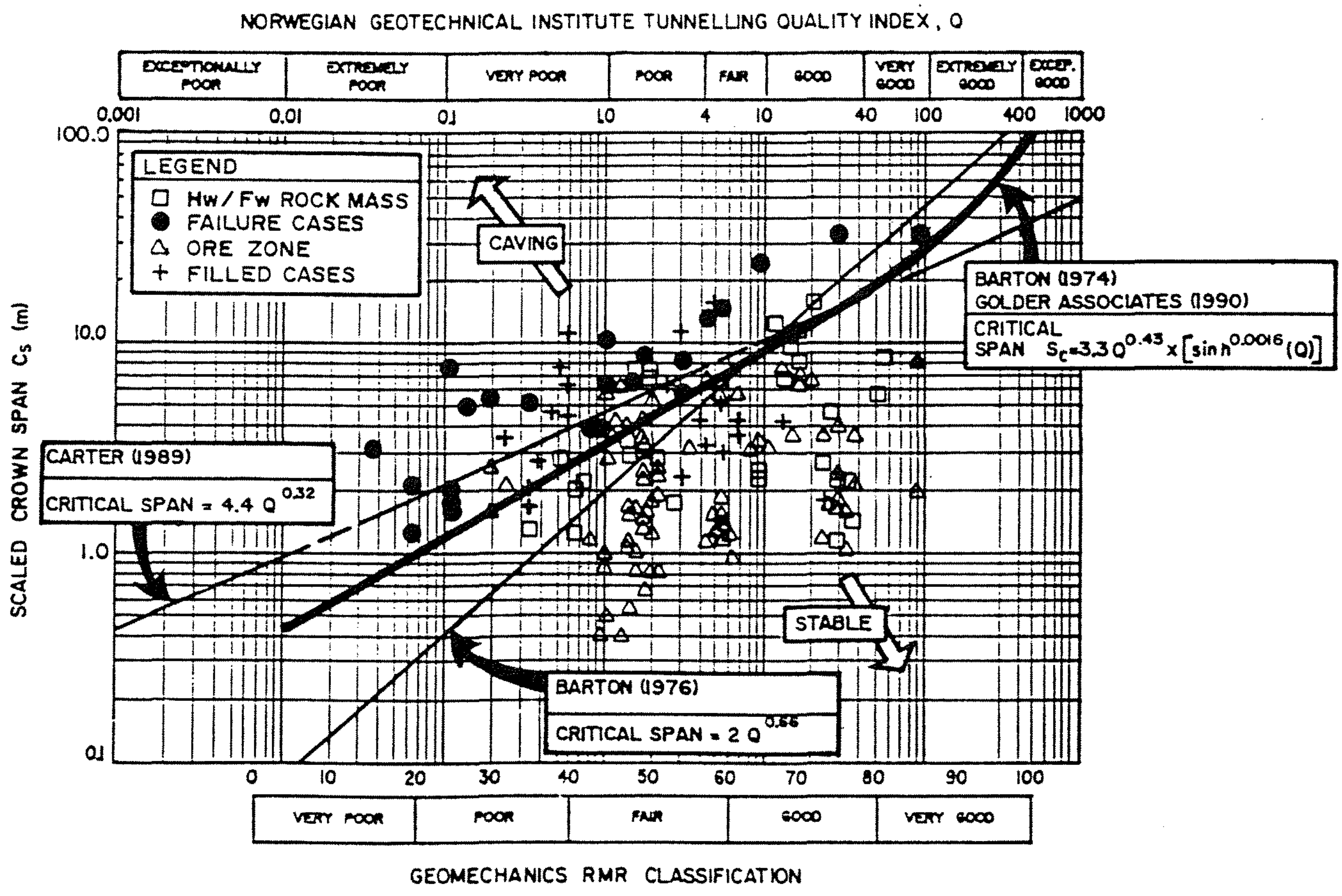

Figure 2 : Summary of Crown Pillar Case Records Plotted as Scaled Crown Spans versus Rock Mass Quality

neither adequately reflects the boundary between failed and stable cases. It is of interest to note, however, that when the original empirical "unsupported span" curve outlined by Barton, in 1974 is plotted, all the case records from the crown pillar database can be divided appropriately. In consequence, the following expression termed the *Critical Span*, S_C has been developed to match Barton's 1974 line:

$$S_C = 3.3Q^{0.43} \times [\sinh^{0.0016}(Q)] \quad \text{(metres)}$$

The hyperbolic sinh term in this expression is introduced to account for the non-linear trend to increasing stability at the very good quality end of the Q/RMR Scale as noted by Barton, 1974 (and as suggested by some of the data on Figure 2). With use of the *Scaled Crown Span*, C_S concept to scale different crown geometries for comparison with the *Critical Span*, S_C expression, a significant improvement can be made to the currently available *Rule of Thumb* approaches for determining safe spans and crown thicknesses.

4. Application to Existing Crowns

Figure 2 can be used as a basic deterministic analysis chart by simply calculating the scaled span of a given pillar, then, with the controlling rock mass quality defined, directly plotting a position on the chart. If the point falls well into the potential caving zone, defined as the area above the critical span line, unless the crown has sufficient support or fill has been used in mining, failure likelihood is high. Establishing an exact Factor of Safety, or Safety Margin, however, is not trivial. Nevertheless, this straightforward approach does allow ready comparison with precedent experience.

Probabilistic Considerations

Probabilistic methods which can take into account the uncertainties and heterogeneities of real rock masses can be used with advantage to improve understanding of the degree of stability. Convenient statistical packages such as the @RISK™ add-in to LOTUS 123™ allow multiple analyses to be readily undertaken with different assigned rock qualities, using Monte-Carlo or other types of simulation.

For most situations, the various controlling rock mass parameters are normally distributed, thus, based on visual review of histograms of RQD and other salient indices, the basic averaging process inherent in completing a full NGI-Q or Geomechanics RMR classification will provide sufficient guidance for defining representative pillar rock mass quality parameters. These can then be used to derive representative mean, $\bar{R}$ and variance, S^2 values for the pillar rock mass. Using these, the shape of the controlling normal distribution can be computed by direct application of the two point probability estimate approach of Rosenbleuth, 1975 along the lines outlined by Hoek, 1989.

For more rigorous evaluation though, core run data and field scan lines should be used to provide individual sample values for use with @RISK type simulations and these should then be normalized to define representative crown pillar characteristics. However, whether pillar variance is computed statistically based on extensive field data, or estimated from a series of independent rock mass classifications, provided that a *representative* distribution is generated, the percentage likelihood (ie. the probability) of crown pillar failure can be readily calculated using the scaled span concept.

The reliability of this type of assessment can be demonstrated by review of the classic collapse of the crown of part of the workings of the Huron Bay Copper Mines. Based on field examination of the geometry of the failed crown, (Carter, 1989), and evaluation of old records (Dekalb, 1900), for the pre-failure condition, an 80° foliation dip, an original crown thickness of 30 ft. (9.15 m), a span of 40 ft. (12.20 m) and a strike length of 300 ft. (91 m) is indicated. For this situation, assuming an average unit weight of 2.7 T/m^3 for the crown rock mass, a

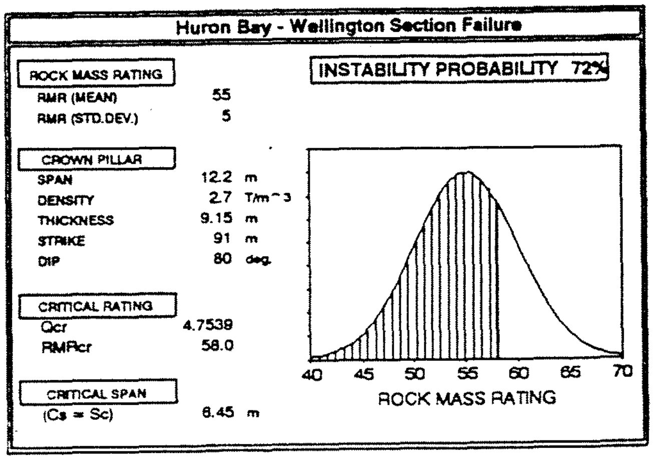

Figure 3 : Probabilistic Stability Assessment of Huron Bay Copper Mine Crown Pillar Failure Using Two-Point Estimate Method

scaled span, C_S of 6.45 m. is calculated. For this scaled span, based on the critical span equation, a critical (minimum) RMR value of 58 ($Q = 4.6$) is required for stability. Note: this critical rock quality can also be approximated for the linear portion of the critical span curve for values of RMR <80 using the following relationship:

$$\mathbf{RMR_{crit} = 21 \log_e S_c + 19}$$

Field inspection of the failure and evaluation of actual crown rock mass conditions indicates a mean RMR of 55 for the weakest section of the crown zone. Assuming this value (and incorporating a standard deviation of 5 based on assessment of available drill data for the area) the probability of failure is over 70% (as shown on Figure 3). This value has been determined directly from the estimated normal distribution curve for the crown rock mass for the as-mined geometry, using the two-point estimate approach, by computing the area under the curve for values less than RMR_{crit}.

5. Empirical Crown Dimensioning

The approach outlined above is addressed toward stability evaluation of *unsupported* crowns by reference to precedent experience. The concept of scaling a given crown geometry to a single equivalent scaled span can however, also be extended to allow estimates to be developed for minimum thickness stable crowns. Although, in doing this it should be appreciated that the critical span line merely reflects the boundary between stable and unstable crowns, (ie., it represents the Factor of Safety of Unity line).

For empirical design of crown geometries for both unsupported and supported openings an assessment is required of the limits of applicability of the approach. Specifically, assessment of precedent experience with supported openings is required as also is an appreciation of the range of safety factors inherent in the original case records. Together, this information can help in defining guidelines for assessing how much deviation from the critical span line is allowable for stability.

Unsupported Openings

For most of the stable case records, it is difficult to determine the precise level of stability of the various crowns. Frequently, there is insufficient information available to define an as-is Factor of Safety; some crowns may be close to marginal, but have not, as yet, failed; others may be totally safe. Fortunately there are half a dozen case records where direct comparisons have been possible between failed and stable crowns within the same area and rock mass.

Some insight has also been gained from review of various *Rules of Thumb* and commonplace design guidelines for instance, for defining the minimum separation between tunnels. Such tunnel layout guidelines suggest that interference effects occur where excavations are closer than two diameters while *Rules of Thumb* for hard rock crown pillar situations suggest that crown pillar thicknesses of the order of 1 to 2 blasts [ie., approximately 8-10 ft. (2.5-3 m) as a minimum] can be physically achieved and can remain stable for well over a Century. However, the fact that in some areas of largely unjointed, hard rock terrain, several surface crown pillars with thicknesses of less than 1ft.(0.3m) exist over stopes with spans in excess of 20ft.(6 m) is not, in itself, sufficient justification for accepting such thin pillar configurations as a standard for design.

Supported Openings

For supported openings the guidelines from basic civil structural analysis methods and from civil and mining engineering rock mass classifications merit consideration (eg. the Mathews method - Golder Associates, 1981, and Potvin et al., 1989; also the DRMS approach of Laubscher, 1984).

The influence on opening stability (and hence on required crown thickness) of the effect of adding support (in the form of bolts, cables, shotcrete, etc.), must also be carefully addressed if rational crown dimensioning is to be undertaken. This can be straightforwardly achieved if the influence of support is viewed, not as an integral component part of the engineered opening, but rather as an effective improvement in rock mass quality. If, based on Barton's 1989 guide for tunnelling support, it is required that a 2.5 m wide opening be excavated and supported in a very poor quality rock mass (with $Q = 0.1$, $RMR = 23$), then bolts and fibrecrete are recommended for support. As this same dimension span is suggested from Barton's data to be stable without any support in a rock mass with a Q rating of about 2, the application of the recommended support can be considered to effect an improvement in rock quality from $Q = 0.1$ to about 2. If this latter value is termed Q_S for the improved, supported condition, and this same approach is taken to examine all Barton's 1974 and 1989 support curves, these can be replotted as illustrated on Figure 4. This same methodology has then been applied to the support lines proposed for use with other classifications (eg., Laubscher, 1977, Bawden, 1988, and Potvin et al., 1989) in order to plot the other curves on Figure 4.

In this form, this chart can now also be used to provide some guidance for crown dimensioning above supported ground. In particular, the various support improvement lines can be used as a means for rationalizing the geometry of a specific crown pillar to account for the effect of installed ground support. This is of most importance at the low quality end of the rock mass spectrum, where crown dimensions can reach significant thicknesses based on thickness to span ratios for unsupported openings. Regression fits have therefore been computed for the linear sections of the tails of each of the various curves shown on Figure 4. These derived expressions are listed alongside the Figure.

For crown dimensioning purposes, two of the plotted curves are of most interest. Curve A, which essentially defines the limit of precedent experience based on Barton, 1989, marks the limit for very heavy support practise, thus it is obviously impracticable to achieve in most mining situations. Curve E, on the other hand plots the lower limit defined by Laubscher, 1977, for initiating patterned support in a mining environment. As this line plots at about the middle of the range for bolting for civil practise, the following trend line, assuming slightly more support effectiveness than the Laubscher line, is suggested for use for *minimum* crown thickness dimensioning purposes for supported ground:

$$Q_S = 4.5Q_U^{0.67}$$

This approach to assessing the effect of support on rock mass quality, then allows development of a broad ranging design chart for sizing crowns for supported openings.

6. Formulation of Design Chart

When precedent practise rules are incorporated with the scaled span curve from Figure 2, and the thickness to span relationship shown on Figure 1, empirical design guidelines can be drawn up for crown dimensioning for both unsupported and supported openings. Using the relationships presented previously, Figure 5 has been developed by plotting curves calculated for crowns of extended strike length (at least ten times span). The graph incorporates both a *scaled span axis*, for use with the critical span curve for stability evaluation purposes and a *crown thickness axis* for use with a set of design span curves for crown thickness dimensioning. Taking the right hand axis, which plots scaled span, C_S the stability of a proposed

	SUPPORT METHOD	Derived Relationship
A	Maximum Support Limit (Barton, 1974)	$Q_s = 150Q_U^{0.2}$
B	Concrete 0.3-0.5m Thick (Barton, 1989)	$Q_s = 40Q_U^{0.5}$
C	Cable Bolting @ 1 per m^2 density (Bawden,1988)	$Q_s = 20Q_U^{0.5}$
D	Fibre/Shotcrete and Bolts (Barton, 1989)	$Q_s = 8Q_U^{0.65}$
E	Mining Support Line (Laubscher,1977)	$Q_s = 2.5Q_U^{0.67}$
F	Patterned Resin Bolts @1.0m. Spacing (Barton, 1974,1989)	$Q_s = 5Q_U^{1.25}$
G	Patterned Mechanical Bolts @1.5m. spacing (Barton, 1974,1989)	$Q_s = 1.5Q_U^{1.25}$
H	Mining Limit for Cable Support (Potvin, 1989)	$Q_s = 12.5Q_U^{0.45}$

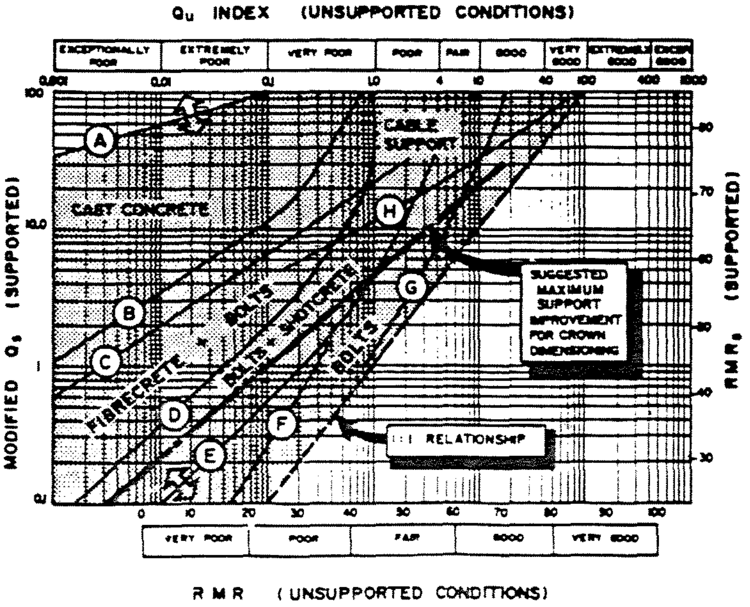

Figure 4 : Effective Rock Mass Quality Improvement for different support methods

crown geometry for any given rock mass quality can be assessed directly by reference to the Critical Span Line. If the geometry point plots below the line, the excavation layout is basically satisfactory and should stand unsupported apart from spot bolting for local kinematic control. If the point plots within the shaded area, patterned or heavy support is needed, but, so long as the point plots well below the top boundary of the shaded zone, based on precedent practise, such support can be implemented. If the point plots above the shaded zone on Figure 5, while the stope geometry would likely be suitable for cave mining (provided that surface disturbance is acceptable), it likely would not be viably supportable as an underground opening.

Crown Thickness Dimension

For crown stopes where proposed mining strike length is well in excess of span (at least 10 times), the overall geometry of the required crown, in particular its thickness, can be established from Figure 5. Specifically, by using the left hand, crown thickness axis and the suite of opening span lines that splay across the chart, it is possible to dimension a crown layout for a given span for any specified rock quality.

The minimum crown thickness line plotted across the lower part of the chart reflects the thickness to span relationship shown on Figure 3. Thus, combining the T/S relationship with the equation for the maximum unsupported critical span, S_C, allows derivation of the *Minimum Crown Pillar Thickness*:

$$T_{min} = 5.11Q^{-0.19} \times [\sinh^{0.0016}(Q)] \text{ metres}$$

As with the formulation for the critical span, S_C expression, the form of this equation is linear for much of the range of rock qualities met with in practise. However, at the good to extremely good quality end of the rock mass scale, the relationship

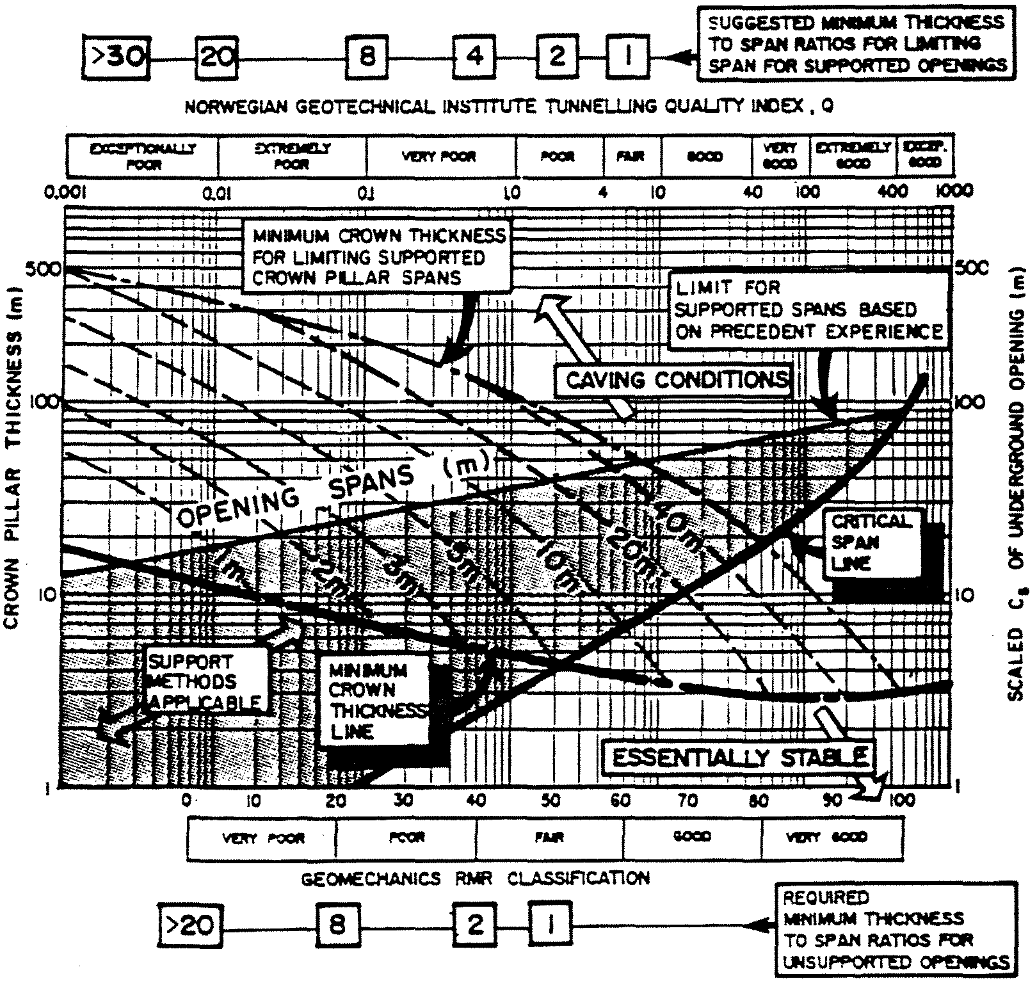

Figure 5 : Surface Crown Pillar Empirical Design Chart for Sizing Crowns of Long Strike Length (Strike Length / Span Ratio > 10) and Rock Mass Unit Weight, $\gamma = 2.7$ T/m^3

curves upward to maintain a minimum thickness of 2.5 to 3.0m at all times. This ensures consistency with *empirical guidelines* for the minimum thickness crown that is practicable to conventionally excavate.

7. Application for Design

When the chart on Figure 5 is used for design, firstly, it must be appreciated that the curves all incorporate no safety factor. Secondly, it must also be noted that all the expressions have been developed based on assumed minimum controlling rock mass quality. Thus, for assessing a design situation, once a comprehensive rock mass classification of the crown and sidewall geology has been carried out, a vertical bar should be plotted on the chart to correspond to the range of known RMR or Q values. This will allow engineering judgement to be used to assess variably in rock parameters. With this bar plotted, some estimate of the range of critical spans can be read directly from the graph. (Alternatively, the values can be calculated using the critical span expression for S_C). With this known, the minimum required thickness can be read from the thickness axis or calculated from the suggested maximum support improvement line on Figure 4.

When using the graph though, it should be noted that the top bounding line to the splay of span curves has been plotted using the maximum support improvement expression but based on Barton's limiting spans from precedent records. The various splay curves between this upper bound envelope and the minimum thickness T_{min} line therefore reflect the transition from this "fully supported" upper limit to the unsupported critical span line, ie., covering the spread of credibly supportable spans as indicated by the shaded zone on the diagram. Thus, as spans are increased, and it is assumed that more support is added, up to the maximum suggested previously, the values read off the thickness axis will become progressively *much less* than would be calculated for an unsupported opening, of the same span.

To further illustrate the use of the chart, take as an example, a particular situation where a 15 m wide, crown stope of fairly long strike length is required in steeply dipping schistose rock of poor to fair quality, characterized by a range in rock mass ratings from about 30 to 42 ($Q = 0.2$ to 0.9). The empirical design chart can be used to provide a first approximation for a) the probable stability of the given crown and b) the thickness of the minimum acceptable surface crown pillar.

For this example, precedent experience suggests that maximum *stable* unsupported spans would be in the range from 1.6 to 2.8 m., thus if a 15m. span stope is required in this rock mass it will require support to prevent caving. Assuming for simplicity, that the stope is vertical and of long strike length, several terms in the scaled crown span, C_S relationship, drop out and thus the required thickness of the crown pillar can be deduced from:

$$T = \gamma \frac{S^2}{S_C^2}$$

where S is the required *actual* design span, and S_C is the *Critical Span* value calculated for the appropriate modified Q_S to account for any installed rock support, up to a maximum where $Q_S = 4.5 Q_U^{0.67}$

For this case, with a rock quality, RMR range from 30 to 42, the thickness of the proposed crown for the stope ie., for a 15m span, can be scaled directly off the left axis of the chart as between 80 and 40m. or calculated using the above relationship with an assumed Q_S improved only about half way to the limit line. Simple checks for evaluating the sensitivity of support improvement to required design thickness can be made a) using the above relationship with both Q_U and various assigned Q_S values and/or b) by calculating the required thickness from the thickness to span relationship, again using both the unsupported Q_U and various supported, Q_S values, up to the maximum suggested.

As a contrast to these considerations for poor rock, because the scaled span concept is based on a database that includes some very thin, stable crown pillars, any of the previously discussed thickness relationships when applied to good rock will suggest very thin crowns. Where this occurs, (for example once rock qualities typically exceed $Q=10$), the minimum crown thickness should never be less than that calculated using the T_{min} expression or taken directly from the lower bounding line on the chart.

Although these examples illustrate the application of the scaled span concept for crown pillar dimensioning, it *must* be stressed that these charts are all based on an ultimate limit state condition; ie., they are based on an assumed dividing line between stable geometries and failures. *No Factor of Safety is incorporated*. Thus, this type of approach should not be used without considerable caution as a guideline for final design.

Estimating a minimum stable crown thickness for a given situation depends not only on the rock mass properties of the crown and wall rocks, it also is influenced by more practical considerations such as excavation method, rock reinforcement sequencing, stress regime and weathering effects. All these factors must be considered, and some compensation made in the design methodology to account for their effects. A factor of safety can also be applied to the final results, or to individual components of the calculation sequence, much along the lines of Barton's equivalent dimension approach, where the design span is scaled by dividing it by an Excavation Support Ratio (ESR) value, which ranges from 0.8 for very important excavations to values of 3-5 for temporary mine openings. Alternatively, probabilistic assessment techniques can be used to assess the degree of allowable risk. Some conservatism may be introduced during crown layout or during the rock mass characterization phase. For instance, it may be appropriate to omit the thickness of the weathered zone when considering design crown dimensions, such as was done by Milne et al., 1991 in one of the first applications of this scaled span approach for preliminary dimensioning of mine crown pillars.

At the current state of development of this concept, insufficient calibration experience is available to fully quantify the degree of safety margin inherent in the suggested approach. In consequence, once a design layout has been formulated, as a check it should also be assessed using the probabilistic approaches outlined earlier in order that the margin of acceptable risk can be quantified.

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