An Update on the Scaled Span Concept for Dimensioning Surface Crown Pillars for New or Abandoned Mine Workings

T.G. Carter
Golder Associates, Toronto, Canada.

ABSTRACT: The empirical scaled span approach for assessing the stability of surface crown pillars for mined openings has been in use for over a decade. In this time it has been widely used not only for dimensioning new crown pillars but also for assessing the stability of often abandoned crowns. This paper re-evaluates and updates the original database compiled in 1989/1990 and re-examines the basic mechanisms considered of relevance to the development of the Scaled Span concept. Improvements to current methodology for properly dimensioning a crown pillar over a shallow mine or tunnel opening are presented, based on updated knowledge of the behaviour of some of the case records.

Some observations and inferences on long term stability are provided, together with discussion of possible correlations that may exist with respect to the age of the pillars that have remained stable, as compared with those that failed. On the basis of observations on the time from original excavation to failure, some suggestions are given on application of the scaled span concept for assessing pillar longevity.

1 INTRODUCTION

The Scaled Span concept was developed over a decade ago, as a procedure for empirically dimensioning the geometry of crown pillars over near-surface mined openings, based on precedent experience, (Carter, 1989, 1992). At the time of its initial development, no acceptable method existed for assessing the stability of the many hundreds of existing mined openings, many of which were found to be sited in locations where collapse posed significant risks to the General Public, (Figure 1).

As crown pillar design for most hard rock mines in the past had been arbitrary at best, and random at worst, based simply on "leaving just one more round to surface" some more logical method of surface crown pillar dimensioning was required. Available "Rules of Thumb" and theoretical methods were evaluated and none were found capable of dealing with the complexities of the rock masses generally found in these crown areas.

A need was recognized, therefore, for developing a simple, yet credible method for evaluating the stability of near-surface crowns over mined openings. The concept of scaling crown spans with respect to their three - dimensional geometry and using this as a basis for comparison with an assessed rock mass quality, was further spurred by having to address the remediation of several catastrophic collapses (Carter et al., 1988).

Figure 1: Geometry of 1987 Cave-in below Highway 11B in Cobalt, Ontario, Canada.
During the past ten years, the “scaled span” methodology has been widely employed, and more than 100 extra case records have been added to the original 1989/1990 database of over 200 case records. This database initially included thirty documented failures and another dozen have now been added.

2 STABILITY ASSESSMENT APPROACH

As the primary purpose of a crown pillar is to protect surface land users, the mine, and those working in it, from inflows of water, soil and rock; it is vital that such surface pillars remain stable throughout their life. Maintaining the stability of the crown is critical, not only to the success of the mine, but also to ensuring the safety of any community or infrastructure that exists above it.

A number of approaches have been proposed over the years to assist miners in dimensioning crown pillars and addressing their stability. However, because of the significant differences that exist in behaviour between identified failure mechanisms, (Carter, 1989, Bétournay, 1987) most of these approaches, have been specifically addressed to one or other of the various characteristic failure behaviours, (eg., Goel and Page, 1982, Hoek, 1989, Bétournay et al, 1994). Others have attempted to examine the resulting influence zone or the actual sinkhole geometry as a function of the collapse process (Szwedzicki, 1999)

In 1987, the catastrophic collapse of part of a major Provincial Highway into an old mine working attracted national media attention, (Figure 1). This collapse, and the follow-up studies which identified several other hazard sites close to or beneath municipal buildings and schools in other parts of the old mining community (Carter et al., 1995), focussed attention at the highest political levels for developing cost-effective solutions for assessing and dealing with this legacy (Mackasey, 1989).

As part of this focus, an extensive study of the factors that controlled crown pillar stability was initiated and various methods of structural analysis were examined, (Bétournay, 1987, 1996, Carter, 1989, and Golder Associates, 1990). These studies demonstrated that for any given rock quality, stability depended principally on geometry. The span, thickness, and weight of the rock mass comprising the crown were found to be the most critical characterizing parameters. (Figure 2). This led to initial attempts at normalizing controlling parameters, recognizing that:

\[
\text{Crown Stability} = f \left( \frac{t \sigma_h \theta}{SL \gamma u} \right)
\]

where increased stability for any rock mass quality would be reflected by an increase in ...
- t, the crown pillar thickness
- \( \sigma_h \), the horizontal insitu stress
- and/or ..in \( \theta \), the dip (of the foliation or of the underlying stope walls), and

where decreased stability for any crown would result from increases in
- S, the crown pillar span
- L, the overall strike length of the stope
- \( \gamma \), the mass (specific gravity) of the crown
- and/or ..in \( u \), the groundwater pressure.

From examination of this grouping, it was evident that all parameters except \( \sigma_h \) and \( u \) were related solely to the geometry of the crown pillar. In order, therefore to normalize the relationship to be only geometry and weight dependent, it was decided that both these terms should be handled as part of rock mass classification, as both the NGI-Q and the
Geomechanics RMR systems take groundwater into consideration (Bieniawski, 1973, 1989; Barton et al, 1974) while the effects of in situ confining stress are well covered in the Q-system (Barton, 1976, Grimstad and Barton, 1993). Accordingly, the final empirical expression, termed the Scaled Crown Span was formulated as follows:

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

where: $S =$ 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 the orebody or foliation (degrees)

Although detailed discussion of the full development of this expression is beyond the scope of this current paper, it should be noted that foliation dip in the above expression reflects the span controlling hangingwall dip, (Figure 2). Moreover, as the dip of the foliation and hence of the stope sidewalls shallows from $90^\circ$ to past $45^\circ$ the effective span of the stope is no longer the ore zone width but rather the hangingwall dip length. It should also be noted that the $C_S$ expression has been normalized in such a way that for characteristic stope spans of 4 - 5m, with a crown rock specific gravity of 3.0g/cc, typical of many ore zone conditions, once the strike length of the stope significantly exceeds the span (as reflected by a very small span ratio, $S_R$) the $C_S$ expression essentially devolves to the 2D case, thereby allowing direct comparison with standard civil tunnel and cavern case record data.

This then allowed comparison of failed versus stable cases, which led to the development of the “Critical Span” limit line shown on Figure 3. This limit line, which, for any given rock quality, defines the widest stable scaled span value for unsupported ground was defined with relation to $Q$, as follows:

$$S_C = 3.3 \times Q^{0.43} \times \sinh^{0.0016}(Q)$$

where: $S_C =$ Critical Span (m)
$Q =$ NGI-Q value = $\exp{(RMR - 44)}$

and $RMR =$ CSIR Rock Mass Rating

As discussed in the papers introducing this concept, (ref. Carter, 1992, Carter and Miller, 1995 or the original Golder Associates’ 1990 report to Canmet), the hyperbolic sinh term in the above expression was introduced to account for the non-linear trend to increasing stability recognized for very good quality rock masses.

### 3 APPLICATION OF THE METHOD

At its simplest, the Scaled Span method can be deterministically applied by comparing the scaled crown pillar span ($C_S$) for any pillar of concern to the critical span ($S_C$) value deemed appropriate for the controlling rock mass. When the scaled crown pillar span, $C_S$, is determined to be less than the critical span, $S_C$, the crown pillar would be considered stable. If, on the other hand, the scaled span, $C_S$, was calculated as greater than the critical span, $S_C$, unless the crown had been sufficiently supported or fill approaches had been used in mining, likelihood of failure would be high.

While straightforward, such deterministic application does not provide direct assessment of the risk level posed by the proposed geometry. Establishing an exact Factor of Safety, or Safety
Margin, however, is not trivial. This is because crown failures have been found to have occurred in a wide variety of ways, ranging from disaggregation and ravelling forms of collapse to intact block slides or chimney failures (Bétournay, 1996). Thus, several quite different controls on failure mechanisms exist.

Failure in pure shear is relatively rare based on the database records, but is the easiest to analyze, so has led to development of the most straightforward analytical methods (e.g. Hoek, 1989). Ravelling failure mechanisms are common in the degradable rocks, but it is virtually impossible to analytically, or even numerically predict rates of ravelling. Nor is it easy to determine a safety factor for any stage in the ravelling process, except perhaps on a case specific basis using sophisticated, computationally intensive approaches, by means of distinct element or particle flow code modelling (eg., Lorig et al, 1995).

Because of its empirical basis, application of the Scaled Span method allows at least a rational assessment of failure likelihood if the method is applied probabilistically. This then, not only allows definition of minimum acceptable crown thicknesses, it also better takes into account heterogeneities within the rock mass. Applied probabilistically, the approach can also better help in defining acceptable or allowable risk for a given situation as per Table 1.

Although it is now becoming commonplace for a new mine design to collect appropriate data, and then analyse crown stability using numerical methods as an adjunct to carrying out Monte Carlo or similar probabilistic evaluations using the scaled span method; often, at an early concept assessment stage, there is a need to rapidly assess likelihood of failure. Some insight gained from evaluation of some of the case records while attempting to define what might control longevity, has led to an approach which may help to facilitate such assessments, (Carter and Miller, 1996). As shown on Figure 4, it was found that, if, rather than

<table>
<thead>
<tr>
<th>Class</th>
<th>Prob. of Failure (%)</th>
<th>Minimum Factor of Safety</th>
<th>ESR Excavation Support Ratio</th>
<th>Design Criteria for Acceptable Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Serviceable Life</td>
<td>Years</td>
<td>Public Access</td>
<td>Regulatory Position on Closure</td>
</tr>
<tr>
<td>A</td>
<td>Effectively zero</td>
<td>&lt;0.5</td>
<td>Forbidden</td>
<td>Totally unacceptable</td>
</tr>
<tr>
<td>B</td>
<td>Very, very short term (temporary mining purposes only; unacceptable risk of failure for temporary civil tunnel portals)</td>
<td>1.0</td>
<td>Forcibly prevented</td>
<td>Not acceptable</td>
</tr>
<tr>
<td>C</td>
<td>Very, short term (quasi-temporary stope crowns; undesirable risk of failure for temporary civil works)</td>
<td>2-5</td>
<td>Actively prevented</td>
<td>High level of concern</td>
</tr>
<tr>
<td>D</td>
<td>Short term (semi-temporary crowns, e.g. under non-sensitive mine infrastructure)</td>
<td>5-10</td>
<td>Prevented</td>
<td>Moderate level of concern</td>
</tr>
<tr>
<td>E</td>
<td>Medium term (semi-permanent crowns, possibly under structures)</td>
<td>15-20</td>
<td>Discouraged</td>
<td>Low to moderate level of concern</td>
</tr>
<tr>
<td>F</td>
<td>Long term (quasi-permanent crowns, civil portals, near-surface sewer tunnels)</td>
<td>50-100</td>
<td>Allowed</td>
<td>Of limited concern</td>
</tr>
<tr>
<td>G</td>
<td>Very long term (permanent crowns over civil tunnels slopes)</td>
<td>&gt;100</td>
<td>Free</td>
<td>Of no concern</td>
</tr>
</tbody>
</table>

Table 1: Comparative Significance of Crown Pillar Failure (from Carter & Miller, 1995)
plotting the crown geometry of all the case records, (expressed as Scaled Crown Span, \( C_S \) values) versus rock quality, each \( C_S \) value was directly compared with the appropriate Critical Span, \( S_C \) value for the given rock quality and the ratio was plotted with respect to probability of failure, then a cumulative probability graph could be drawn. As the distribution on this graph is approximately normal, an error function relationship can be formulated between \( P_f \) and the quotient \( S_C/C_S \) (designated as \( F_C \) in the following expression, where \( F_C \) can be considered as a crude crown pillar stability safety factor):

\[
P_f = 1 - \text{erf} \left[ \frac{2.9F_C - 1}{4} \right]
\]

where \( P_f = \) Probability of failure

and \( F_C = S_C/C_S \)

In utilizing this expression, it should be realized firstly that matching of this trend line to the case record data has been targeted to the low probability end of the scale, \( (P_f << 50\%, F_C>1) \) as this is generally the area of the distribution of most importance for practical applications. As a consequence, calculation of \( P_f \) values where \( F_C << 1 \), tend to be overestimated due to the characteristics of the error function used in the curve-fit equation. Secondly, the relationship assumes a mid-line to the spread of the plotted case record database information, which generally suggests rock quality variation to typically be well defined by a standard deviation of 10 RMR units.

4 LONGEVITY CONSIDERATIONS

Despite the usefulness of such probabilistic methods for assessing current pillar stability, the approach falls far short when it comes to addressing longevity, a key question now frequently requiring discussion in closure documents. Further, although it has long been known that changes in stability state occur as an excavated opening deteriorates by ravelling of the stope walls or crown, thereby leading to wider spans or thinner crown conditions, little quantitative is known about rates of ravelling.

Although limited use was made at the time of the 1990 compilation of the original database of information pertaining to the *time to failure*, some basic data was collected on longevity of the crowns.

Experience gained from a decade of applying the crown pillar scaled span approach for both new mine situations and in analysis of existing and failed older crowns has further added to this understanding of crown behaviour, with the most interesting result being that a marked disparity in behaviour seems to exist between crowns in hard non-degradable rock masses compared with those in the more breakdown-prone degradable lithologies. Based on some limited data on progressive failures, some tentative correlations have been drawn between initial rock quality, potential caving rates and survival probability as shown on Figure 5(after Carter and Miller, 1996).

Examination of the case records that give rise to the trends shown in Figure 5, suggests that initial...
geometry, irrespective of rock quality, controls short term stability (of the order of 0-20 years) but that rock competence controls later stages in the failure process. The data furthermore shows two classic periods where failures are more common. One period occurs at less than 20 years from initial excavation, the other at about 60 years. In some of the earlier period failure cases, surface breakthrough or crown collapse is known to have developed simply because the overburden/bedrock profile above the crown of a particular stope was irregular and much deeper than anticipated by the miners. The second period, by contrast seems to be much more related to progressive ravelling failures.

The plot on Figure 5 of survival probability for the database case records, seems to show a classic initial exponential increase in failure probabilities (possibly due to "defects", e.g. cavalier mining too close to surface), with a Weibull type of decay behaviour for the later decades, (possibly reflecting an increase in failures due to "wearing out" effects, e.g. degradation due to progressive ravelling and weathering), (Carter and Miller, 1996).

As is apparent from Figure 6, if, rather than plotting the data as span versus stand-time, as classically portrayed, the data is plotted against rock quality, then a remarkable disparity becomes evident between some of the “short-term” tunnelling stability cases and most of the “long-term” crown pillar failure cases. On this diagram, the two major data groups plot as two bands. The data points extending diagonally across the centre of the graph are the tunnelling and mining drift case records from Bieniawski and Barton and other sources, while the set extending across the complete width of the graph at fairly long stand times is the crown pillar data set.

As is apparent a fundamental difference in the effective definition of time to failure exists between these two data sets. Time to failure for the tunnelling cases, plotted as triangles and circles, is defined as the point of original initiation of spalling, i.e., the traditional concept of Lauffer (1958), which, expressed in terms of rock quality, RMR, can be estimated from $I_s = 0.0156e^{0.165RMR}$ as summarized in the following table.

<table>
<thead>
<tr>
<th>RMR</th>
<th>Spalling Initiation Time, I (Hours)</th>
<th>Threshold Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bieniawski</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.22</td>
<td>0.42</td>
</tr>
<tr>
<td>40</td>
<td>8.17</td>
<td>14.00</td>
</tr>
<tr>
<td>60</td>
<td>299.03</td>
<td>200.00</td>
</tr>
<tr>
<td>80</td>
<td>10943.8</td>
<td>8000.00</td>
</tr>
<tr>
<td>100</td>
<td>400525</td>
<td>?</td>
</tr>
</tbody>
</table>

While there is enough data available to make some estimate of initial spalling initiation times, it is much harder for a surface crown pillar case to estimate "time to failure", defined as breakthrough to surface. Examination of the failure case records, which are plotted as squares on Figure 6 suggests, however, that whether a stope caves through to surface or not, depends on not only the thickness of the crown pillar, but also the volume of void existing in the stope to accept any spalling rock, and the effective bulking of the rock as it spalls into the stope. For the poorest quality rock masses, mean

Carter - Update on the Scaled Span Concept
block size is very small and effective bulking is low (in the 10 to 15% range). For better quality rock masses where the blocks fall out in cobble to boulder sizes upwards, bulking exceeds 40%. For both cases, some estimate of the limiting height of potential cave development is achievable based on Laubscher's and others caving recommendations for different bulking conditions, (eg. Laubscher and Taylor, 1976, Just and Free, 1971). These caving prediction approaches, in turn can be tied to block size vs. rock quality relationships (such as are suggested by work by Barton,1974, Franklin and Palassi,1993 and others.)

As is evident from inspection of Figure 6, the difference between the two data sets also provides a direct measure of the "rate of ravelling", the data groupings pointing to the fact that the maximum divergence between the two trends occurs for very poor quality rock masses where initial stand-up times are extremely limited once a critical threshold span is exceeded (This limiting threshold span, which can be estimated from $S_{\text{max}} = 7.5Q^{0.38}$ should not be confused with the Critical Span, $S_C$ line, as the latter defines a lower probability of failure condition for unsupported ground, for which support could still be installed, while the former defines an upper bound "immediate collapse" limit line beyond which support would be largely ineffective.

5 CONCLUSIONS

The concept of scaling the three dimensional geometry of a mine crown pillar in terms of its characteristic span was first introduced in 1990 in an attempt to advance the then available methods of crown pillar stability assessment. From the data collected over the years since the initial studies on crown stability were done in 1988/1989, it has been found that failure of individual surface crown pillars can be related more rationally to rock mass characteristics than to discrete failure mechanisms. The data set suggests that 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. By contrast, where rock quality is poor, and block size is small, failure seems to occur by ravelling and breakdown of the blocks comprising the crown and hangingwall. This suggests two basic, quite different crown pillar rock mass behavioural characteristics; i.e.,

- the essentially non-degradable, competent rock types (hard igneous and metamorphic types and well cemented sedimentary units) which exist, tend not to spall and hence seem to survive, while
- the degradable, weathering susceptible, weak or highly fragmented rock types, most commonly fail in due course of time, due to disaggregation and spalling.

The history plots of the crown pillar data suggest that there are two periods of most common failure, one fairly soon after excavation and one at a much later time, probably when the progressive failure cases break through to surface. The plots suggest that the likelihood for ultimate failure (i.e., uncontrollable breakthrough to surface) depends on (a) governing rock quality and particularly the propensity of the rock to degradation due to time-dependent effects and (b) crown thickness.

Although the examples included in this paper illustrate the application of the Scaled Span concept for crown pillar dimensioning and for starting to assess longevity, it must be stressed that these charts and derived relationships are all based on limited data, and on various cases which are assumed to be at an ultimate limit state. In consequence, this type of approach should not be used without considerable caution as a design guideline. 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 during design to account for such effects.

ACKNOWLEDGEMENTS

Part of the original work to develop the Scaled Span concept was funded by CANMET under Contract No.23440-8-9074/01-SQ. other parts were funded by the Ontario Ministry of Northern Development and Mines or conducted as part of programmes funded by various mining companies. Over the past decade, studies for many of these same mining companies have contributed to advances in current
understanding. While specific thanks is due to these organisations that have supported the work by supplying unpublished, often confidential, information to form a case study data base, acknowledgements must also go to many colleagues at Golder Associates who have made major contributions to the formulation and testing of some of the methods outlined herein.

REFERENCES


Grimstad, E. and Barton, N. (1993) Updating the Q-System for NMT. Proc. Int. Symp on Sprayed Concrete, fagernes, Norway, 21pp


