Q-slope application to coal mine stability

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Abstract. The Q-slope classification system is used to assess the stability of excavated rock slopes and provide an indication of long-term stable, reinforcement-free slope angles. Q-slope is based on over 500 rock slope case studies from mines, road and rail cuts hosted in igneous, sedimentary and metamorphic rocks around the world. Q-slope has successfully been applied to slopes ranging from less than 5 m to more than 250 m in height in both civil and mining environments since its introduction in 2015. This paper describes the application of Q-slope to excavated coal mine slopes which are often hosted in complex, interbedded sedimentary strata. Q-slope application to coal mine slopes is compared to the likelihood of failure calculated by the Slope Stability Assessment Methodology (SSAM). A relationship between Q-slope and SSAM is also provided.

1. Introduction
Empirical rock mass classification systems and design charts provide geotechnical engineers: (i) a rapid means of predicting of slope behavior; and (ii) guidance on stable slope geometry (e.g. bench face angle, height and width). They are most effective when the geometry, geology, hydrogeology and geomechanical properties of the slope under review are similar to known performance of precedent slopes [1], [2], [3].

The Q-slope classification system [4], [5] and SSAM [6], [7] are two classification systems that have been designed for excavated rock slopes. This paper describes the application of Q-slope to 38 failed and intact slopes from Australian open cut coal mines. It further describes the relationship between Q-slope and SSAM to predict slope performance.

2. The Q-slope Classification System
The Q-slope classification system was introduced by Barton and Bar [4] to provide a correlation between Q-slope ratings and long-term stable, reinforcement-free slope angles. Q-slope is an adaption of the Q-System [8] which was initially developed to assess tunnel and rock cavern stability and support requirements. Q-slope is based on over 500 open pit mine bench slopes and road and rail cuts from Asia, Australia, the Americas and Europe, which are hosted in igneous, sedimentary and metamorphic lithologies [5], [9]. Q-slope has also been applied to saprolitic and highly weathered rocks [10] and faulted rocks and fault zones [11].

Q-slope uses the same six parameters as the Q-System: RQD, $J_n$, $J_r$, $J_a$, $J_w$ and SRF, but in Q-slope $J_w$ is replaced with $J_{wice}$ to account for the wider range of environmental conditions rock slopes are exposed to compared to tunnels or excavations, and SRF is replaced with $SRF_{slope}$. The Q-slope rating is calculated using equation (1).
where $RQD$ = rock quality designation [12];
$J_n$ = joint set number;
$J_r$ = joint roughness number;
$J_a$ = joint alteration number;
$O$ = orientation factor (O-factor)
$J_{wice}$ = environmental and geological condition number, and
$SRF_{slope}$ = the maximum strength reduction factor for weathering, low strength and/or faulted zones that may adversely affect slope stability.

Ratings for each of these factors are described by Bar and Barton [5], [9]. Q-slope ratings can be used to derive the steepest slope angle, $\beta$, equation (2), not requiring reinforcement or support. Equation 2 has a probability of failure of 1%.

$$\beta = 20 \log_{10} Q_{slope} + 65^\circ$$ (2)

Q-slope can be applied to slopes ranging in angle from 35º to 85º, and slopes ranging in height from less than 5 m to more than 250 m in height in both civil and mining environments. Q-slope may not be applicable if the slope is a combination of poor rock mass quality zones mixed with good quality zones. In these instances, and in cases where slopes require several stages of excavation (i.e. slopes larger than 50 m in height), more rigorous analysis is both warranted and advised [5].

Q-slope has not yet been widely applied to coal mines in Eastern Australia. The Q-slope classification system has been correlated with the Slope Mass Rating, SMR [13], Basic Quality, BQ [14] and Continuous Slope Mass Rating, CSMR [15].

3. Method Description: Q-slope applied to coal mine slopes

In this study, 38 failed and stable slope cases from Australian open cut coal mines have been assessed using the Q-slope classification system. These comprise 24 failed and 14 intact slope cases that have been sourced from the Hunter and Gunnedah Basins in New South Wales and the Bowen and Callide Basins in Queensland.

Failed slope cases ranged in height from 18 m to 65 m and slope angles from 50º to 76º. Intact slope cases ranged in height from 15 m to 42 m and slope angle from 59º to 73º. Examples of failed slope cases are displayed in figure 1.

Figure 2 displays slope performance and Q-slope rating for 531 slope cases (384 intact, 8 quasi-stable and 139 failed cases) from a database of civil and mining slope cases.

On the applicability of Q-slope to predict excavated coal mine slope performance, figure 2 illustrates a good correlation between Q-slope’s prediction of stability [5].

An average RQD of 75 has been applied to estimate the Q-slope rating of coal mine slopes. Higher RQD, $J_r$ and $J_a$ are likely in coal mines where physical measurements of these parameters are limited due to the restriction of physical access to within 15 m to 20 m of the base of the slope as part of mandatory industry safety protocols.
Figure 1. Typical composite coal mine slope failures in Queensland & New South Wales.

Figure 2. Q-slope and slope angles for over 500 cases studies including coal mine slopes.
4. **Worked Example – Q-slope applied to coal mine slope**

The following section demonstrates the application of Q-slope to a case study from a failed slope in an open cut coal mine in New South Wales, Australia [6].

The case study slope was 30 m high and had an as-built slope geometry of 65°. This case study, shown in figure 3, represents a single geotechnical domain (i.e. zone of expected similar ground behaviour). The failure is bounded by two intersecting sub-vertical discontinuities projected to form a wedge [6].

![Figure 3. Slope failure at an open cut coal mine, New South Wales. Q-slope of 0.39.](image)

A Q-slope value of 0.39 was estimated for the case study slope, per the following inputs:

- Average RQD = 70% across varying interbedded strata of varying rock mass quality.
- \( J_a = 12 \)
- Set A: \( J_r = 2, J_a = 4, O_{factor} = 0.75 \)
- Set B: \( J_r = 2, J_a = 4, O_{factor} = 0.90 \)
- \( J_{wice} = 1 \)
- \( SRF_{slope} = 2.5 \).

A Q-slope of 0.39 equates to a stable slope angle, \( \beta \), of 57° (i.e. 8° shallower than as-built slope geometry).
5. Comparison with Slope Stability Assessment Methodology (SSAM)

The Slope Stability Assessment Methodology (SSAM) was developed by McQuillan et al. [6] to predict the risk of excavated coal mine slope failure using multiple linear regression. Required inputs can be estimated from visual observations, or predictions, of slope conditions.

SSAM inputs are based on a back analysis of 140 (67 intact and 73 failed) excavated slopes sourced from open cut coal mines in Australia and Canada. SSAM ratings are determined by selecting the slope conditions most applicable from the list of critical parameters defined in table 1. SSAM ratings can then be used to estimate a slope’s likelihood of failure, equation (3).

$$\text{LoF} = \frac{1}{1 + e^{0.660 \cdot (0.0769 \cdot \text{overall SSAM rating})}}$$

where SSAM = overall SSAM rating as calculated from conditions selected in table 1. In table 1, ratings assigned to each critical parameter are highlighted in Italics to the left of each Slope Condition description.

Application of SSAM to assess slope stability is discussed by McQuillan [7]. SSAM has not yet been applied to excavated slopes outside an open pit mining environment.

For the example case study in figure 4, an overall SSAM rating of 107 was estimated, which corresponds to a LoF of 80% as per a summation of the following conditions:

1. 5: Interbedded - Fine: 1+ persistent joint set w/ average bedding thickness < 5m
2. 30: 2+ intersecting persistent discontinuities both striking < 50 degrees relative to the excavated hardwall orientation
3. 20: Structure dip > 60 degrees into the excavation
4. 20: Strata consistently rolls or dips into the face
5. 1: No water seepage or dry slope conditions
6. 1: Straight wall geometry, no inflections or elbows
7. 10: Moderately weathered
8. 10: Smooth, low undulations
9. 5: Batter height of 41 to 60 m
10. 5: Slope angle of 63 to 67 degrees

The SSAM LoF of 80% for a 65 degree slope angle supports the estimated Q-slope value of 0.39 and equivalent stable slope angle of 57º, where a greater than 50% LoF is predicted and as-built geometry is 8º steeper than Q-slope predicted stable slope angle.

6. Method Description: Q-slope correlation with SSAM for stable slopes

Overall SSAM ratings were calculated for the new case studies and compared to the Q-slope ratings calculated for the same slope case studies. The relationship between Q-slope and SSAM ratings are illustrated in figure 4.

In addition to the 38 coal mine case studies, figure 4 includes an additional 6 failed and 10 intact cases from a gold mine in Western Australia. From the gold mine, failed cases ranged in height from 12 m to 36 m and slope angle from 53º to 77º. Intact slope cases ranged in height from 8 m to 24 m and slope angle from 52º to 66º.
Table 1. The SSAM classification technique for excavated coal mine slopes.

| Critical Parameter | Slope Condition |
|--------------------|-----------------|
| **1** Rock Mass Unit | 1 Massive: No persistent beds |
| 5 Interbedded – Fine: 2+ persistent beds with average bedding thickness < 5 m |
| 10 Interbedded – Coarse: 2+ persistent beds with average bedding thickness 5–10 m |
| 15 Massive: 2+ persistent beds with average bedding thickness > 10 m |
| **2** Structure – orientation relative to excavated hardwall | 1 No persistent structure OR 1+ persistent discontinuity striking > 30 degrees from hardwall orientation |
| 15 2+ intersecting persistent discontinuities, with 1 persistent discontinuity set striking < 50 degrees and 1 persistent discontinuity set striking > 50 degrees relative to the excavated hardwall orientation |
| 30 1+ persistent discontinuity striking < 30 degrees from hardwall orientation OR 2+ intersecting persistent discontinuities both striking < 50 degrees relative to the excavated hardwall orientation |
| **3a** Structure dip 1 persistent discontinuity | 1 Structure dip < 80 degrees into the face OR no persistent discontinuities |
| 5 Structure dip < 40 degrees into the excavation |
| 15 Structure dip > 60 degrees into the excavation |
| 20 Structure dip 40 to 60 degrees into the excavation OR structure dip 80 to 90 degrees into the face |
| **3b** Structure dip 2+ persistent discontinuities | 5 Structure dip < 40 degrees into the excavation |
| 15 Structure dip > 60 degrees into the excavation |
| 20 Structure dip > 60 degrees into the excavation |
| **4** Lateral conditions | 1 Strata/bedding is horizontal or dips away from the face |
| 10 Strata/bedding locally rolls or dips into the face |
| **5** Water | 1 No water seepage OR Dry slope conditions |
| 10 Consistent water seepage out of face (i.e. stable head) |
| 20 Change in seepage conditions (e.g. sudden new, increase, decrease, or stoppage in seepage conditions without causal weather event OR water ponding at crest OR water saturated at toe) |
| **6** Wall geometry | 1 Straight, no inflections OR elbows |
| 10 Concave inflection/s < 180 degrees |
| 15 Convex inflection/s > 180 degrees |
| 20 90 degree elbow (bullnose) |
| **7** Weathering | 1 Fresh: no orange staining on defect surfaces OR in fresh horizon |
| 10 Moderately weathered: some orange staining on defect surfaces – may be in weathered or fresh horizon |
| 20 Extremely weathered: > 70% orange staining on defect surfaces OR in weathered horizon |
| **8** Structure surface waviness | 1 Wavy, several undulations |
| 5 Wavy, moderate undulations |
| 10 Smooth, low undulations OR known previous shearing on discontinuity surface OR surface conditions unknown |
| **9** Height | 1 > 20 m |
| 5 21 to 40 m |
| 10 41 to 60 m |
| 15 > 60 m |
| **10** Angle | 1 < 62 degrees |
| 5 63 to 67 degrees |
| 10 68 to 72 degrees |
| 15 > 73 degrees |
Figure 4 indicates two correlations between Q-slope and SSAM ratings for stable slopes. Equation (4) is a line-of-best fit indicating the main boundary between stable and failed slopes. For Q-slope values equal to, or exceeding 2, the upper bound equation (5), may also be used to estimate SSAM. However, equation (5) should be cautiously used given it is based on relatively limited data.

\[
\text{Overall SSAM Rating} = 7.5 \log_{10} Q_{\text{slope}} + 82.5 \tag{4}
\]

\[
\text{Upper Bound Overall SSAM Rating} \text{ (when } Q_{\text{slope}} \geq 2) = 65 \log_{10} Q_{\text{slope}} + 65 \tag{5}
\]

7. Discussion
This paper describes the application of Q-slope to 38 new slope cases sourced from Australian coal mines. Previously, Q-slope has not included excavated coal mine slopes in its founding database. This paper has shown that Q-slope can be used to predict the performance of excavated coal mine slopes with a probability of failure of 11%.

This paper has also shown the relationship between Q-slope and SSAM for stable slopes. Both methods have been applied successfully to excavated coal mine slopes and have been built into online applications for rapid industry application [16], [17].

Future research will consider the wider application of SSAM (i.e. external to open pit coal mine application) and the Q-slope use in interbedded strata of varying rock mass quality.

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