The evolution and application of 3D limit equilibrium modelling to assessing open cut coal mine slope stability

A. McQuillan
Rocscience, Inc. Southport, Australia

G. Guy
Encompass Mining, Brisbane, Australia

ABSTRACT: Over the last five years the application of 3D modelling to assess slope stability has increased significantly as 3D modelling software becomes more widely commercially available and user friendly. 3D modelling is particularly beneficial if: (i) the failure mechanism is driven by the interaction of structure as well as breaking down of rock bridges (implying the rock mass under investigation is anisotropic); and (ii) the slope analysed includes confining or variable geometries that will not be accurately represented in a 2D model. When modelling in 3D generic material parameters, or those derived from the back analysis of 2D cases, should not be directly applied to 3D models. This is because the failure mechanism being modelled in 2D does not generally represent the actual failure mechanism observed in the pit, with 2D modelling often oversimplifying a slope. This paper outlines four cases studies where slope geometry is complex and 3D limit equilibrium modelling has been used to back analyse material strengths in open pit coal mines. 3D back analysed strengths are compared to 2D back analysed strengths to demonstrate the differences in range of strengths calculated using the different analysis methods.

1 INTRODUCTION

An industry survey of geotechnical engineers working in the Australian coal mining industry indicated kinematic and 2D limit equilibrium (LE) modelling techniques were the most routinely applied to assess slope stability (McQuillan et al. 2020). Since this study was completed, the application of 3D modelling to assess slope stability has increased significantly due to 3D modelling software becoming more widely commercially available and user friendly (Bar et al. 2019a, Bar et al. 2019b, Bar et al. 2020, McQuillan et al. 2020). 3D modelling is particularly beneficial if the rock mass under investigation is anisotropic and/or the slope design includes confining or highly variable geometries. Bar and McQuillan (2018) detail examples of such conditions and compare results to 2D analysis for slope optimisation and risk management.

When moving to 3D analysis several assumptions may need to be made to fulfil 3D model requirements. One key assumption will be material properties. It is well known that strength properties back analysed from 2D analysis are generally not appropriate for use in 3D analysis, and vice versa (Duncan 1996, Zettler et al. 1999, Wines 2016). This is where 2D analysis does not account for shearing through in situ rock mass to release a failed block at the sides of the failure surface or other confining or variable characteristics. This often leads to back analysis scenarios where 2D-derived material strengths will be higher than 3D-derived material strengths.

Historically generic material strength properties based on 2D back analysis have been applied at coal mining operations across the Bowen and Hunter Basins in Australia. These parameters are often utilised without regard for the anisotropy of the material or confining effects of slope geometry being analysed.

This paper outlines four case studies from open pit coal mines in Australia in which the material properties were back analysed using 3D LE modelling software. Case studies include slip surfaces through rock mass and heavily jointed material in excavated slopes. An additional case study is presented that shows the range in material strengths that are back calculated when using 2D and 3D modelling techniques to model the same failure.

The intent of this paper is to: (i) show the value in using 3D methods to assess the stability of anisotropic rock masses; and (ii) demonstrate the variance in material properties that can be back calculated using both 3D and 2D LE analysis.

2 CASE STUDIES

Rocscience, Inc.’s (2020) Slide3, 3D LE modelling program, was used to back analyse case studies. Slide3 calculates a factor of safety (FOS) using the methods of columns approach described by Cheng and Yip (2007).

The case studies discussed in this paper are from the Bowen Basin coalfields in central Queensland, Australia and from the Hunter Basin coalfields in New South Wales, Australia.

Slide3 model settings included: Ellipsoid slip surface, Cuckoo with Surface Altering Optimisation slip surface search method. Results are reported as a FOS calculated using the Spencer or GLE search method.

2.1 *Case Study 1*

Case study 1, Figure 1, was excavated using a dragline for the main overburden and then truck and shovel for coal removal. The slope was pre-split to a design of 65º and consisted of a sandstone upper band approximately 10 to 15 m thick, followed by an interbedded sandstone and siltstone horizon down to the target coal seam. Failure occurred through intersecting joints, bounded at the base of the failure by a coal seam. Elevated water pressures behind the pit crest were present at the time of failure. Back analysis was completed to determine appropriate material strengths for 3D LE modelling. Initial assessment of slope stability had been completed using 2D LE analysis and had indicated a FOS of > 1.2. This slope geometry was the first case study the authors had back analysed in Slide3 software in 2017. For the first iteration of 3D modelling generic Bowen Basin material strengths were input into the model. Material strengths assigned for fresh coal measure rock (cohesion = 450 kPa; friction angle = 42º) were isotropic and did not explicitly account for persistent joints. The calculated FOS was 2.5, Figure 2.

Figure 1 Case study 1, post failure slope conditions

Subsequent iterations of Slide3 modelling downgraded fresh coal measure rock strength and introduced anisotropy into the slip surface calculation process to account for the persistent sub-vertical joints observed in the slope. The back analysis aimed for a FOS of 0.95 to 1.05 to indicate potentially unstable conditions, where Hussain and Stark (2010) comment that slope movement has been observed to initiate at FOS of up to 1.05 (Stark and Ruffing 2017). The material strengths applied to Slide3 modelling which obtained a critical FOS of 1.05, Figure 3, are summarised in Table 1.

Table 1 Slide3 input parameters for case study 1

Material	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)
Fresh coal measure rock	24	110	30
Joint	15	2	12
Jointed CMR	Generalised Anisotropic function		
Coal	15	35	30

Slope geometry was constructed from pre-failure survey data. A groundwater surface 30 m below topo was applied. Rock mass strength was considered anisotropic, with dip and dip direction of modelled joint sets measured from post failure survey data. Applied defect orientations were as follows:

Joint set 1: Dip = 81°; Dip Direction = 222°

Joint set 2: Dip = 74°; Dip Direction = 319°

A = 5°; B = 10°

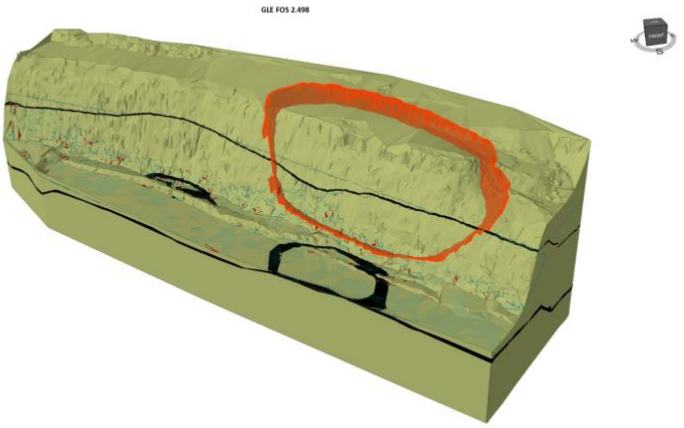

Figure 2 Slide3 predicted critical failure surface, FOS ~ 2.5, case study 1, applying generic 2D material strengths

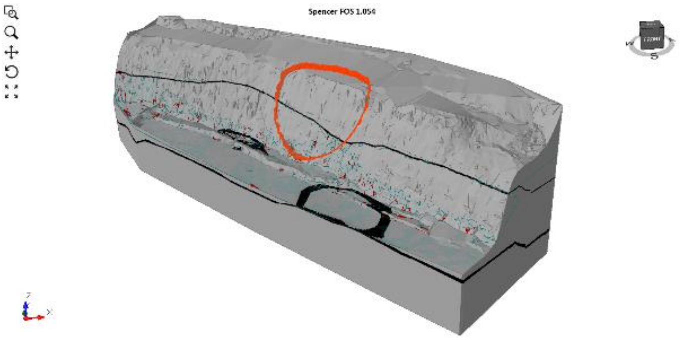

Figure 3 Slide3 predicted critical failure surface, FOS ~ 1.05, case study 1

Slide3 model results using back analysed anisotropic material strengths are presented in Figure 3. There is good correlation between the location of the Slide3 predicted critical slip surface and where failure actually occurred, Figure 4. The material strengths back analysed for case study 1 were subsequently applied as starting inputs for case study 2.

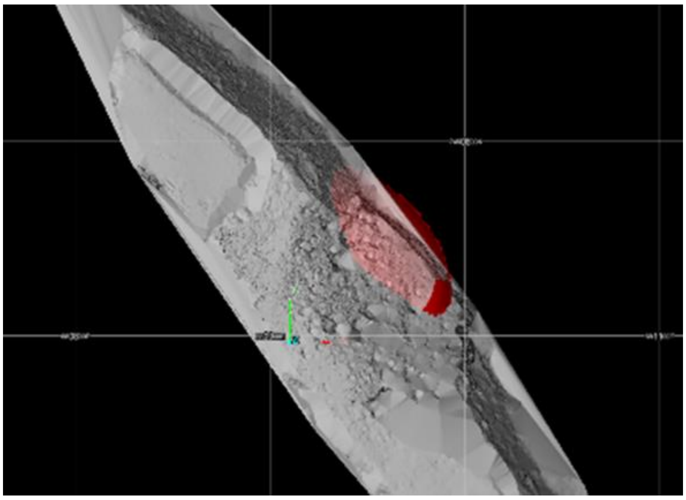

Figure 4 Plan view map showing Slide3 predicted critical failure surface (red polygon, FOS ~ 1.05) and actual failure location (greyscale), case study 1

2.2 *Case Study 2*

Case study 2 was sourced from an operational open cut coal mine in Queensland. Case study 2 was excavated using a dragline for the main overburden and then truck and shovel for coal removal. The excavated slope under review was pre-split to a design of 75° and consisted of a sandstone upper unit approximately 10 m thick, followed by an interbedded sandstone and siltstone horizon down to the target coal seam. Failure occurred through three intersecting persistent joints (two sub-vertical and one oblique joint set) daylighting in the excavated face, Figure 5.

Figure 5 Case study 2, post-failure slope conditions

Fresh coal measure rock and joint strengths applied were the same as the parameters applied in case study 1. Slope geometry was constructed from pre-failure survey data. Dry slope conditions were modelled where no seepage or ponding was observed near the crest or face at the time of failure. Rock mass strength was considered anisotropic, with dip and dip direction of modelled joint sets measured from post failure survey data. Applied defect orientations were as follows:

Joint set 1: Dip = 85°; Dip direction = 076 °
Joint set 2: Dip = 82 °; Dip direction = 140 °
A = 5 °; B = 10 °
Weak plane: Dip = 42 °; Dip direction = 066 °

Slide3 model results are presented in Figure 6. A critical FOS of 0.49 was calculated.

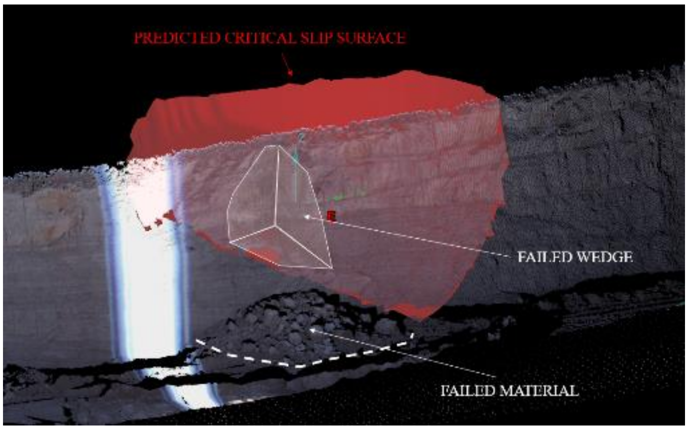

Figure 6 Perspective view showing Slide3 predicted critical failure surface (red polygon) and actual failure dimensions (white polygons), case study 2

Comparing the location of the critical failure surface calculated for pre-failure slope conditions with Slide3 results, there is good correlation between the Slide3 predicted critical slip surface and where failure actually occurred, Figure 6. A minor discrepancy can be observed in the size of the failure predicted, with Slide3 predicting a larger failure than actually occurred, Figure 6. This is attributed to no failure size restrictions being placed on the search command. A FOS appreciably lower than 1, i.e. 0.49, was accepted where slope failure was kinematically likely given the intersection and daylighting of three persistent defects. Under such conditions a FOS appreciably lower than 1.0 could be expected.

A back analysis using probabilistic inputs was then carried out on case study 2 to determine the range of material properties that would give a FOS of 1.0. Figure 7 summarises the combinations of joint cohesion and friction angle that result in a FOS of 1.0.

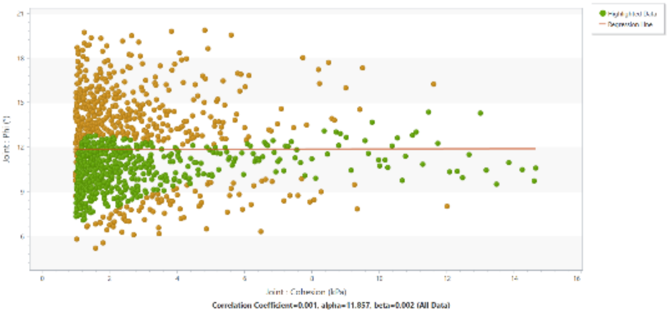

Figure 7 Slide3 scatter plot of combinations of joint cohesion and friction angle values that result in a FOS of 1.0 (green highlighted points)

To obtain a FOS of 1.0, a range of joint cohesions of approximately 1 to 15 kPa can be applied in combination with a range of friction angles of 7 to 13°. These combinations of joint strengths support the material strengths applied in case study 1 and 2 for joints, but also highlight the variance in combinations of cohesion and friction angle that would also result in a FOS of approximately 1.0 being calculated for the same slope geometry.

To compare the cohesion and friction angle values that would be calculated for a 2D back analysis, a 2D section was cut at the point of intersection between the three joint planes contributing to failure. This technique of modelling the line of intersection of bisecting joint planes has been commonly observed (rightly or wrongly) to model wedge-type failures in 2D. Rocscience, Inc's (2020) Slide2 software was used to complete the 2D LE back analysis.

To obtain a FOS of 1.0, 2D back analysis resulted in a range of joint cohesions of approximately 1 to 8.5 kPa can be applied in combination with a range of friction angles of 6 to 18°.

This example shows that different combinations of cohesion and friction angle are calculated for the same material (i.e. joint strength) when back-calculated using 2D and 3D modelling techniques. The difference in range of combinations of parameters that will result in a FOS of 1.0 is attributed to the difference in failure mechanisms that are being calculated in 2D (plain strain) and 3D (true failure dimensions) albeit for the same slope failure (Stark and Ruffing 2017).

2.3 *Case Study 3*

Case study 3 is a 30 m high excavated slope pre-split to a design of 75°. The case study is sourced from an open cut mine in New South Wales, where the slope consisted of predominantly sandstone down to the target coal seam. A prominent fault intersected the slope at an acute angle (within approximately 20° of the slope orientation) and dipped in the same direction as the slope orientation. Failure occurred at the intersection of the fault and batter scale persistent joints, Figure 8. Elevated water pressures behind the pit crest were present at the time of failure due to surface water seepage from a recent rainfall event.

Material strengths applied to Slide3 modelling are summarised in Table 2. The Generalised Anisotropic function in Slide3 was used to model the persistent joints observed in field.

Figure 8 Case study 3, post failure slope conditions

Table 2 Slide3 input parameters for case study 3

Material	**Unit weight (kN/m^3)**	**Cohesion (kPa)**	**Friction angle (°)**
Fresh coal measure rock	24	150	28
Joint	15	0	24
Jointed CMR	Generalised Anisotropic function		
Coal	15	35	30
Fault	24	0	19

Slope geometry was constructed from pre-failure survey data. Water pressure was applied to the rockmass in front of the modelled fault. Rock mass strength was considered anisotropic, with dip and dip direction of modelled joint sets measured from post failure survey data. Applied defect orientations were as follows:

Joint set 1: Dip = 81°; Dip Direction = 205°
Joint set 2: Dip = 75°; Dip Direction = 180°
Joint set 3: Dip = 70°; Dip Direction = 100°
A = 5°; B = 10°

Slide3 model results are presented in Figure 9. A FOS of 0.95 was calculated. Good correlation is observed between the location of the critical failure surface predicted by Slide3, for pre-failure slope conditions, and where failure actually occurred, Figure 10. The back analysis aimed for a FOS of less than 1.0 to indicate failed conditions. Back analysis indicates that rock mass stability is affected by both defect orientation and potential deterioration in strength from blasting around persistent structure.

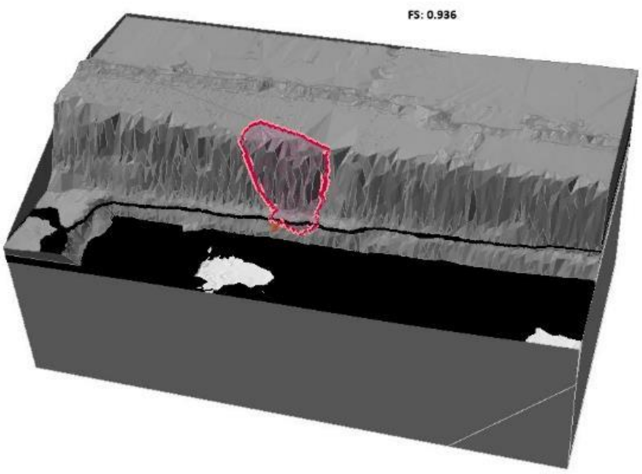

Figure 9 Slide3 predicted critical failure surface, FOS ~ 0.95, case study 3

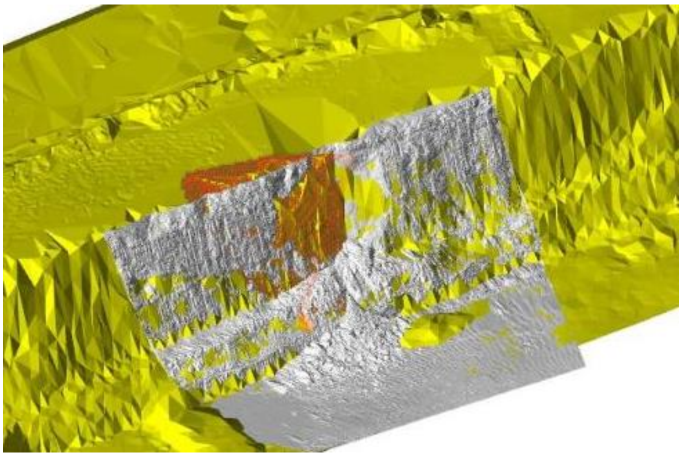

Figure 10 Perspective view map showing Slide3 predicted critical failure surface (red polygon, FOS ~ 0.95) and actual failure location (greyscale), case study 3

2.4 *Case Study 4*

Case study 4 back analysed the movement observed in a box cut at an open cut mine in Queensland. The slope comprises of an approximately 100 m high multi-bench configuration that has been excavated into Permian coal measures strata to extract the target coal seams. The slope is excavated as part of a box cut and is situated near the coal sub-crop line where the strata can dip up to 45° but in general 10° or less below the excavation. The sub-floor conditions comprise strata that are a laminated mix of shale, thin coal bands, weak mudstones and tuff layers that are often sheared due to tectonic flexure from seam compression. Previous slope instability in the area has been attributed to movement on these weak layers and as a result the box cut was developed as a series of 100 m wide slots to confine any potential slope movement.

During the excavation of the second slot localised slope movement was detected by slope stability radar (SSR) indicating dilation of the jointed coal measures rock mass, Figure 11. In order to refine the material strength properties for the slope, a back analysis was undertaken to match the actual versus predicted slope movement observed. The back analysis aimed for a FOS of 1.0 to 1.1 to indicate meta-stable (slight movement) conditions.

Defect data collection from pit exposures and downhole acoustic scanner interpretation had allowed rock mass defect orientations to be defined for the coal measures rock mass. Sensitivity analysis was then computed for strengths of the intact fresh coal measures and weak mudstone units until a FOS indicating slope movement, but not failure, was obtained.

Slide3 model results are presented in Figure 12. A FOS of 1.08 was calculated using material strengths in Table 3.

Table 3 Slide3 model input parameters for case study 4

Material	**Unit weight (kN/m^3)**	**Cohesion (kPa)**	**Friction angle (°)**
Spoil Unsaturated	18	50	27
Fresh coal measure rock	25	250	28
Weak Mudstone	24	0	12
Joint	24	0	30
FC5 Shear	20	0	12
Coal	15	30	35
Jointed CMR	Generalised Anisotropic function		

Slope geometry was constructed from pre-failure survey data. Water pressure was applied to the rockmass in front of the modelled fault. Rock mass strength was considered anisotropic, with dip and dip direction of modelled joint sets measured from post failure survey data. Applied defect orientations were as follows:

Joint set 1: Dip = 70°; Dip direction = 130°
Joint set 2: Dip = 60°; Dip direction = 070°
A = 5°; B = 10°

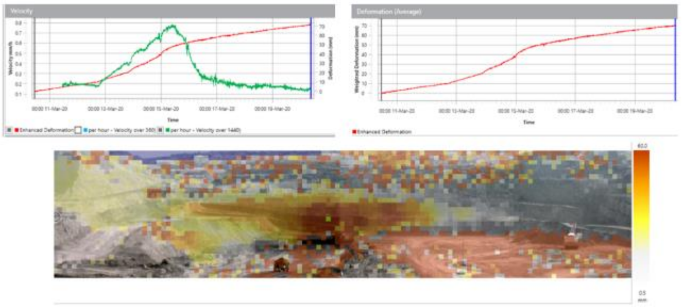

Figure 11 Slope stability radar deformation data of case study 4

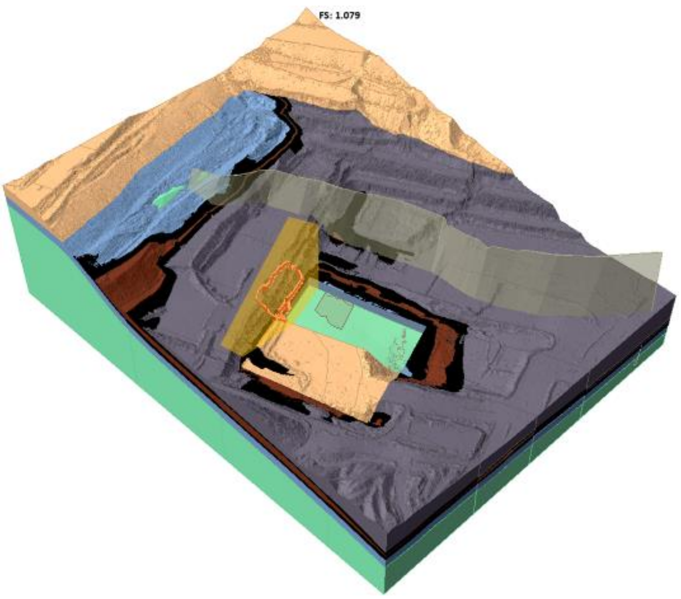

Figure 12 Slide3 model results showing predicted critical failure surface, FOS ~ 1.08, case study 4

3 DISCUSSION

The case studies presented in this paper apply materials typically modelled in slope stability analysis for Queensland and New South Wales coalfields. These include: fresh coal measure rock, mudstone (representative of immediate roof or floor material), coal, bedding shears, joints and waste rock. The cases presented show that slope instability needs to be considered in 3D to account for the natural variability in: (i) structure orientation; (ii) rock mass conditions; and (iii) slope geometry which more often than not cannot be accurately represented in a 2D analysis. Studies by Akhtar and Stark (2017) show that the FOS calculated by 3D methods can be up to twice as high as the corresponding FOS calculated for the same critical sliding mass using 2D methods (Stark and Ruffing 2017).

3D back analysis of failed, or meta-stable, slopes will derive a set of material strengths that differ from those back analysed in 2D. 3D-derived material strengths are invariably lower for intact rock mass when defect characteristics are included in an anisotropic material.

The back analysis of case studies 1 and 2, of primarily structurally driven slope failures, has shown that if only 2D material properties are available for input, results for 3D analysis using 2D-derived material properties should be interpreted with caution. This is because 2D-derived material strengths are generally higher than 3D-derived material strengths, where the failure mechanism modelled in 2D does generally not represent the true 3D dimensions and mechanics (i.e. anisotropy) of the actual slope failure. As a starting point, if only 2D-derived material strengths are available for input into 3D analysis, it is recommended results be used to assess the relative change in FOS with different designs only. In such scenarios, the calculated FOS should not be reported as absolute values of stability measures.

Material strengths applied to successfully back analyse the stability of open pit slope cases are summarised in Figure 13. The geotechnical environment these material strengths have been derived in typically fall within a GSI range of 45 to 55 for fresh coal measure rock (10 to 20% lower for jointed coal measure rock), which equates to an approximate RMR range of 40 to 50.

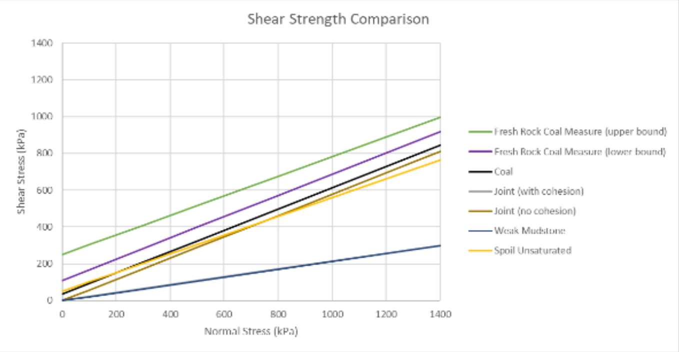

Figure 13 Shear strengths applied to 3D LE modelling for coal measure rocks

The range of material properties that were back analysed for joint strength in case study 2 shows the variance in material strengths that can be applied to achieve the same FOS. As such several back analysis of known slope conditions (stable or failed) are required to build confidence in the dataset of material parameters applied to both 3D and 2D analysis. The material strengths summarised in Figure 13 are therefore presented as a starting reference only. Several additional back analyses will be required to refine the range of material strengths for routine application in 3D LE analysis.

4 CONCLUSION

Traditionally kinematic and 2D LE analyses have been the most routinely applied to assess open cut slope stability with generic 2D material strength properties applied to models without consideration of anisotropy or slope geometry. 3D LE modelling is however now being used more readily to assess slope stability, particularly for concave or convex slope geometries, or where rock mass strength is anisotropic.

2D analysis often produces conservative indications of slope stability where 2D sections are cut to represent worst case scenarios. To reliably predict the performance (e.g. propensity for failure) and critical failure mechanism (including spatial location and slip surface dimensions) of slope failure, geotechnical engineers must select appropriate tools to complete slope stability assessments. 3D LE is such a tool that can adequately account for the failure mechanisms typically observed in highly anisotropic geological settings.

A common query when commencing 3D modelling is what material properties to include in the model. If no prior 3D modelling has been completed, material strengths back analysed from 2D analysis are often (incorrectly) included in 3D analysis. If 2D-derived properties are input into 3D analysis, the FOS calculated should be interpreted as a relative indicator of stability only (e.g. how does the FOS change with varying design geometries, and which sections of the pit have the lowest FOS even though the calculated FOS may be greater than 1.0). The FOS calculated from 3D analysis should only be interpreted as an absolute value of stability when material properties are back analysed using 3D modelling. This is because material strengths derived from 2D analysis have been found to over-estimate material strengths for application in 3D analysis (if 3D failure mechanisms have been modelled using 2D techniques).

This paper outlines four cases studies where 3D LE methods have been used to back analyse material strengths in open pit coal mines. It is shown in all cases that material strength properties differ from the set of generic coal measures properties typically applied for 2D slope analysis. Case studies include slip surfaces through rock mass and heavily jointed material excavated slopes. Case studies include an example that shows the difference in combinations of material properties that are calculated for the same material using 2D and 3D modelling techniques.

The intent of this paper was to demonstrate the application of 3D LE modelling to anisotropic coal measure rock masses and highlight the variance in material properties that can be back calculated using both 3D and 2D LE analysis.

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