3D limit equilibrium and finite element model development for coal mine slopes

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INTRODUCTION

Traditionally geotechnical design assessments for both excavated and dumped slopes in open cut coal mining have been undertaken using simplistic two dimensional (2D) limit equilibrium (LE) methodologies, prevalent hydrogeological assumptions and generic shear strength properties. This was satisfactory in simplistic strip mining of the past where excavation depths were limited and continuity in geotechnical conditions could be assumed outside of a section line.

As open cut coal mining has progressed deeper and conditions have become more complex due to stress, geological structure, and consequently the groundwater regime this 2D LE approach has shown to be limited often leading oversimplification of a slope model or the manipulation of conditional assumptions to meet an expected outcome. The assumption made can often lead to misrepresenting a potential failure mechanism and over engineering a solution to mitigate instability concerns that may not be justified or conversely missing a potential failure mechanism that exists outside a 2D plane.

Over the past five years in open cut coal mining slope evaluation, the application of three-dimensional (3D) modelling has increased significantly as software has become more user friendly but also areas requiring evaluation have become increasingly complex. Often simplistic 2D LE modelling and analysis has been poorly used to solve slope stability issues by back analysis and then subsequently applied these conditions forward predictive analysis where a plane strain condition with slope movement perpendicular to the slope strike is assumed where in reality the problem is more complex.

This paper presents two recent case studies where the initial slope assessment was undertaken as a 2D LE model which led to either an overly conservative and costly remedial solution being implemented or underestimation of the potential slope failure. Subsequent modelling of the slope using both 3D LE and Finite Element (FE) methods were able to provide a better understanding of the structural complexities associated and correlate well with slope monitoring data to create a more realistic outcome.

CASE STUDY A IN SITU ENDWALL BUTTRESS

Case study A is located in coal bearing sediments of Queensland's Bowen Basin where one to two economic coal seams are targeted using a combination of dragline and excavator mining methods. Dragline mining typically targets long strikes or strips of gentle to moderately dipping coal measures with mining advancing down dip, an active dragline and truck waste dump formed up dip and an advancing in situ highwall down dip. Often strips are confined by faulting which will be part of an in situ endwall, these walls are often only exposed for a limited period of time before the advancing dump covers them.

Case study A involves an endwall that was adjacent to an infrastructure corridor that was also bounded by known faulting. As part of routine inspections potential instability triggers where noted including cracking and displacement of the rockmass. An initial assessment stability was undertaken using 2D LE modelling with a representative section cut through the assumed affected area and the underlying geological structure. Rockmass and groundwater conditions were manipulated until failure conditions (Factor of Safety less than 1.0) were obtained. Assumptions were made around the strength and continuity of a bedding parallel shear, groundwater levels, fault location and shear strength with the rock mass assessed as an isotropic medium. Based on these results remedial measures in the form of a waste rock buttress was installed to mitigate any potential mass movement.

The assumed 2D back analysis conditions were then utilised to undertake further 2D LE and FE forward analysis for the end wall further down the strip to replicate the same conditions. Representative sections were developed perpendicular to the slope and analysis run however the identified failure mechanism in the initial slope could not be adequately replicated and assessed in 2D (See Figure 2). This was concluded largely due to the cross dip of the bedding allowing a block to fail sub-perpendicular, the interplay of intersecting faults and confinement of the installed buttress.

The initial 2D analysis had also made several assumptions during the initial slope assessment to replicate the potential failure conditions. These conditions were assumed to be ubiquitous within the geological environment but required validation.

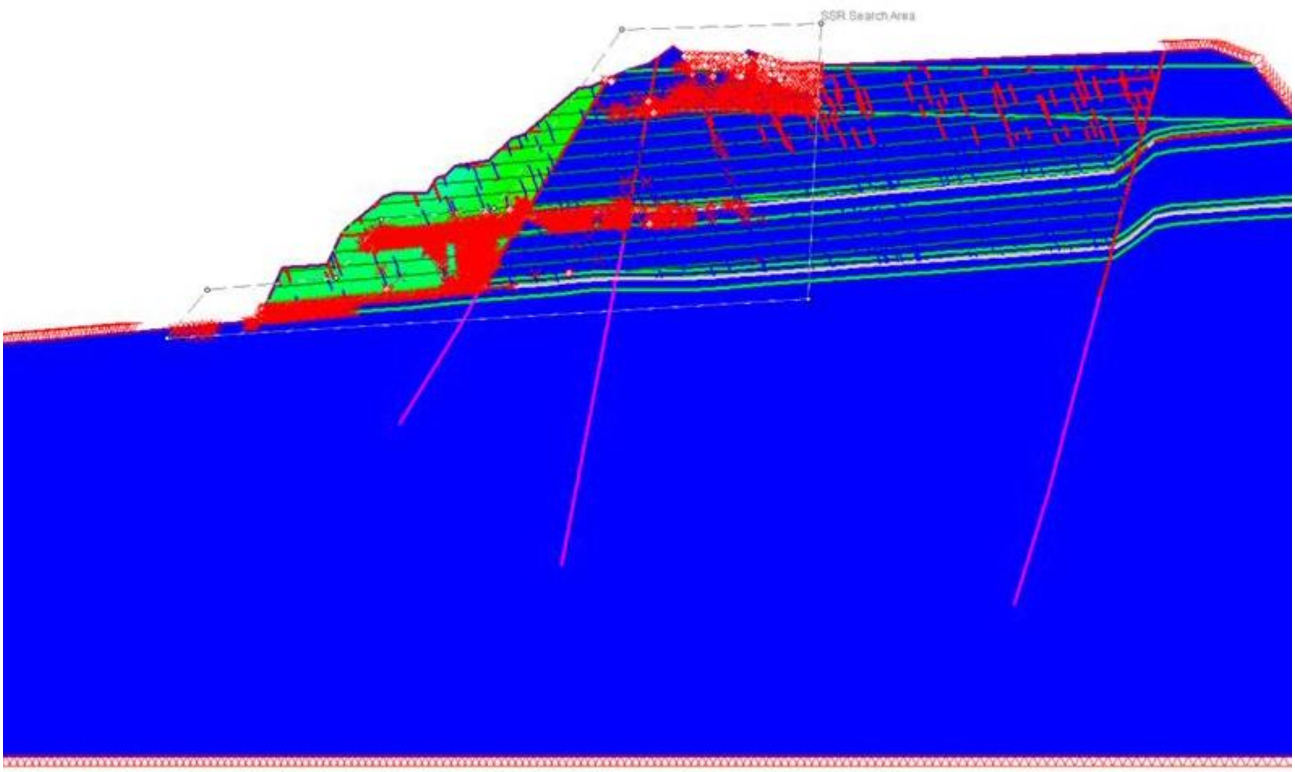

FIG 1 – 2D FE Output for Endwall Stability Assessment

Following further data collection to validate the initial slope failure assumptions slope models were developed using the proposed slope design, the geological structure wireframes for coal surfaces and major faulting in both 3D LE and FE analytical software.

Analytical iterations were run initially in 3D LE to validate the slope model before 3D FE to determine the magnitude and location of potential slope deformation. Modelling indicated that;

- Ubiquitous low strength bedding parallel surfaces throughout an in situ wall are unlikely to be present. Weak layers may be present and reduce in strength due to unloading near the excavated face,
- Groundwater affects are localised due to features such as faulting and bedding dip, and
- Rockmass strength is anisotropic with the orientation of defects playing a major part in stability,
- Intact rock shear strength will vary depending on the stress it has been placed under, this is shown to be different in a 3D analysis compared to a cross-sectional assessment.

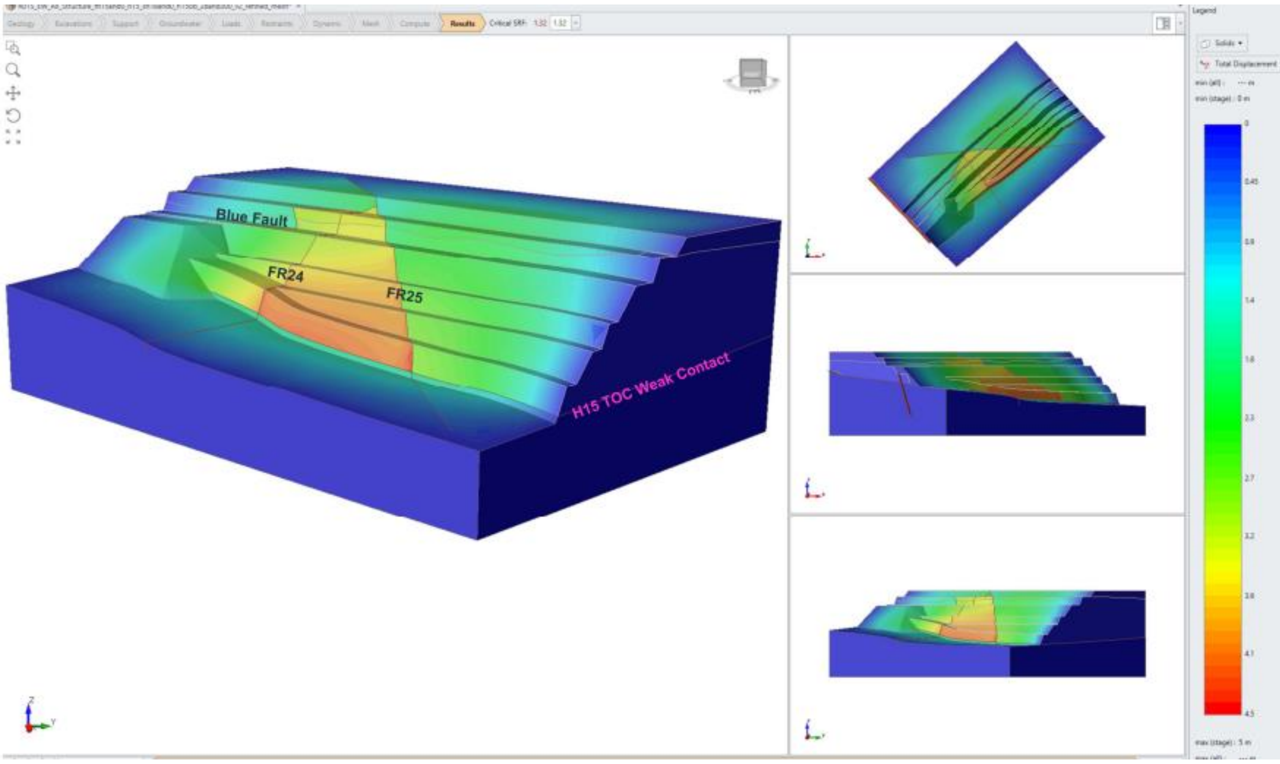

FIG 1 – 3D LEM Output for Endwall Assessment

CASE B IN SITU HIGHWALL STRUCTURAL FAILURE

Case study B is situated in the multi-seam Permian aged sediments of the Sydney basin in an open cut truck and shovel mining environment. In situ excavated walls are often exposed for extended periods until covered by an in-pit waste rock dump.

The highwall in question was initially modelled using 2D LE as part of the life of mine (LOM) design assessment. A representative cross-section was cut through the slope design and the underlying geological model for analysis. This involved the strata bedding and major rockmass structure such as faulting and intrusions with the apparent dips being represented in the geotechnical model. The section cut through an area cut by a main fault and locally affected bedding orientation. Isotropic material strengths were applied to the geotechnical domains identified.

Analysis was run using a Cuckoo search methodology to determine the factor of safety of the slope with results indicating a stable slope with a preferred failure envelop incorporating a multi-bench failure scenario.

Precursors to instability were noted during routine inspection as the slope excavation progressed with mitigation measures in the form of separation and bunding applied. The slope ultimately collapsed with a failed volume larger than that expected and allowed for (see Figure 3).

FIG 3 – Highwall Rockmass Failure

As part of the slope failure investigation a back analysis of the slope was undertaken using 3D LE modelling software to fully capture the role of the geological structure such as bedding variation and faulting orientation in the failure. It was also found that rockmass jointing fabric and localised variation in saturation may have also played a role in the wall collapse

Modelling in 3D LE was able to replicate the location and extent of the rockmass failure that had occurred and show that the failure was intensely related to three dimensional effects such as structural orientation for both rockmass jointing and faulting, local variations in bedding dip and changes in rockmass condition from blasting. The discrete 2D plane that was modelled to initially assess the slope would have not been able to truly represent these conditions without applying unreasonable assumptions to the model to simulate failure conditions.

DISCUSSION

The stability of a rock slope is always an interaction between the excavated design profile and the underlying geology and structure. This relates to both the shape of the excavation with regard to the orientation of excavated wall, the dip of slopes on an individual or overall slope basis and the interplay with the orientation of faults, strength anisotropy in the rock mass and spatial distribution of weaker zones.

2D analysis will infer plain strain conditions where any out of the plain effects such as strain or confinement aren't considered. The interaction of excavation and geology is directional and therefore best represented in 3D rather than an apparent or estimated parameter produced in a 2D model.

Although 2D has been reliable when coal mine development was in a simplistic geotechnical environment namely the continuity of conditions away from the sectional plane, as conditions have become more complex within the underlying geotechnical model 2D analysis has been difficult to represent actual conditions without compromising assumptions. It should be recognised that all geology, structural, and groundwater models are created in 3D, all mine planning is undertaken in a variety of 3D packages, geotechnical engineers will collect data in 3D, such as defect and groundwater data, however slope analysis is often reduced to a simplified 2D plane.

As coal mining moves away from a simplistic strip mining environment to a more geotechnical complex environment that can be modelled and designed in 3D it makes sense to be able to represent that in a slope stability assessment model.

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REFERENCES