Numerical Modelling of Undermined River Valleys — A Case Study

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ABSTRACT

Ground subsidence due to mining is a common dilemma confronting the underground coal mining industry. The effects of underground longwall mining on river valleys have come under scrutiny, especially when mining is located underneath catchment areas. As public awareness of mining impacts on the environment increases, there is the need to develop damage mitigation strategies. Results of numerical modelling show that river valley response to underground longwall mining can be simulated and evaluated.

INTRODUCTION

Various methods are used to predict closure, upsidence and compressive strain caused by valley buckling, and regional horizontal movements due to redistribution of *in situ* horizontal stresses around a mining area (Waddington Kay and Associates, 2002). While these predictive methods are useful, there is also a need to appreciate the deformation mechanics leading to valley base failure, ie why do some valleys base fail yet others do not, even when the same amount of closure has occurred? What factors determine the magnitude of vertical and lateral failure in river valleys?

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The aim of this project is to develop a set of guidelines to be used in the construction of a numerical model that can be implemented to assess underground longwall mining impacts on river valleys. This paper discusses the key elements in the construction of such a model with the explicit finite difference program FLAC 2D V4. A field site, WRS1, was nominated as a suitable validation site for the study. This site is located on the Waratah Rivulet, Helensburgh NSW, and has been undermined by Metropolitan Colliery. The site contains rock bars that were previously unaffected by longwall mining.

SITE DESCRIPTION

Metropolitan Colliery is located in Helensburgh, approximately half hour drive north of Wollongong and is mining the 3.2 m thick Bulli seam. The longwall panels are 140 m wide with 35 m wide chain pillars. The colliery is currently undermining the Waratah Rivulet, which is a major tributary to the Woronora Reservoir.

The rock bar, nominated 'WRS1' is located in the base of a valley and has been chosen as the site to study the effects of underground coal mining on valley bases. The WRS1 rock bar is located approximately 130 m from the maingate edge of Longwall 9 (Figure 1).

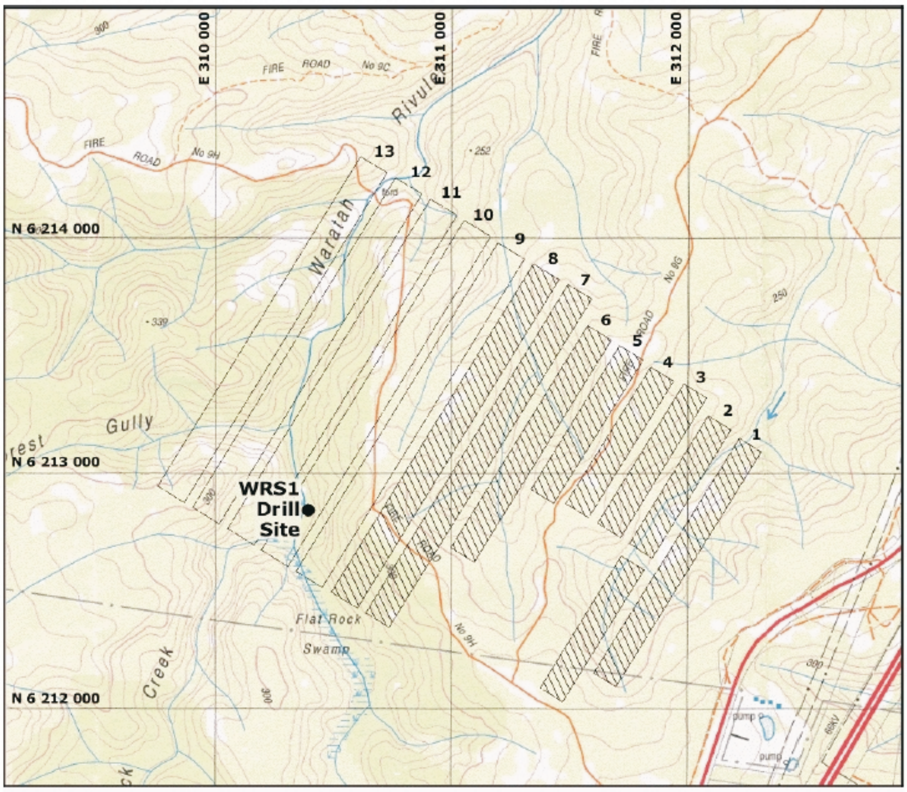

FIG 1 - Location of WRS1 (Mills, 2002).

RIVER VALLEY DEFORMATION AND FAILURE

According to Waddington and Kay (2002), river valley deformation is comprised of three main components. These are:

1. horizontal stress redistribution,
2. valley bulging, and
3. valley base failure.

Horizontal stress redistribution

Generally, *in situ* horizontal stress is greater than the *in situ* vertical stress. This phenomenon is not uncommon, and seems particularly pronounced in the Southern Coalfields.

When an opening is extracted under a valley (Figure 2):

1. The pre-existing horizontal stress is redistributed around the opening, concentrating above and below the opening.
2. This in turn increases the vertical stress, which causes the roof and floor of the opening to fail.
3. The previously redistributed horizontal stress, is displaced once more, and must find somewhere to go. As the extracted opening is in the process of creating a caved zone, the horizontal stress travels upward until it finds competent strata. This competent strata is usually located between the caved zone and the surface.

As a result, the pre-existing horizontal stress near the surface will be increased due to the redistribution of horizontal stresses due to mining. This implies that at the surface, the strata is compressed horizontally from the increased horizontal stress and expands vertically due to lack of confinement at the surface.

Valley bulging

Valley bulging is the term given to describe the inward movement of valley walls and bulging of the valley base. Valley bulging is a natural phenomenon but is accelerated as valleys are undermined or approached by underground mining. During valley formation, there is a redistribution of the *in situ* horizontal stress in the valley walls. The displaced horizontal stress is transferred to the valley base, causing upward movement of the base, as there is no confinement (Figure 3).

Valley base failure

With regards to valley base failure, it is known that the maximum compressive stress occurs in competent strata close to the surface. When the valley is undermined or approached by mining, the increased horizontal stress may be sufficient enough to fail the surface strata. As a result, failure progresses downward until equilibrium is reached. Figure 4 illustrates three types of failure, which are:

1. buckling,
2. wedging, and
3. shear on low angle discontinuities.

The upward buckling of the surface strata creates voids below the surface, which may impact on the hydrological aspects of rivers or creeks in valley bases. Lastly, failure of the valley base allows the valley walls to relax, resulting in closure. Due to this closure, tension cracks may be observed on the valley shoulders (Figure 3).

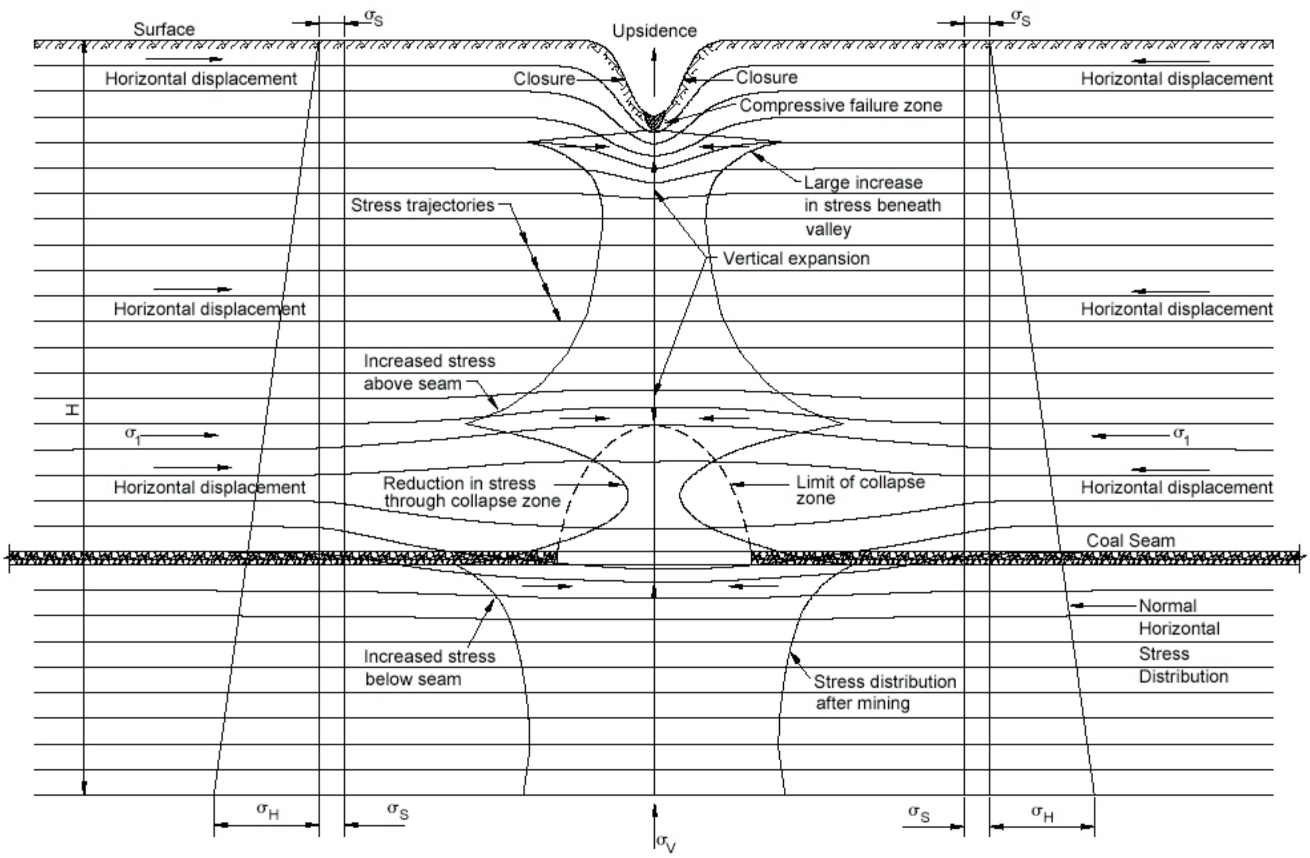

FIG 2 - Horizontal stress redistribution (Waddington, Kay and Associates, 2002).

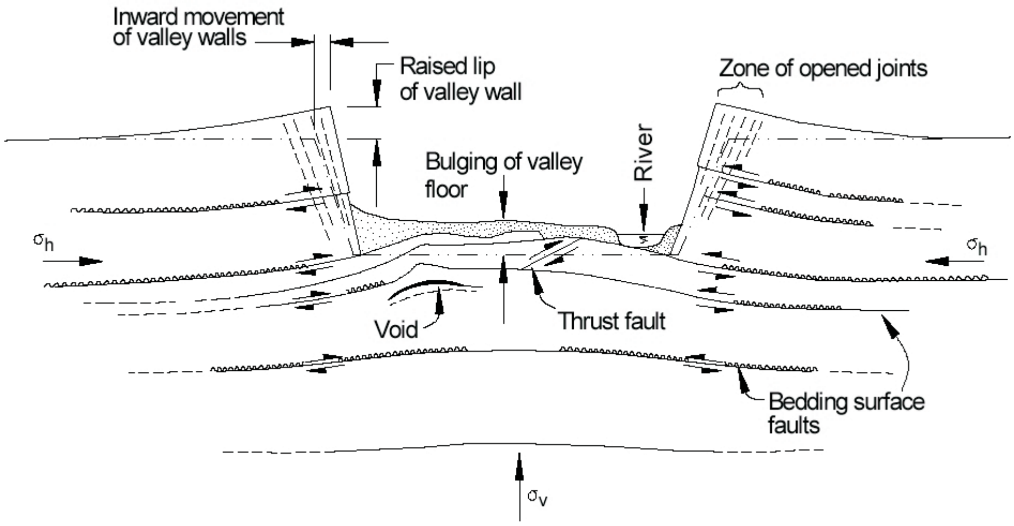

FIG 3 - Principles of valley bulging (Fell, MacGregor and Stapledon, 1992).

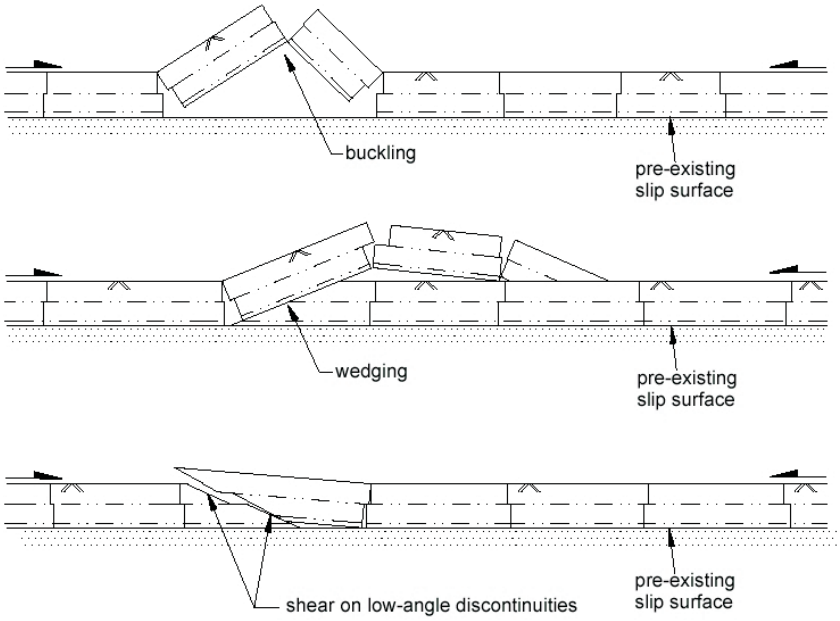

FIG 4 - Possible failure mechanisms in the bottom of a valley (Waddington, Kay and Associates, 2002).

THE NUMERICAL MODEL

Model geometry

The model geometry is based on the coordinates of survey line 3 (Figure 5), which traverses the rock bar and is used for evaluating horizontal and vertical movements. The model geometry was generated by extending the survey line, in conjunction with topographic maps, to obtain a more complete surface profile. Consideration was given to extending the line to adjacent topographic highs but the resultant geometry would be too large in terms of model building and run times. The final model geometry was determined after a parametric study, which varied the extension of the survey line and assessed whether element failure exceeded model boundaries (Figure 6).

Material properties

A series of triaxial tests were carried out on core samples from two boreholes (one vertical and one angled) at WRS1 to determine geomechanical properties. These properties have been incorporated into the model and a parametric study with 25 per cent, 50 per cent and 75 per cent reduction in strength and stiffness properties has also been carried out.

Constitutive model

FLAC 2D V4 offers a variety of plastic and elastic constitutive models. At the moment, the constitutive models of interest are:

1. Mohr Coulomb,
2. ubiquitous joint,
3. strain softening, and
4. bilinear strain hardening/softening ubiquitous joint.

The ubiquitous joint model is based on the Mohr-Coulomb failure criterion, but one problem associated with the Mohr-Coulomb constitutive model is the absence of strain softening, which cannot be ignored with a material like rock. However, this can be overcome with the strain softening and bilinear strain hardening/softening ubiquitous joint models but

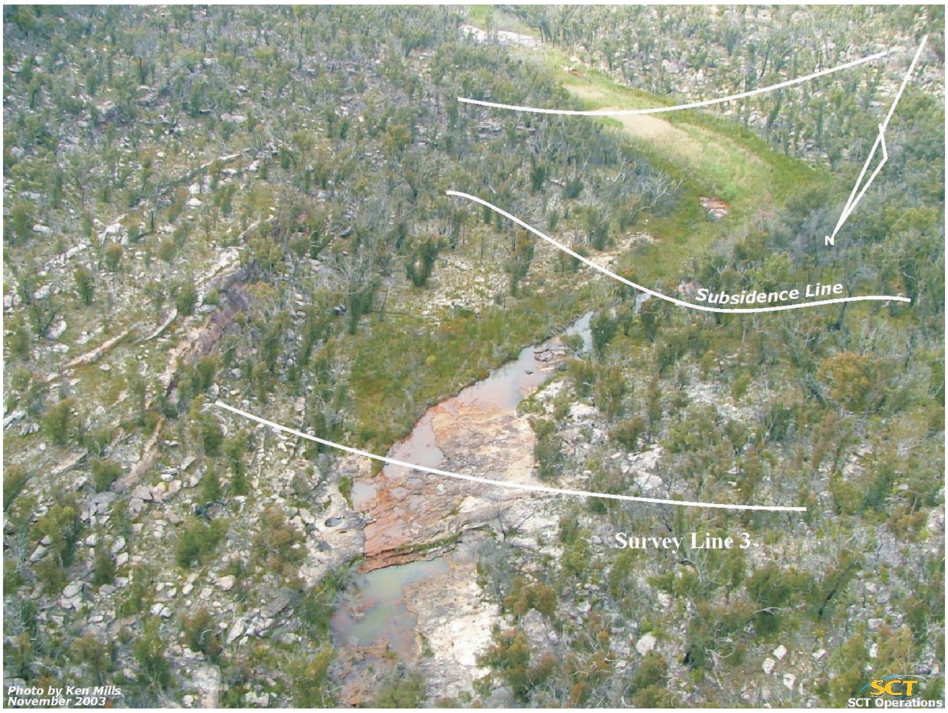

FIG 5 - Survey line 3 (after Mills and Huuskes, 2004).

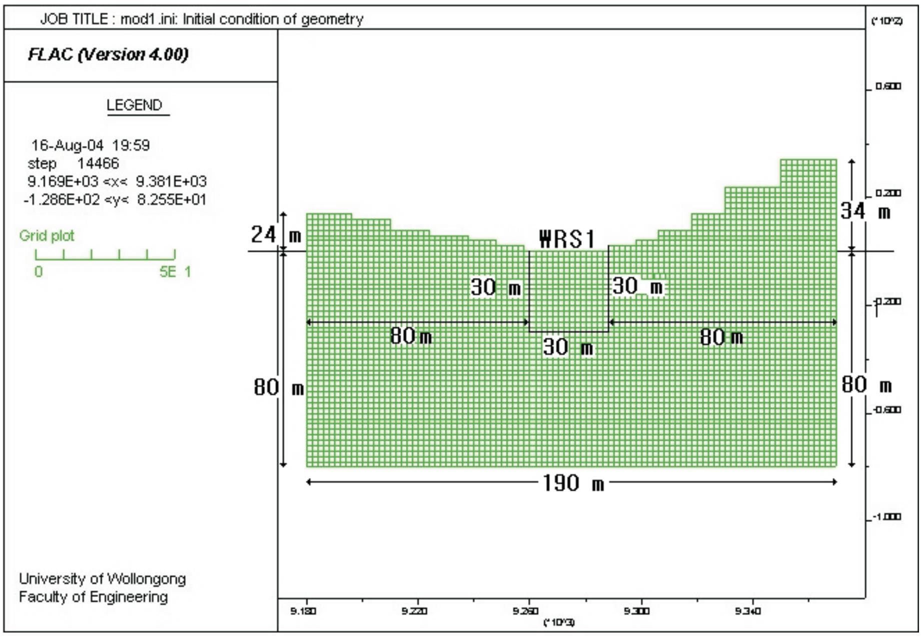

FIG 6 - Model geometry, north facing into page (Lee, 2005).

either model is complex and time consuming to set up, although they may be considered at a later date. The constitutive model chosen for the initial WRS1 model is a modified version of the ubiquitous joint model, which simulates instantaneous strain softening by resetting cohesion and tension to zero in the event of element failure. If required, discontinuities can also be incorporated with minimal effort.

In situ stress initialisation

The formation of the river valley was expected to play a significant part in the resultant *in situ* stresses. Ideally, excavating the valley in stages and then cycling the model to equilibrium after each excavation would have been preferred. This option was not possible because it was felt that the model would have to encompass the entire valley and surrounding topography, instead of focussing on the immediate area around WRS1. It also raises concerns about model runtimes and grid sizes. It was decided to excavate the entire valley and then cycle the model to equilibrium in conjunction with the chosen *in situ* stress regime.

In situ stress measurements conducted by Strata Control Technology Pty Ltd, have indicated that the magnitude of horizontal stress is double the vertical stress at a depth of ten metres, with principal stress magnitudes of 2.1 MPa, 1.4 MPa and 0.9 MPa (vertical) (Mills, 2002). Whilst it may be simplistic to utilise a ratio (k) of horizontal to vertical stress throughout the entire model, Pells (1993) suggested the use of such a ratio for depths of up to 100 m.

In the model, a user defined function that calculates horizontal stress based on the given k ratio is used. A parametric study was carried out with k values of one, two and three respectively. Pore pressure has not been incorporated into the model.

Valley closure simulation

Valley closure from undermining was simulated by applying a loading velocity at the model boundaries (Figures 7 and 8). It was found that a loading rate of 1×10^{-4} m/s on both sides was a sufficient rate of loading without shock loading the model and causing premature failure.

NUMERICAL MODELLING RESULTS

A parametric study has been carried out to study the effects from varying parameters of k ratio, reduction factors for material properties and loading type. The results have been compared with expected behaviour, not field observations.

Effect of *k* ratio

It was found that when the valley was excavated and the model was cycled to equilibrium, valley closure and upsidence occurred (Figure 9), which is consistent with movements resulting from valley formation. This behaviour was observed for all values of k ratio tested. Also, the nature of the resultant stress distribution showed basic agreement with theoretical explanations with a concentration of horizontal stress at the base of the valley using a k ratio of two (Figure 10).

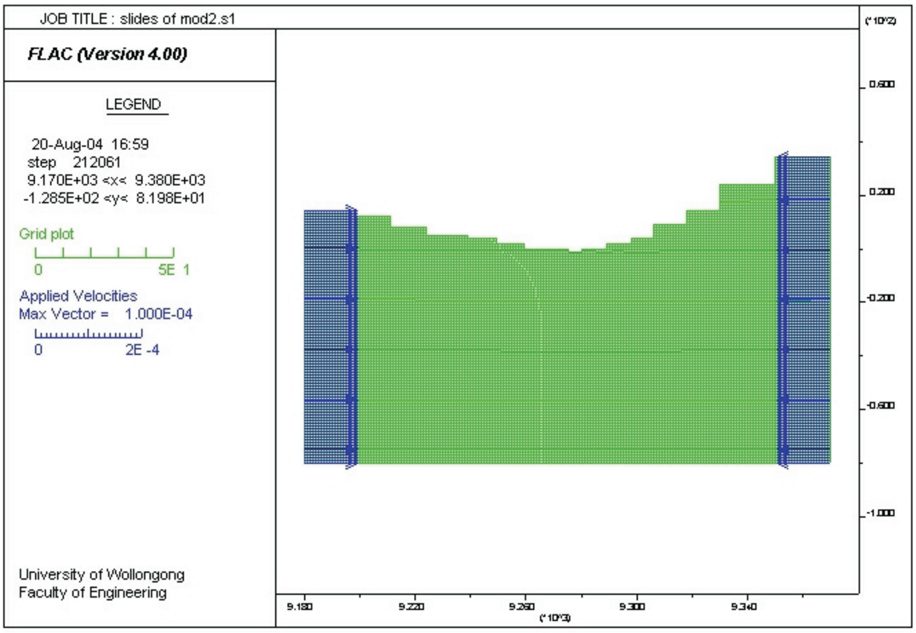

FIG 7 - Loading type 1 (Lee, 2005).

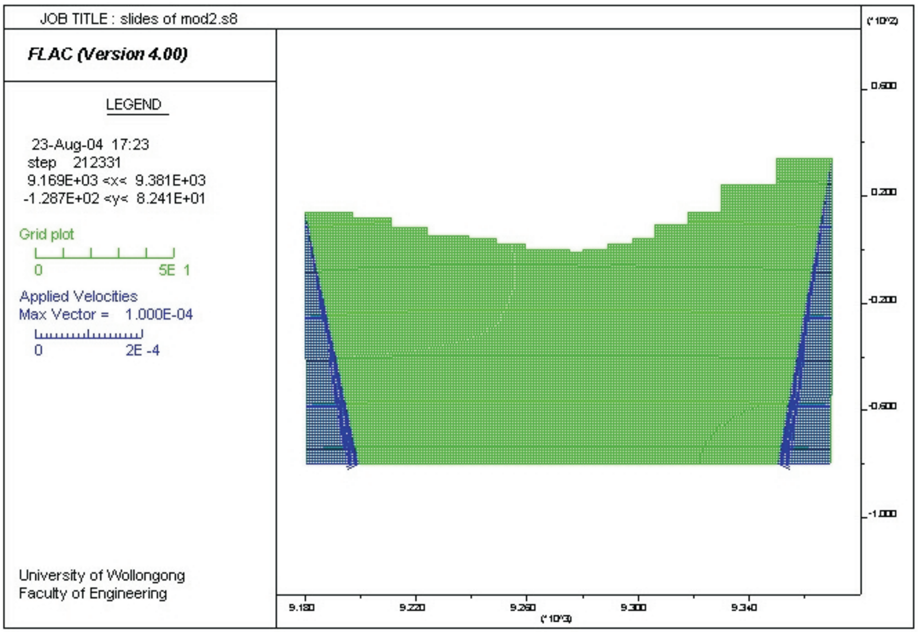

FIG 8 - Loading type 2 (Lee, 2005).

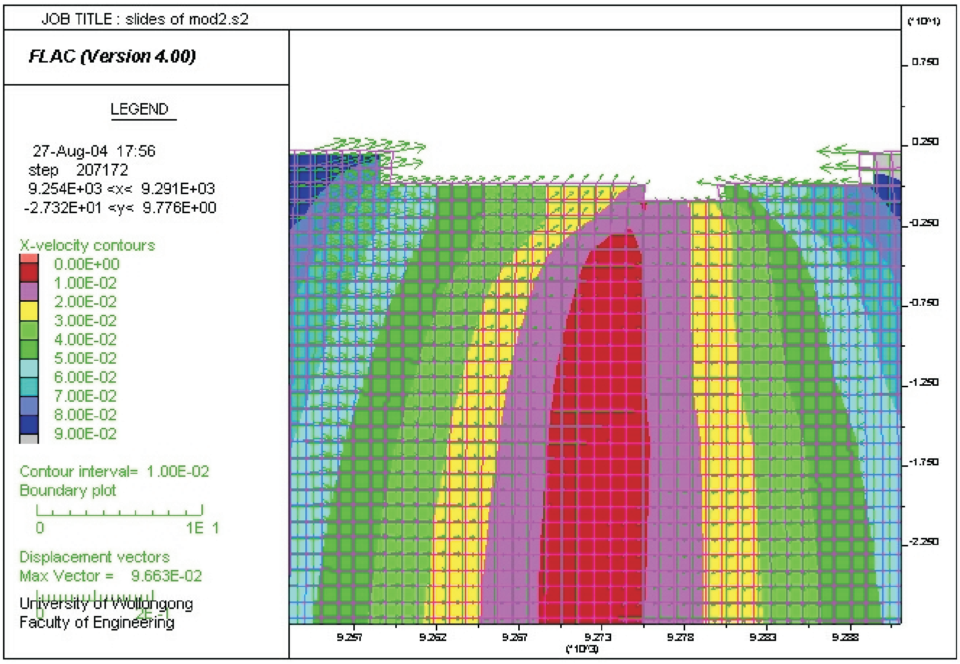

FIG 9 - Resultant closure and upsidence when cycling to equilibrium (Lee, 2005).

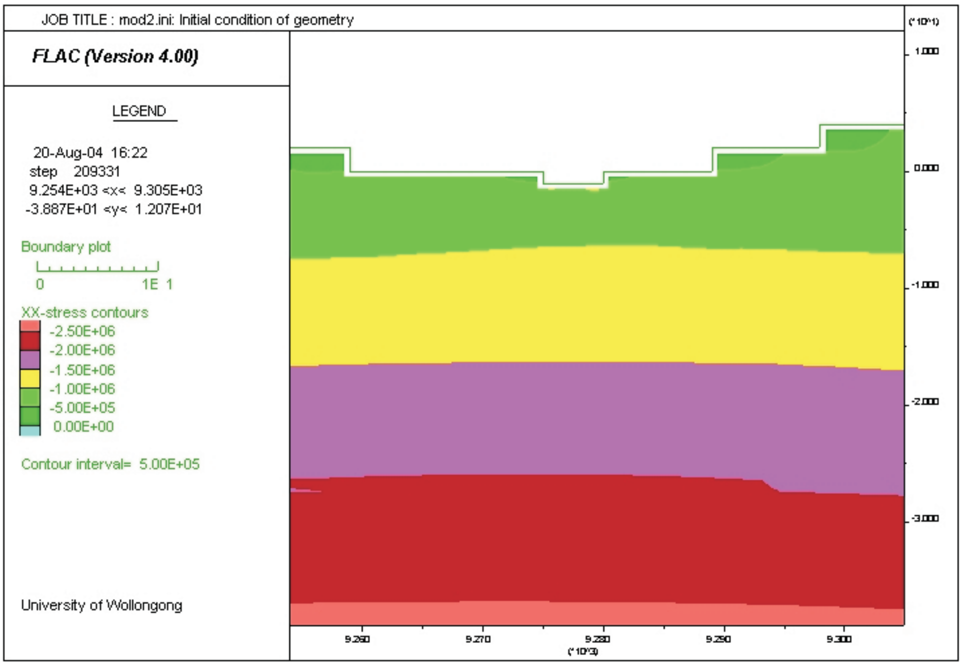

FIG 10 - Horizontal stress distribution at equilibrium, $k = 2$ (Lee, 2005).

Effect of reduction factors

As expected, variations in the reduction factors yielded considerably different results with valley bulging and valley base failure occurring at an earlier stage when higher reduction factors were applied.

Effect of loading type

It was found that 273 mm of lateral displacement on each side was the maximum allowable displacement required to initiate valley base failure, without failure propagating and contacting the fixed boundaries.

When loading type 1 was implemented, it was found that failure occurred in the base of the valley and then propagated downwards and outwards. It must be noted that failure in general did not exceed 6 - 10 m below the base of the valley (Figure 11). It was also noted that 15 m below the base of the valley; the strata appeared to dilate, with strata above this point moving upward and strata below this point moving downward. This is in agreement with Figure 3.

When loading type 2 was implemented, and it was found 492 mm of lateral displacement was required to produce element failure in the model without boundary interference. The pattern of failure was quite different, with failure occurring at the bottom of the model, with insignificant valley base failure (Figure 12).

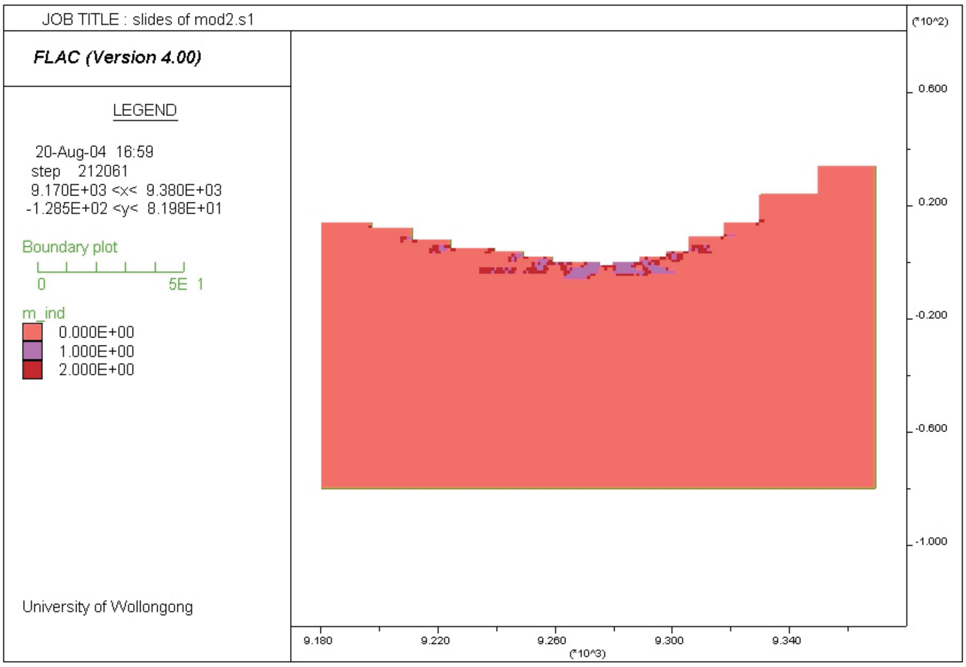

FIG 11 - Valley base failure for loading type 1 (Lee, 2005).

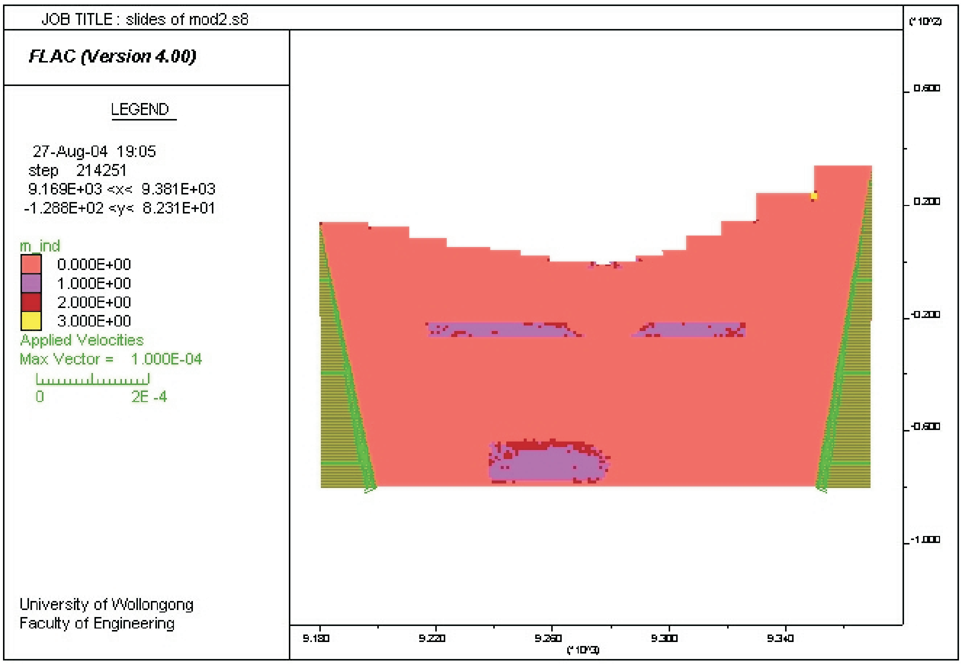

FIG 12 - Valley base failure for loading type 2 (Lee, 2005).

SUMMARY

It was found that the numerical modelling of the WRS1 field site would be best achieved by implementing a model with the following attributes:

- model geometry as illustrated in Figure 6,
- modified ubiquitous joint constitutive model,
- 50 per cent reduction in strength and stiffness properties,
- horizontal to vertical stress ratio (*k*) of two,
- loading type 1, and
- loading rate of 1×10^{-4} m/s.

Overall, the results from this study have indicated that numerical modelling with FLAC 2D V4 is capable of replicating theoretical behaviour with respect to *in situ* stress initialisation, valley bulging and valley base failure.

MODEL IMPROVEMENTS

The following key aspects have been identified for improvement:

- model geometry,
- incorporation of discontinuities,
- constitutive model, and
- loading type.

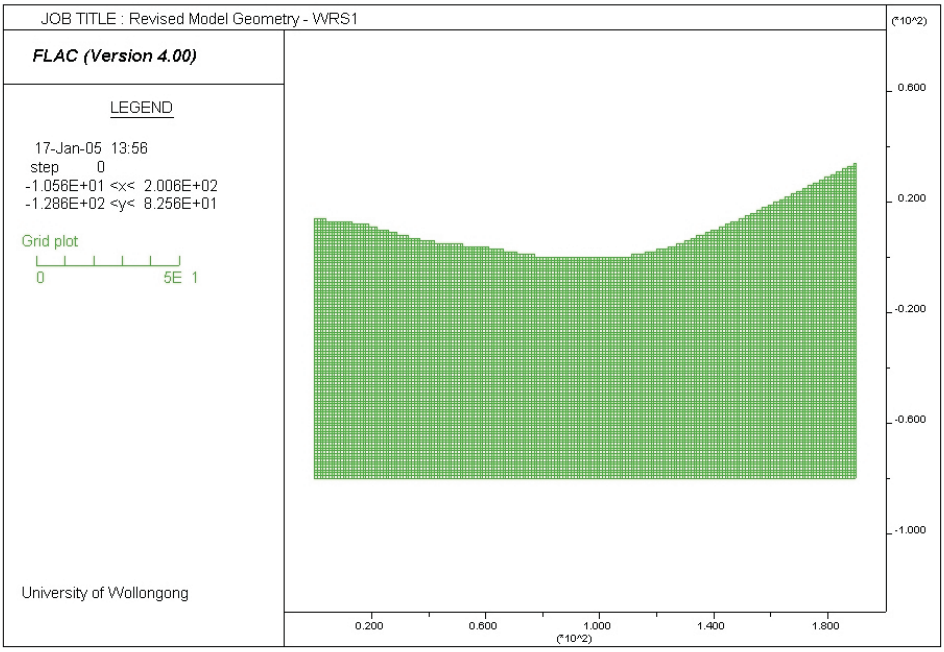

FIG 13 - Revised model geometry of WRS1.

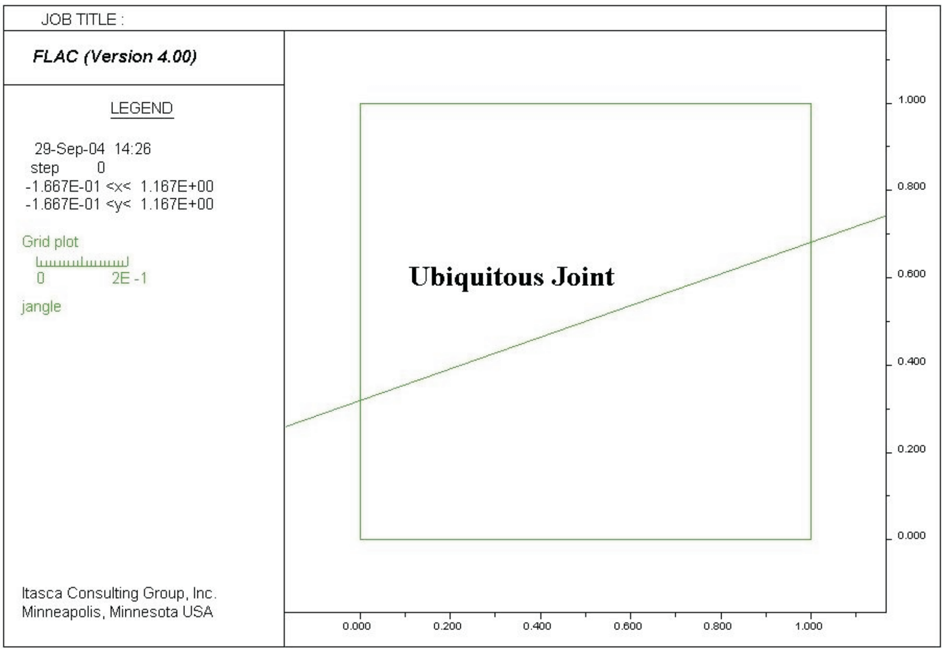

FIG 14 - Representation of a ubiquitous joint.

Model geometry

The original model geometry contains several 'blocky' steps in the valley sides. In order to reduce potential stress concentrations, the valley sides have been refined (Figure 13). This refined geometry is also a more accurate representation of the field site, smoothing out the lack of detail generated by topographic maps.

Incorporation of discontinuities

Ubiquitous Joints (Figure 14) and Interfaces (Figure 15) both represent a plane of weakness within a material, but the key difference between the two is that an interface consists of two boundaries separated by null zones.

The advantages of modelling weak planes using ubiquitous joints is that:

1. they are simple to incorporate into the model, and some constitutive models have 'inbuilt' ubiquitous joints; and
2. the joint properties can be derived from triaxial testing with angle core, but this is rather simplistic.

The disadvantages of using ubiquitous joints are:

1. slip and separation along a plane cannot be measured. Engineering judgment must be used to decide the magnitude of movement; and
2. erroneous results may occur if bedding plane properties are assumed to be the same as joint properties.

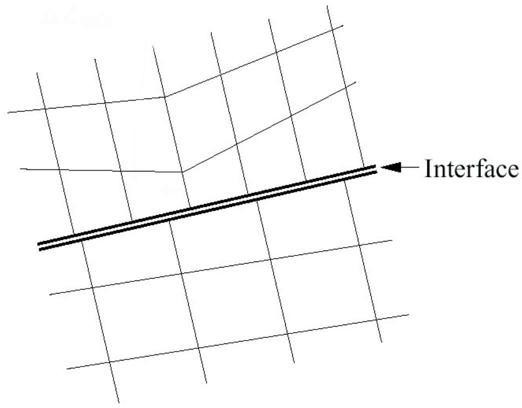

FIG 15 - Representation of an interface.

The advantages of using interfaces are:

1. slip and separation along a plane is measurable; and
2. bedding plane response in high horizontal stress fields are more accurately represented.

Likewise, the disadvantages of using interfaces are:

1. the model geometry would need extensive configuration if a lot of interfaces are required; and
2. the interface properties are difficult to determine.

It is envisaged that the WRS1 model will trial discontinuities represented by ubiquitous joints and interfaces.

Constitutive model

In order to reduce the runtimes and eliminate the lack of plotting features in modified constitutive models, it would be advantageous to use a built-in constitutive model that can represent strain softening and can incorporate discontinuities as either ubiquitous joints or interfaces.

If it is decided to use interfaces to represent discontinuities, the strain softening model will be used. On the other hand, if ubiquitous joints are introduced, then the bilinear strain hardening/softening ubiquitous joint model will be sufficient.

Loading type

From the results of initial modelling, it can be seen that loading type 2 was far from suitable for further investigation and loading type 1 produced more realistic results. However, loading type 1 assumes that lateral displacement is the same on both sides and does not vary with depth. Examination of the survey data from survey line 3 reveals that the west side of the valley closed in approximately 100 mm and the east side of the valley closed in approximately 200 mm. It is proposed that lateral displacement be applied to the model as dictated by survey measurements and be kept constant with depth.

CONCLUDING REMARKS

From the results of initial modelling, it is felt that the WRS1 model is capable of replicating the essential components of valley base failure, even in its simplified state.

The next stage of modelling will be aimed at refining and completing the model. This will include the selection of constitutive model, refinement of the model geometry, incorporation of discontinuities and selection of loading type. It is envisaged that once the model is completed, it will be validated with field observations and the resulting model construction guidelines will prove useful for application to other field sites.

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