Impact of Changes in the in-situ Stress Regime and Time Dependent Characteristics on Borehole stability in Brown Coal

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SLIDE 1

Bill & Richa are both busy in Melbourne, involved with laboratory testing of brown coal samples cored a few days ago from the Western Batters of the Hazelwood brown coal mine in Gippsland, so I have been asked to deputize for them.

The test program, which is outlined in the paper, is the first significant scientific study of the geomechanics of brown coal in Victoria since that of Ted Brown and Kevin Rosengren, supervised by Hugh Trollope at the University of Melbourne 50 years ago.

SLIDE 2

Tim Sullivan, in his report a few months ago on Geotechnical Stability issues relevant to the surroundings of the Hazelwood and Loy Yang coal mines, mentioned the existence of high horizontal in-situ stresses (in his Paragraph 41).

This fact seems to be not widely appreciated in the industry, with the erroneous assumption that gravity loadings and water pressures are the only significant de-stabilizing factors affecting stability issues.

High in-situ horizontal stresses are known to affect stability in hard-rock mines;
it may come as a surprise to some that these stresses can also affect stability in soft rocks, such as brown coal.

SLIDE 3

In his Paragraph 42 Tim Sullivan again emphasizes that the high in-situ stress leads to large movements.

Paragraph 43 summarizes some salient points, including the fact that deformations caused by mining of brown can be very extensive, both in extent away from the mining excavations, and in extended time after excavation processes have ceased.

The time-dependent testing carried out by BRTS is intended to improve the understanding of the time-dependent creep behaviour of brown coal, as an aid to interpreting the significance of the ground deformations being measured in the field.

SLIDE 4

On the left-hand edge of the picture : the Western Batters of the Hazelwood coal mine.

On the bottom edge of the picture, just left of centre : the Hazelwood Power Station.

In the upper right-hand corner of the picture : the town of Morwell.

In the centre of the screen, just below Morwell, the triangular “corner” of the mining excavation, is the original Morwell Open-cut mine, now worked out.

SLIDE 5

The grey areas are mining excavations and waste disposal areas.

The green diagonally-hatched areas are town areas.

The contours show the total measured subsidence, in millimetres:

The dashed light yellow-green lines show the subsidence from 1950/1958 values to 2004/2005 values.

The solid black lines show the subsidence from 1950/1958 values to 2009/2010 values.

Note the steepest gradients occur between the city of Traralgon and the Loy Yang mine, and between the city of Morwell and the Hazelwood mine.

Why? Possibly because the towns were allowed to establish themselves too close to the resources, at a time when the eventual magnitudes of ground movements that would eventually be caused by extracting the resources were not fully understood?

Possibly also because extensive recharging of groundwater by lawns and gardens?

Note also an appearance that the contours trending vertically, along the western side of the Hazelwood mine, seem to be closer together than the contours trending horizontally, along the south side of the Hazelwood mine and the north side of the Yallourn mine.

I'll refer to this when addressing a later slide.

SLIDE 6

An aerial view showing the active mining extraction area – the Western Batters, which is being progressively worked towards the Morwell River.

SLIDE 7

Another aerial view showing the active mining extraction area – the Western Batters, which is being progressively worked towards the Morwell River and the Strezlecki Highway.

This diminishing strip of land is being actively monitored to enable timely mitigation of any threats to the stability of river or highway.

SLIDE 8

An oblique aerial view, showing the main extraction area for the coal which provides a large proportion of Melbourne's electrical power, which is progressively approaching the Morwell River in the background.

SLIDE 9

The direction of the major in-situ horizontal stress.

Note that it is parallel to the face of the Western Batters, which are situated about 4 kilometres west of the Morwell Open Cut.

SLIDE 10

A concept sketch of how the deformations which would develop around a circular excavation in an unstressed body could be changed if that body was in fact stressed.

If we use this sketch as a rough analogue of the Hazelwood, we should mentally rotate the picture through almost 90 degrees, so that the tectonic force is acting from top to bottom of the picture, rather than from left to right : in other words, in a North-West direction in plan.

Note that this would put the ground to the west of the Western Batters into a state of horizontal compression, parallel to the mining faces.

Could this be related to the observation, in Slide 5, of an apparent clustering of the subsidence contours – a steepening of the subsidence gradient – to the west of the Hazelwood mine, as compared to an apparent widening of the subsidence contours – a flattenening of the subsidence gradient – to the south of the Hazelwood mine, which is conceptually shown as being in a relatively tensioned zone?

SLIDE 11

Modelling of the deformations caused by elastic stress relief, after a pit has been excavated into a pre-stressed medium.

Each drawing shows the left half of an axisymmetric body, which was a rectangle loaded up with an arbitrary stress field, then had an excavation cut into it. The right hand side of the dashed vertical line would be a mirror image of the half to the left, which is shown.

On the left, in blue, is shown the case where the loading was due to gravity, and a Poisson's ratio of 0.25 caused a horizontal stress equal to one-third of the vertical stress to be induced. K=0.33
[$\sigma_H = \nu/(1-\nu)*\sigma_V$]

On the right, in red, is shown the case where the horizontal in-situ stress was equal to 3 times the vertical gravity stress. K=3.0

The vector lines show the directions and relative magnitudes of deformations taking place post-excavation, at any point in the model.

Note particularly along the upper edge of the model, near the crest of the slope, how the gravity-loaded model shows deformations **upwards and away** from the crest, diminishing to zero at a horizontal distance from the crest equivalent to about the pit depth;

The horizontally-stressed model shows near the crest of the slope large horizontal deformations **towards the crest** (with a little uplift), but also quite large horizontal and upwards deformations extending for more than 2 times the pit depth away from the crest.

Interpretations of surface ground movement monitoring observations in terms only of gravity sliding of unstressed blocks towards a void, could be quite erroneous, if the deformations were in fact caused, at least part, by the effects shown in these models.

Apparent large deformations towards the crest could be an artefact of the in-situ horizontal stress relief, rather than solely to blocks sliding along a discontinuity.

SLIDE 12

This shows coloured plots of the results of three-dimensional computer modeling of a pit being dug :
In the lower 4 pictures, into a gravity-stressed medium with the horizontal field stress being equal to half of the vertical gravity load (i.e. Poisson's ratio = 0.33)

In the upper 4 pictures, into a tectonically-stressed medium with the horizontal field stress being equal to double the vertical gravity load.

Note the contrast between the lower pair of pictures in each block of 4.
The interface between the blue (depicting displacements of 0.15 to 0.3 metres) and the green (depicting displacements of 0.3 to 0.45 metres) moves significantly further outwards from the slope crest as the pit's depth is doubled, in the case of gravity loading than in the case of tectonic loading.

This is a confirmation of the desirability of knowing what in-situ horizontal stress field is acting, in order to be able to validly interpret deformation measurements around an open-cut mine.

SLIDE 13

This is a reminder of the famous Kirsch equations, for calculating stresses and displacements around a circular excavation, such as a borehole.

They are used to produce the results shown in the next slides.

SLIDE 14

The Kirsch equations were used to calculate the stresses at any point around a borehole, with 3 different stress fields acting in the undisturbed ground well outside the borehole.
At any point, the 3 stresses calculated were :
Radial stress, acting horizontally in a direction normal to the borehole wall σ_r
Tangential stress, acting horizontally in a direction parallel to the borehole wall σ_t
Vertical stress, acting in a direction parallel to the borehole axis σ_v

Three-dimensional Mohr circle construction was used to compare the 3-dimensional state of stress with the Mohr-Coulomb failure criterion, using the material properties published by Trollope, Rosengren and Brown in Geotechnique in 1965, and the horizontal field stress recently reported from the Latrobe Valley coal mines area.

The radial distance outwards at which the three-dimensional stress just balanced the strength of the coal was plotted.

The green markers show a symmetrical failure zone, as would be expected for an equal biaxial loading case, extending 35 mm outwards into the coal from the borehole wall.

If the stress field ratio changed from 1:1 (i.e. East-West stress equal to North-South stress) to 0.75 (i.e. East-West stress = 0.75 * North-South stress, or North-South stress = 1.33 * East-West stress), the blue markers show that the failed zone extends outwards to 40 mm, in the North-South direction, while slightly retracting (or rather, healing) in an East-West direction.

If the stress field ratio changed from 1:1 (i.e. East-West stress equal to North-South stress) to 0.5 (i.e. East-West stress = 0.5 * North-South stress, or North-South stress = 2 * East-West stress), the blue markers show that the failed zone extends outwards to 43 mm in the North-South direction, and to 47mm in NE, SE, SW, and NW directions, while significantly retracting (or rather, healing) in an East-West direction.

This modelling indicates how a borehole installed some distance away from a mine face can be expected to distort as a mine face is working towards it.

In the case of a borehole installed near the Morwell River, the magnitude of the North-South stress field may be expected to increase as the in-situ horizontal (North-South) stress field is progressively concentrated, parallel to the north-south oriented face of the Western Batters.
At the same time, the in-situ horizontal East-West stress field may be expected to progressively be relieved, in the “shadow” zone normal to the north-south oriented face of the Western Batters.

The 3 cases modelled in the slide give an indication of how the yielding zone around a borehole may be changed by the changing stress concentrations caused by progressive mining.

Any deformation measurements taken in such a borehole might be influenced by very local distortions of the immediate vicinity of the borehole, rather than by more regional translations.

SLIDE 15

The same modelling techniques used in the previous slide were used to illustrate the changes in the stability of the same borehole, in response to it being filled with water.

It can be seen that, for the modelled situation, an internal pressure of 650 kPa in the borehole would be sufficient to suppress failure, and keep the borehole walls acting elastically, rather than undergoing plastic deformation. (i.e. the pressure head generated by about 60 metres depth of water).

Note that if the internal fluid pressure dropped, for instance due to seasonal fluctuations of a few metres in the ground water level, this could lead to failure of the borehole walls.

Deformation measurements made in the following year might then indicate an alarming step-change.   The cause might be an impending major failure, or it could be a “harmless” local failure caused by fluctuations in the “stabilizing” water pressure.

This modelling indicates a mechanism for checking this.

SLIDE 16

The effects of fluctuating internal pressures in a borehole were further investigated, using the methods explained by Evert Hoek in Chapter 12 of his “Rock Engineering” notes. Elastoplastic analyses utilised the same material properties and ground stresses as modelled in Slides 14 and 15.

This slide shows the proportional thickness of the zone of plastic yielding outside a borehole in brown coal, as a function of the internal pressure of water in the borehole.

The effect of reductions of water level, and therefore the water pressure, are demonstrated.

If the internal pressure was 1 MPa, there would be no failure.
If the internal pressure dropped to 0.4 GPa, the plastic zone radius would be 1.5 times the borehole internal radius.
If the hole became dry, the plastic zone radius would be 5 times the internal borehole radius.

Unappreciated changes in borehole internal pressure could cast serious doubts on the validity of monitoring that assumed ideal elastic behavior of the ground.

SLIDE 17

Assuming the same borehole diameter of 300mm as used previously, the actual thickness of the zone of plastic yielding here.

The dimensions are quite significant : 50mm thick, for a borehole pressure of 44 kPa (or about 40 metres head of water),   570mm for a dry hole.

SLIDE 18

Finally, we look at the dimensions of the predicted closure, or convergence of the walls of a borehole in yielding brown coal.

The worst-case scenario modelled here would result in as much as 10mm of closure, due to removal of internal water pressure – totally independent of any deformations due to stress changes in the solid brown coal.

This may be worthy of consideration, when interpreting field measurements in geomechanics.

SLIDE 19

Conclusions.