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Impact of *in situ* stresses on underground cavern design

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ABSTRACT: The existence of a significant horizontal *in situ* stress field within the relatively shallow Triassic strata of the Sydney Basin in Australia is well established. The *in situ* stress state can have significant impacts on tunnelling conditions and on induced ground movements in the vicinity of underground openings. A parametric study has been undertaken to assess the impact of this critical *in situ* horizontal stress state on the performance of underground caverns. The study included using a constant lateral pressure coefficient, K of 1 or 4, and a variable stress profile. Various numerical model complexities were assessed ranging from simple homogeneous models to fully jointed models with various types of discontinuities. This paper discusses the parametric study undertaken and documents some of the predicted behaviour of the underground openings.

1 INTRODUCTION

The geotechnical design of excavations in weathered rock depends on a number of factors, including the geological profile of the site, the strength and compressibility of the rock substance, the location and properties of any defects and the virgin *in situ* stresses of the rock mass. In particular, the *in situ* stress state of the rock mass surrounding the excavation is one of the most important factors influencing the performance of the excavated openings. The importance of this design parameter has been discussed in various papers (e.g. Myrvang et al. 1998, Kumar *et al* 2004, Thuro & Gasparini 2000, Crawford & Bray 1983, McQueen 2004 & Walker 2004).

While the effect of high *in situ* stress field on the performance of tunnels and underground openings has been observed in the field and described qualitatively in various papers (e.g. de Ambrosis & Kotze 2004 & McQueen 2004), relatively limited assessment has been undertaken numerically to quantify the impact of various *in situ* stress assumptions on the behaviour of underground openings.

As part of the design process, the authors have conducted a numerical parametric study of the *in situ* stresses using different modelling software and model complexities.

2 UNDERGROUND EXCAVATION MODEL

The shape of the underground opening is important to the performance of the opening and the induced ground movements. This aspect had been assessed as part of the preliminary study, but will not be reported herein. The adopted underground excavation model included a main cavern with a 20 m wide arched span and 14 m high, a lower, slightly smaller cavern immediately alongside the main cavern and exit shafts at the two ends of the smaller cavern. A 3-D (half) model showing the interrelationship among the three facilities is shown in Figure 1.

Figure 1. 3-D Representation of the adopted underground opening model.

It is noted that the assumed geological profile of the model was varied among different models to assess the impact for different numerical idealisation approaches.

3 HOMOGENEOUS ROCK MODEL

3.1 *Methodology and assumptions*

Three different computer packages had been utilised for the analysis of the homogeneous rock model in order to confirm the validity of the analysed results. Each of these three packages utilised an independent analysis method to calculate rock responses including Phase[2] (a 2-D finite element program), 3DEC (a 3-D distinct element program) and Examine[3D] (a 3-D boundary element program).

A total of four separate idealised geological models had been considered for the homogeneous rock model. These geological models included high strength sandstone and low strength shale commonly encountered in Sydney, Australia.

With regard to the *in situ* stress state, it was assumed that the horizontal stresses were the major principal stresses while the vertical stress was the minor principal stress, consistent with typical Sydney Basin geological environment. Three different horizontal stress assumptions were analysed as follows:

$$\sigma_H = 1.0\ \sigma_v \quad \text{(i.e. K=1.0)} \tag{1}$$

$$\sigma_H = 4.0\ \sigma_v \quad \text{(i.e. K=4.0)} \tag{2}$$

$$\sigma_H = 0.5\text{MPa} + 2.5\ \sigma_v \tag{3}$$

where σ_H and σ_v are major horizontal and vertical stresses respectively.

3.2 *Observations*

Analyses conducted using all three packages showed that in homogeneous materials with high lateral stress field, the excavation of the adopted underground opening model resulted in upwards displacements both in the cavern crown and at the surface. Further review of the results showed that this behaviour was:

- Independent of the properties of the homogeneous material. It was found that both low strength shale and high strength sandstone resulted in the same behaviour.
- Dependent upon the *in situ* stress field. Surface heave only occurred in the cases where lateral stresses were greater than vertical stresses, i.e. K > 1.
- Dependent upon the homogenous nature of the material. Limited modelling showed that the introduction of material layering, with progressive increases in material stiffness with depth, resulted in settlements or downward displacements of the ground surface and in the cavern crown. Additionally, the introduction of further details into the geological model i.e. bedding planes resulted in further increases in settlement at the surface and tunnel crown. These results illustrate the potential errors introduced by oversimplifying the *in situ* geology into homogeneous or layered rock models. The effect of layering and presence of defects was further studied and reported in the following.

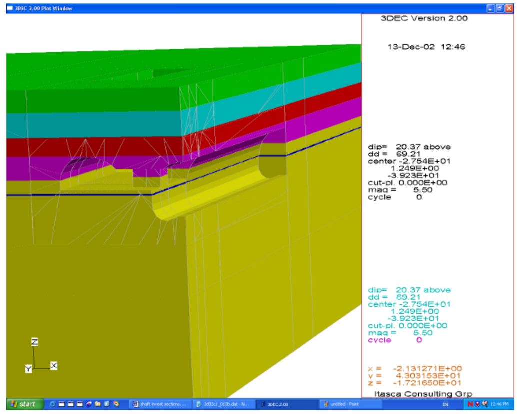


Figure 2. 3DEC model at transverse centreline.

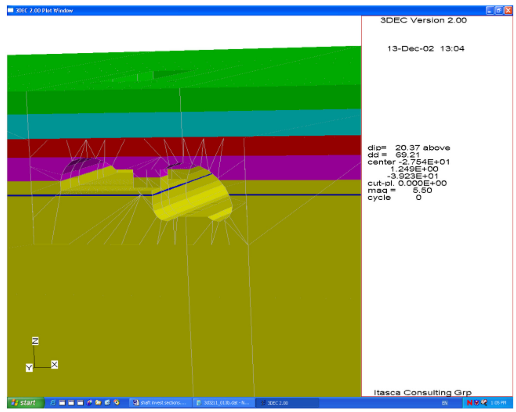
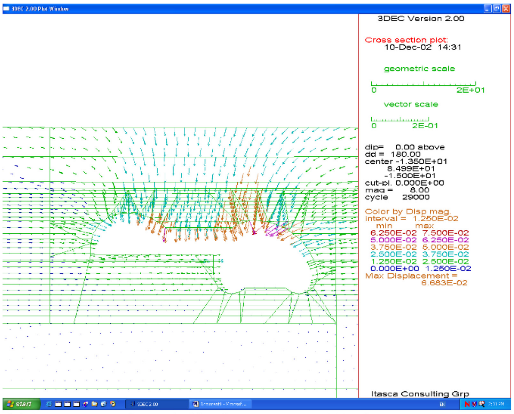


Figure 3. Model at main cavern centreline.

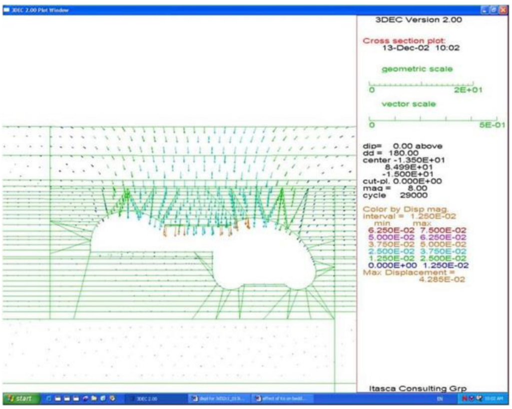
4 HORIZONTALLY BEDDED MODEL

4.1 *Geological models and approaches*

The impact of *in situ* stresses on horizontally bedded sandstone was studied using 3DEC. The model analysed was half image of the adopted configuration with an axis of symmetry at the centreline of the excavation opening. For parametric study purposes, the underground opening was assumed to be excavated as one stage of construction. The geological model was layered and included horizontal bedding partings. The layering included residual soil at the ground surface underlain by low strength shale, inter-bedded siltstone and sandstone, and high strength sandstone. The 3-D model is illustrated in Figures 2 and 3 showing two sections cutting through the model at the transverse centreline and longitudinal centreline of the main cavern respectively. The assumed horizontally bedded model is considered to be applicable in areas where the surrounding bedrock is relatively intact with major bedding planes and minimal intersecting cross beds or sub-vertical joints.

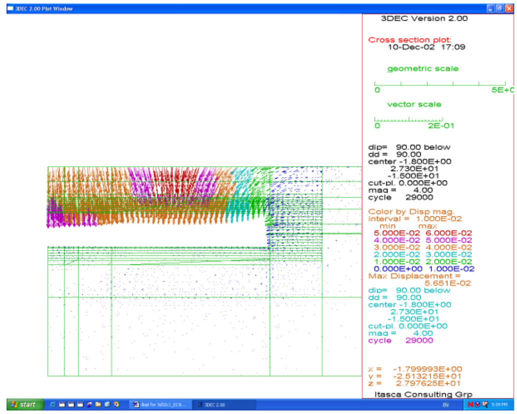


(a) Vectors of total displacement – K=4.

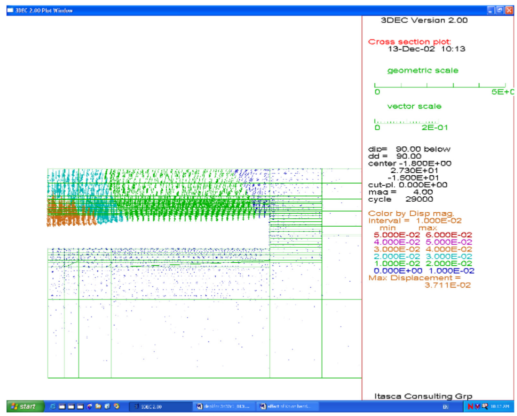


(b) Vectors of total displacement – K=1.

Figure 4. Comparison of predicted total displacement vectors at transverse centreline.



(a) Vectors of total displacement – K=4.



(b) Vectors of total displacement – K=1.

Figure 5. Comparison of predicted total displacement vectors at longitudinal centreline of main cavern.

4.2 *K = 1 versus K = 4*

Figures 4 and 5 present comparisons of calculated displacements for the full excavation with *in situ* stresses equal to K = 1 and K = 4 for the transverse and longitudinal sections respectively. Displacement vector colour coding was kept consistent between models at each section for comparison purposes.

Significant differences between the calculated vectors of total displacement presented in Figures 4 and 5 showed that the assumed *in situ* lateral stress conditions had a considerable impact on the amount of interaction between the adjacent cavern structures. For the case with K = 4, a maximum (lateral) displacement of 67 mm was predicted, whilst for the K = 1 case, the displacement was reduced to about 43 mm.

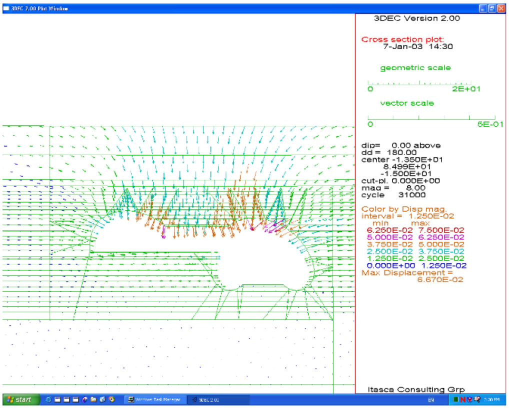
It is noted that the stress fields considered in these two cases were simplistic, in that they consider one constant K value for all the material layers. It is expected that the lateral stresses will tend to vary between different geological strata (and stiffness). In particular, a K = 1 condition is considered more appropriate for the upper soil/low strength shale while K = 4 could apply for the more competent sandstone.

Similarly, the section through the main cavern centreline confirmed that higher *in situ* stress conditions resulted in larger crown sag. The predicted maximum displacements along the main cavern centreline were 57 mm and 37 mm for the K = 4 and K = 1 respectively.

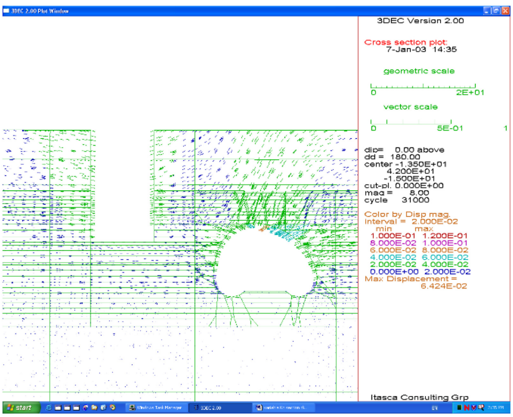
The above results were in contrary with the homogeneous model results which predicted upward displacements with high *in situ* stresses.

4.3 *Impact of variable K*

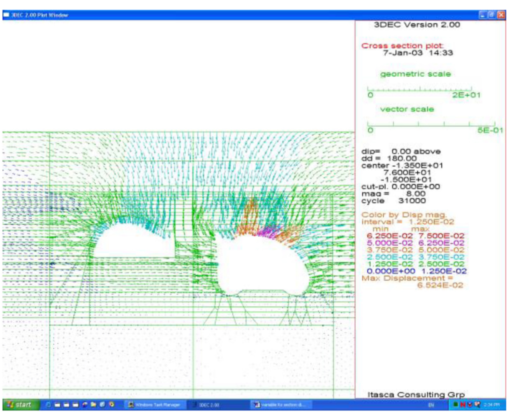
The above two constant K models were considered to be of academic values and useful for parametric study purposes only. It is noted that the natural *in situ* stress field within the Traissic rocks of the Sydney Basin is highly dependent upon the weathering and stiffness of the rocks. For modelling purposes, a variable K distribution had been assumed using the previous 3DEC model. From the ground surface to a depth of 11.5 m, a K = 1 condition was assumed in the residual soil and low strength shale. A transitional K = 2.5 was adopted



(a) At transverse centreline.



(b) Interaction between main cavern and exit shaft.

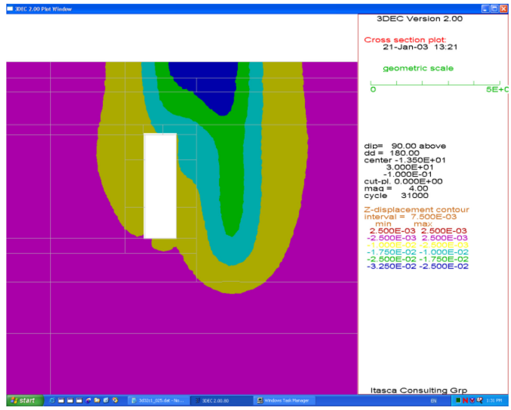


(c) At rock pillar between caverns.

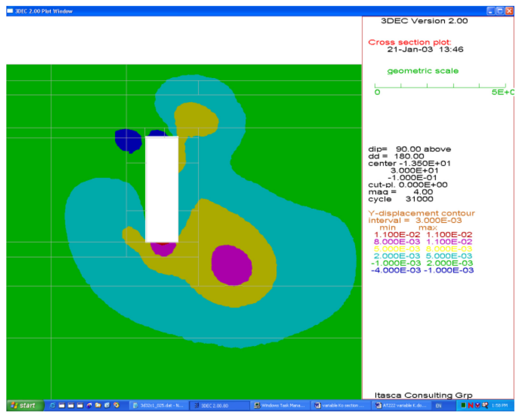
Figure 6. Predicted total displacement vectors for variable K conditions.

for the interbedded stratum, while K = 4 was assumed in the underlying more competent sandstone.

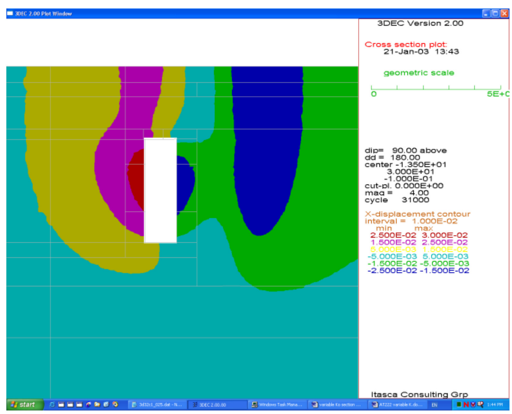
The results showing displacement vectors for the transverse sections are presented in Figure 6, while



(a) Vertical displacement contour at ground surface.



(b) Longitudinal horizontal displacement contours.



(c) Transverse horizontal displacement contours.

Figure 7. Predicted displacement contours at ground surface.

the results for the ground surface deformation pattern are shown in Figure 7. The following conclusions can be made from the results:

– Comparison between the displacements calculated along the section intersecting the main cavern and the exit shaft for lateral stresses K = 1, K = 4 and variable K showed that the stepped increase in K had resulted in a lateral deformation profile down the shaft that was greatly reduced from the uniform K = 4 condition. The maximum displacement in the variable K case was about 30 mm in comparison with 110 mm for uniform K = 4.

- In fact, the displacement for the variable K case was close to the K = 1 case which demonstrated that, for the exit shaft, the lateral ground displacements were dominated by the adopted K condition for the upper stratigraphy.
- Conversely, extensive similarities between the displacements calculated in the immediate vicinity of the cavern for the K = 4 case and the variable K case suggested that the lateral displacements in the cavern area were dominated by the K = 4 condition with little influence from the upper K = 1 part of the distribution. Further comparison of displacements calculated for other planes supported this assertion. Calculated displacement fields are essentially the same for these two cases in which all excavation was confined to the K = 4 sandstone. As such, the results for K = 4 model most likely remained valid for rock response calculated within the high strength sandstone.
- A comparison of the direction and magnitude of the surface displacement vectors for the three *in situ* lateral stress conditions considered suggested that the surface vertical displacements above the main cavern were largely dominated by the behaviour of the cavern itself. The results for K = 4 and variable K appeared to be similar.
- However in the area of the exit shaft, the total displacement vectors at this point were dominated by relatively large lateral displacements into the shaft excavation. As outlined above, the results for variable K and K = 1 were similar.
- The pattern of surface deformations, both vertical and lateral, given as contours on Figure 7, for the variable K condition showed that the maximum vertical displacement was some 30 mm for this model.

5 MODEL WITH CROSS BEDS AND JOINTS

5.1 *Modelling approaches and assumptions*

Due to the complexity of the 3-D model with the three openings, the various rock units and the simulation of the discontinuities, the 3DEC analyses were limited to the horizontally bedded models only. However, it was recognised that the Traissic rocks of the Sydney Basin could contain extensive cross beds and sub-vertical joints, at least in localised areas. It is therefore desirable to assess the impact of the various *in situ* stress conditions on the performance of the fully jointed models.

For the "fully jointed" model analyses, the 2-D Phase^2 software was adopted. The Phase^2 models contained the various rock units and the horizontal bedding partings as described previously. In addition, low angle cross beds and sub-vertical joints were introduced into the models. Both the interaction between the main and adjoining caverns, and that between the main cavern and the exit shaft were analysed as separate models. The 3-D effect of the rock pillars between the two caverns and of the variable horizontal extent of the exit shaft were approximated by applying "smearing factors" to the elastic moduli of the rock units after model calibration with 3DEC. Furthermore, both end-anchored bolts and a 250 mm thick structural liner were included in the models. The excavation sequencing and the installation of the rock bolts and structural liner were simulated in different stages of the models. The two-cavern model and the cavern/shaft model are shown diagrammatically in Figures 8 and 9 respectively.

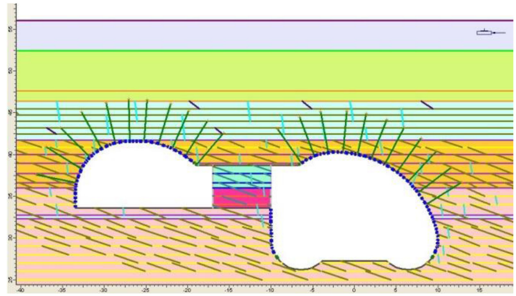


Figure 8. Model with the main and adjoining caverns.

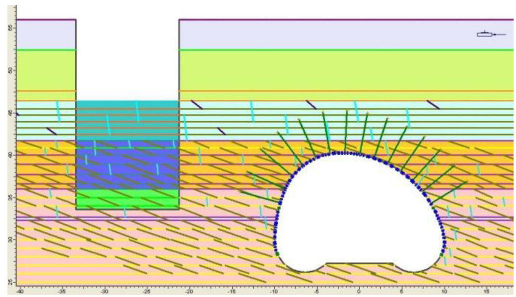


Figure 9. Model with main cavern and exit shaft.

Similar to the horizontally bedded models, different *in situ* stress conditions were analysed, *viz*: K = 1, K = 4 and the previously described variable K model.

5.2 *Modelling results*

The analysis results for the two fully jointed models are summarised in Table 1. As can be seen from the table, the general behaviour of the fully jointed models was similar to the horizontally bedded model. The high *in situ* stress (K = 4) conditions induced larger displacements than the low *in situ* stress case.

Furthermore, the results for the variable K model were similar to those for the constant K = 4 case for the two-cavern configuration. This behaviour is consistent

Table 1. Summary of Phase 2 analysis results for the fully jointed models.

In situ stress assumption	K = 1 mm	K = 4 mm	Variable K mm
Main and adjoining caverns: Maximum bedding plane shear displacement near cavern crown	9.1	14.5	14.5
Maximum crown sag – main cavern	56.2	70.2	70.2
Maximum crown sag – adjoining cavern	30.8	36.9	37.1
Maximum ground surface displacement	39.9	44.6	44.6
Main cavern and exit shaft: Maximum bedding plane shear displacement near cavern crown	5.2	12.6	11.9
Maximum crown sag – main cavern	26.8	37.3	35.1
Maximum ground surface displacement	15.5	23.8	20.6
Maximum exit shaft lateral displacement	10.9	255.8	31.9

with the fact that both caverns were located entirely within high strength sandstone with assumed K = 4.

Conversely, for the cavern/shaft model, the predicted displacements near the exit shaft using the variable K were similar to the results using K = 1 because of the low K assumption for the upper sections of the variable K model. The displacements near the main cavern for the variable K model were between the two constant K (1 and 4) model results.

6 CONCLUSIONS

The impact of the *in situ* stress field is very significant in the prediction of underground openings. However, such impact is dependent upon the presence of defects within the rock mass. Analysis using homogeneous rock models without discontinuity predicted that underground excavations in high *in situ* horizontal stress conditions could induce upward movements of the crown and ground surface. Conversely, for horizontally bedded and fully jointed environments, modelling indicated that higher *in situ* horizontal stresses predict larger crown sag, ground surface settlement and lateral displacements.

Therefore, any assessment of the impact of *in situ* stresses on the underground openings must consider carefully the presence of defects in the vicinity of the openings. It also implies that appropriate numerical models must be used if correct behaviour of the rock mass is to be predicted. The use of simplistic continuum models to simulate jointed rock mass without taking cognisance of the presence of defects could result in erroneous predictions.

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