Numerical Analysis of Large Adjacent Caverns for Sydney's Epping to Chatswood Rail Line

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Abstract: The Epping to Chatswood Rail Line is the NSW Government's largest publicly funded infrastructure project. It is currently being constructed through the Triassic age sandstones, siltstones and shales of the Sydney Basin. The project consists of twin, 12.5km, 7.2m diameter rail tunnels, 4 new station caverns and numerous shafts/tunnel service buildings. Macquarie Park, Macquarie University and Delhi Road Stations are 3 of the 4 stations along the route. The layout of each of these stations requires the construction of a number of large caverns (20m span) and shafts within close proximity of each other.

As part of the design process, a large amount of numerical modeling has been conducted to investigate the potential interaction between these large adjoining cavern structures. The presence of relatively high insitu lateral stresses has presented a number of challenges for the design process. This paper briefly describes a suite of three dimensional distinct element analyses (3DEC) conducted to investigate the behaviour of these large adjacent excavations. Particular reference is made to how these analyses were used as part of a larger design process.

INTRODUCTION

Major construction for the Epping to Chatswood Rail Line commenced on the 25th November 2002. Upon completion, up to 25km of rail tunnel, 4 new station caverns and numerous shafts/tunnel service buildings will be added to Sydney's current rail infrastructure.

This paper aims to present an insight into how, as part of the station cavern design process, three dimensional (3D) numerical analyses were used to enhance plane strain modeling in order to develop a fuller understanding of the likely interaction between the various adjacent caverns and shaft structures.

ROUTE GEOLOGY

The route of the Epping to Chatswood Rail Line lies within the Triassic age sandstones, siltstones and shales of the Sydney Basin. In particular, the three uppermost formations, the Wianamatta group (typically Ashfield shale), the Mittagong formation and Hawkesbury Sandstone constitute the encountered bedrock.

Figure 1 presents the stratigraphic sequence for these three formations (Herbert, 1983). In general, a movement up the sequence sees a progressive decrease in the encountered grain size, from the medium to coarse quartz grained Hawkesbury Sandstone to the claystones and siltstones of the Ashfield Shale. The Mittagong formation, being a transitional sequence between the adjacent formations, retains aspects of both depositional environments, with interbedded shales and fine to medium grained sandstones typifying this sequence. All three formations are near horizontally bedded and in general contain horizontal stresses significantly higher than the corresponding geostatic pressures (Enever et al., 1990, Pells, 1990, Enever, 1999).

<table>
<tr><th>AGE</th><th colspan="2">STRATIGRAPHIC UNIT</th></tr>
<tr><td></td><td colspan="2">South of Hawkesbury River</td></tr>
<tr><td rowspan="5">MIDDLE TRIASSIC</td><td rowspan="3">WIANAMATTA GROUP</td><td>Bringelly Shale - Potts Hill Sandstone
- Cobbitty Claystone Bed</td></tr>
<tr><td>Minchinbury Sandstone</td></tr>
<tr><td>Ashfield Shale - Mulgoa Laminite
- Regentville Siltstone
- Kellyville Laminite
- Rouse Hill Siltstone</td></tr>
<tr><td colspan="2">Mittagong Formation</td></tr>
<tr><td colspan="2">Hawkesbury Sandstone</td></tr>
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Figure 1: Stratigraphic sequence for the upper Sydney Basin formations (Herbert, 1983).

Whilst the proposed tunnel alignment is such that excavation is predominately within the Hawkesbury Sandstone, the proximity of the station caverns to the surface, as well as the gradational nature of the Hawkesbury/Mittagong contact has meant that the engineering properties of both the Mittagong formation and Ashfield Shale have had to be considered for the station cavern design.

CAVERN LAYOUT

Figures 2 and 3 present a plan view and typical cross section for the Macquarie Park Station Cavern. Whilst, strictly speaking, the set out of each station cavern is unique, the general layout of the platform and concourse cavern and the typical cross section for Macquarie University and Delhi Road Stations are similar to those shown here.

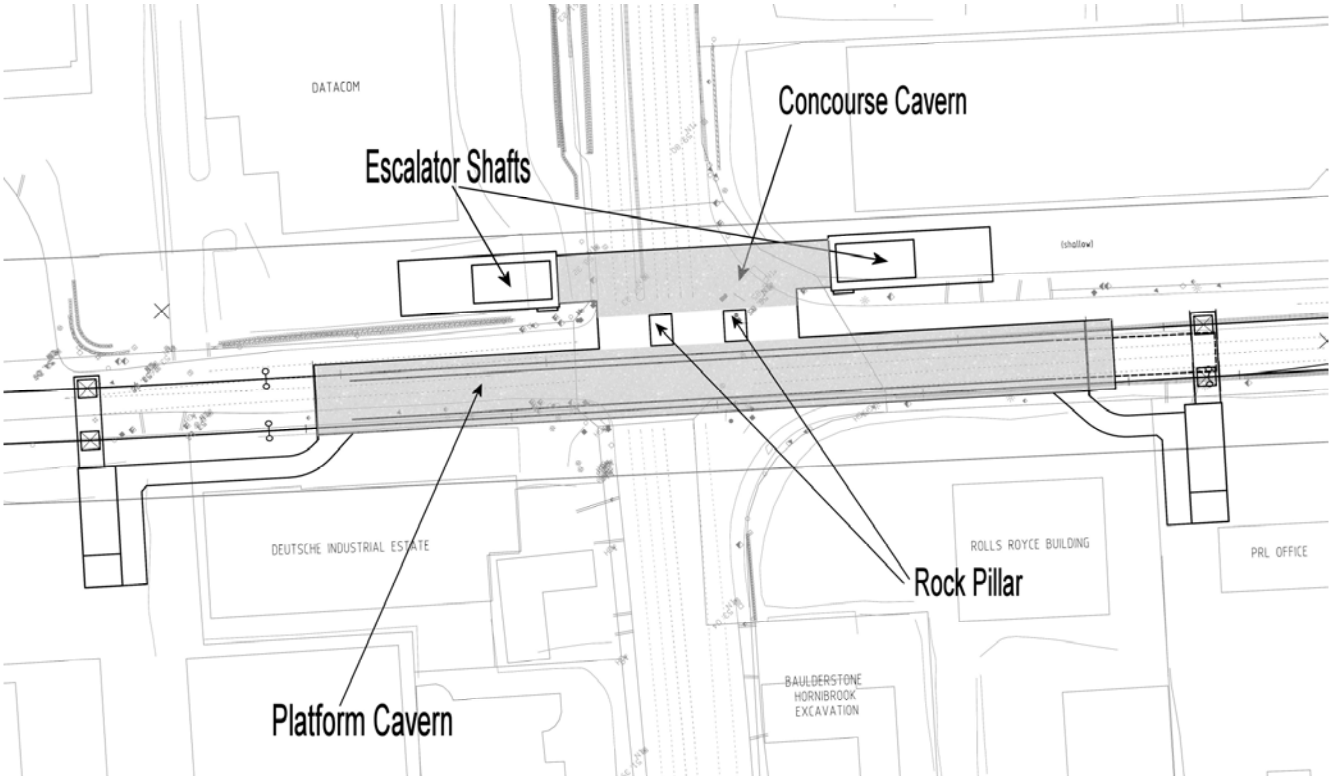


Figure 2: Plan view of Macquarie Park Station Cavern.

The main station structure is the 190m long, 15m high, and 20m wide platform cavern. When completed this cavern will contain the rail passenger platforms. Immediately adjacent to the platform cavern sits the smaller concourse cavern. This 50m long, 15m wide and 8m high cavern will contain ticketing booths and barriers. Access to the caverns from the surface is via two open shafts, which can be seen connecting to either end of the concourse cavern.

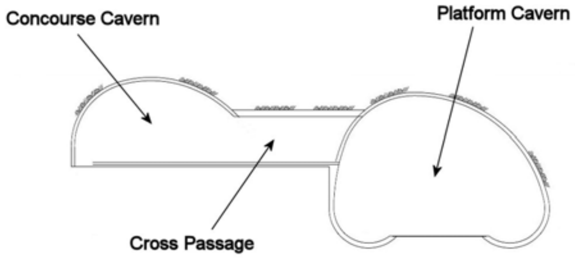


Figure 3: Typical cross section for the Macquarie Park, Macquarie University and Delhi Road Station Caverns.

ANALYSIS METHODOLOGY

As can be seen from Figures 2 and 3, the layout of the station caverns and the nature of the access tunnels between them is such, that modeling the structures using entirely plane strain conditions is challenging. In particular, note is drawn to the pillars formed by the cross passages between the concourse and platform caverns and a narrowing of the access shaft length towards the base. Such features are intrinsically 3D and as such a modeling methodology that was capable of considering the 3D nature of the caverns needed to be developed.

Notwithstanding this, tight design deadlines in conjunction with the desire to use parametric studies in order to deal with the uncertainties inherent to the analysis of discontinuous rock (where the nature and location of the discontinuities is preponderant in determining the behaviour of the rock mass) meant that time taken to set-up, run and review the analyses was also of consideration.

In order to deal with these potentially conflicting demands, it was proposed that the modeling methodology involve a combination of 2D and 3D analyses. The influence of 3D restraint would be approximated within the plane strain models using various numerical techniques (e.g. material smearing). Limited 3D modeling could then be used to ‘truth test’ these plane strain approximations at different locations within the caverns via comparison of ‘equivalent’ 2D and 3D models.

In this way, the parametric studies carried out using the relatively rapid 2D plane strain analyses could be enhanced using the results of the 3D analysis, with the 3D 'truth testing' process providing increased confidence that the adopted 3D approximation techniques were providing a reasonable approximation of the 3D interaction between the cavern structures.

ANALYTICAL PROGRAMS

The following three computer packages were selected for the analysis process:

- Examine^{3D} (Rocscience)
- 3DEC (Itasca)
- Phase^{2} (Rocscience)

Each package utilizes an independent analysis method to calculate rock response (Examine^{3D} is a 3D boundary element program, 3DEC is a 3D distinct element program and Phase^{2} is a 2D finite element program). A conscious decision was made to use independent analysis methods, because by comparing the results of 'compatible' analyses, some indication could be had as to the influence of the various simplifications and assumptions inherent to each specific method.

EXAMINE^{3D} (Rocscience)

Examine^{3D} is a commercially available 3D boundary element program. It uses infinite and semi-infinite elements to model the rock mass surrounding the tunnel. The method provides significant computational efficiency for 3D analyses, because only the model surface is discretised. As such, it was originally intended to be used for the majority of the 3D parametric variation work. Unfortunately however, the programs inherent assumption that the rock mass can be represented by an isotropic, homogeneous, linear elastic material proved restrictive for this application (see section titled 'Effects of material layering') and consequently use of Examine^{3D} was typically restricted to visualisation of the complex cavern facilities and basic validation/parametric studies. As an example of the programs visualisation capabilities, Figure 4 presents a view from inside the platform cavern, created using Examine^{3D} and a customized plotting program.

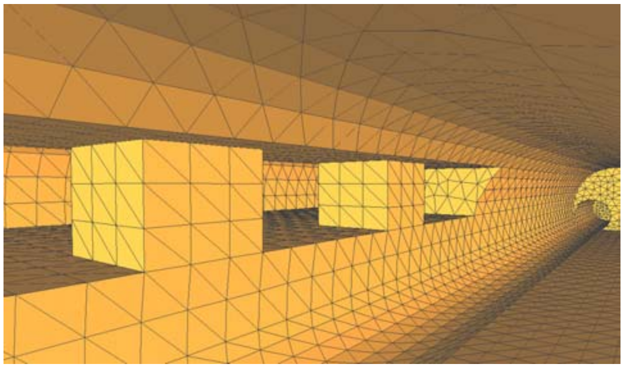
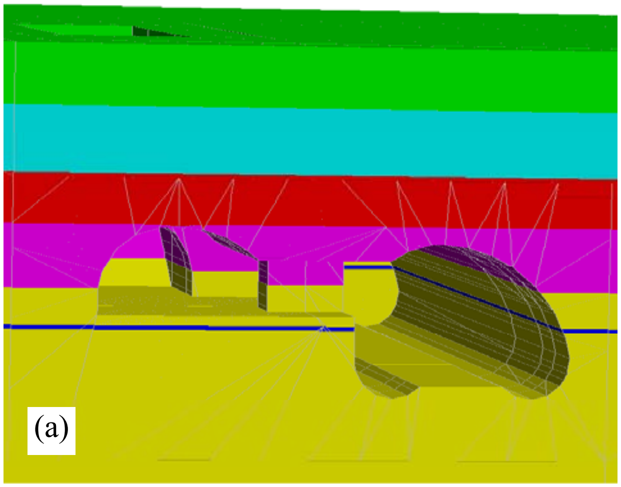


Figure 4: 3D view looking from inside the Platform Cavern, across to the concourse cavern.

3DEC (Itasca)

3DEC is a 3D distinct element program. The considered model is broken up into a series of deformable or non-deformable blocks, which then interact with each other according to various inbuilt joint behaviour models. A solution is obtained through the use of a 'time-marching' scheme to solve the equations of motion.

3DEC is well suited to model a rock mass where the behaviour of the discontinuities has a significant influence on the total rock mass behaviour. The model geometry is regularly updated during the calculation process, so the effects of large strains or concentrated displacements can be considered. Different material properties can be incorporated into the model and complex models (including staged excavation) can be developed.



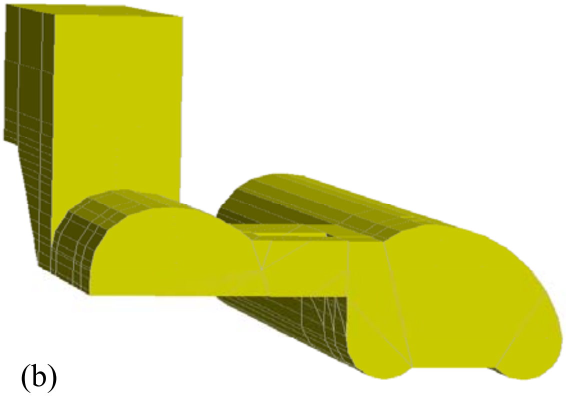


Figure 5: 3DEC model of the Station Cavern (a) blocks remaining following excavation of full cavern (b) excavated blocks.

As an example of the complexity of model attainable, Figure 5 presents one of the station cavern models developed for the project. As can be seen, both major caverns, the escalator shaft and the interconnecting tunnels have been specifically modeled (an axis of symmetry across the station centerline has been used to reduce the required model size). Further, material layering (the colour layering shown in Figure 5 (a) indicates the modeled material layering) and horizontal bedding features (modeled as Mohr-Coulomb joints) have also been considered.

Whilst both analytically rigorous and capable of considering complex 3D models, for the type of model shown, 3DEC required considerable time for model development, analysis and result review (some of the considered models took up to four days to analyse). This meant that extensive parametric variation and option evaluation was not feasible solely using 3DEC. Instead the program was used to target specifically 3D issues (e.g. the validation of plane strain smearing techniques or the analysis of the cross passage pillar).

PHASE^2 (Rocscience)

Phase^2 is a commercially available 2D finite element program developed for the calculation of stresses and displacements around underground or surface excavations. The program is capable of modeling plane strain or axisymmetric models in jointed, layered, elastic or plastic materials with or without rock reinforcement (the formulation has 4 inbuilt bolt models and 2 inbuilt liner models).

Compared with the other packages Phase2 is relatively rapid for project set-up, analysis and review. The inbuilt staging devices mean that the program is versatile in its ability to consider various excavation options and to compare the relative effect of the considered permutations. This means it is well suited to assist with parametric studies, option evaluation and design queries.

As with any 2D finite element program, there are a number of simplifications inherent in the formulation. In order to assess the impact of these simplifications, a series of validation procedures were developed. Of particular interest to this paper are the 3D smearing techniques, which were used to approximate the effects of out of plane restraint (see section titled ‘Estimation of 3D restraint’). Via this process, it was possible to perform and review a vast suite of analyses so that a broad understanding could be had of how the rock mass responded to excavation of the caverns and what factors principally drove this behaviour.

ANALYSIS RESULTS

In terms of the scope this paper, it is intended that the work presented herein provide an insight into how the problem of analysing an intrinsically 3D structure, in a limited time period was approached by the numerical modelers for this project. In keeping with this, results relating to two specific issues are presented, namely:

- 2D estimation of 3D restraint, and
- Effects of material layering.

These two areas have been ‘singled out’ because they encompass issues which impacted on how the proposed analysis methodology was eventually enacted.

2D ESTIMATION OF 3D RESTRAINT

Figure 5 (b) presents a 3D view of the 3DEC station cavern model excavated elements. As can be seen, the layout of the escalator shaft is such that, for the bottom half of the shaft, the length of the opening decreases with depth. Figure 6 shows a section through the 3DEC blocks remaining after excavation. The section has been cut approximately through the centre of the shaft, with all the blocks in front of the section hidden from view. As can be seen, the action of the sloping floor behind the section provides restraint to the shaft sidewalls in line with the section.

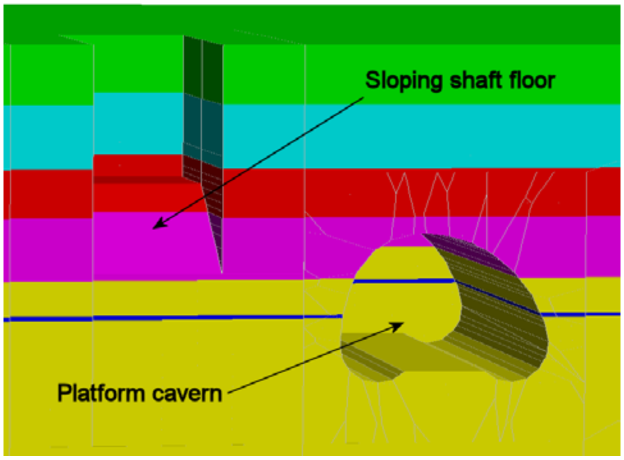


Figure 6: Section through 3DEC unexcavated blocks at escalator shaft mid section.

In order to develop a 2D, plane strain model of this section, it was necessary to approximate the action of this 3D restraint. This was achieved by a process of material smearing, whereby (instead of full removal) excavated material is replaced with a reduced stiffness material. The final smearing factors used were based on comparisons of the calculated displacements for the 3DEC model and a suite of Phase^2 models (each considering different smearing schemes). Displacements at a number of specific ‘points of interest’ within the two models (e.g. at the cavern crown or between the platform cavern and the shaft) were compared.

As an example, Figure 7 shows a comparison of the calculated horizontal displacement for the 3DEC model and the adopted Phase^2 model, at a location between the shaft and the platform cavern. Also shown is the final smearing scheme. As can be seen three separate smeared zones were required. For the top half of the shaft, the length of the sidewall (approx. 50m) meant that no smearing was required to approximate the conditions at the query point. For the bottom half of the shaft two zones, using an 85% and 70% reduction in stiffness respectively, were required. These smearing factors were subsequently adopted for 2D plane strain analysis of this cavern section.

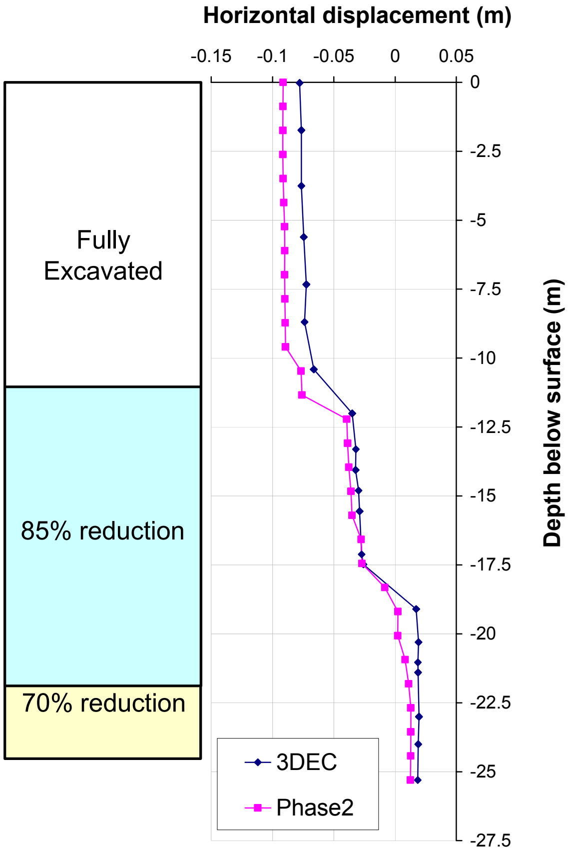


Figure 7: Comparison of the calculated horizontal displacement – 3DEC and Phase2 (with smearing).

EFFECTS OF MATERIAL LAYERING

It has been mentioned previously, that the intended role of Examine^{3D} was re-evaluated after initial program validation. Studies showed that the program's inbuilt assumption that the rock response could be approximated as a simple isotropic, homogeneous, linear elastic material, proved to be too restrictive for the intended purpose.

Figure 8 presents the results of verification work conducted using 3DEC. These results provide an example of the impact assuming a simple isotropic, homogeneous, linear elastic material had on the calculated behaviour. Figure 8 (a) shows the displacement vectors calculated using the simplified homogeneous material (this behaviour is essentially identical to that displayed by the Examine^{3D} model). In particular, note is drawn to the heave calculated in the crown of the platform cavern and at the surface. Figure 8 (b) shows the effect of introducing some material layering so that the Young's Modulus of the rock mass increases with depth. As can be seen, the calculated displacement mode of the cavern is significantly different for the layered soil, with the cavern crown and ground surface now sagging into the excavation.

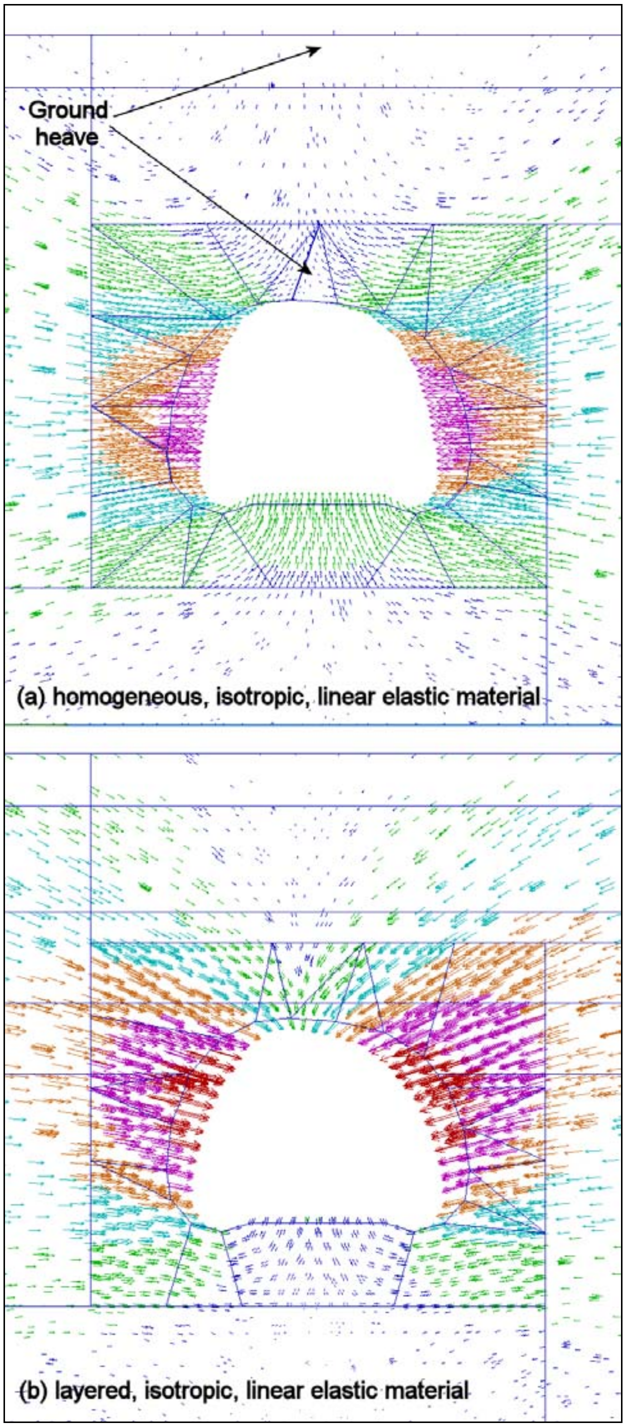


Figure 8: Vectors of total displacement calculated for (a) homogeneous material and (b) layered material.

Once the calculated surface heave was identified, a series of analytical investigations were conducted using all three analysis programs. These investigations sort to (a) reproduce the behaviour using independent analysis methods and (b) understand what was driving this mode of displacement. In summary, the results of this investigation showed that the 'homogeneous' displacement mode (Fig. 8(a)) was:

- Independent of the properties of the homogeneous material (material properties consistent with highly weathered shale and fresh sandstone both displayed similar patterns of soil displacement, with only variations to the magnitude of the displacements).
- Dependent upon relatively high horizontal insitu stresses. Surface heave did not occur in cases where the lateral stress was equal to the overburden stress (the results in Fig. 8 assume $\sigma_h = 0.5 + 2.5\sigma_v$ (MPa)).
- A result of mainly modeling the rock mass as a simple homogeneous material (Fig. 8 (b) shows that the introduction of basic material layering changed the predicted cavern crown behaviour considerably (i.e. from heave to sag)).

As these investigations showed, the oversimplification of the insitu geology had the potential to significantly alter the predicted behaviour.

CONCLUSION

Numerical modeling for the Epping to Chatswood Rail Line posed numerous challenges. This paper details how, in order to meet these challenges, an analysis methodology was employed which used detailed 3D modeling to enhance extensive 2D plane strain modeling, so that a broad understanding could be had of the response of the rock mass to the excavation of the station caverns.

As is explained, in areas where the out of plane cavern geometry was seen to be providing restraint to the in plane geometry, the results of 3D modeling were used in conjunction with 2D 'material smearing' techniques to approximate the action of the out of plane restraint. This system meant that numerous permutations (relating to either parametric studies, option evaluation or even responding to analysis queries) could be considered in a timely manner.

ACKNOWLEDGEMENTS

The above paper considers a small portion of a voluminous body of innovative work conducted for the Epping to Chatswood Rail Line. The author would like to gratefully acknowledge the tutelage and guidance provided by the project design team, in particular Mr. Peter Stone and Mr. Kim Chan who are responsible for a lot of the work described herein.

REFERENCES

1. HERBERT, C, "Sydney Basin Stratigraphy", 1983, p.7-26, in Geology of Sydney 1:100 000 sheet, Dept. of Mineral Resources.

2. ENEVER, WALTON and WINDSOR, "Stress Regime in the Sydney Basin and its Implications for Excavation Design and Construction", 1990, Institute of Engineers, Australia, Australian Tunneling Conference, 1990.

3. PELLS, P.J.N., "Stresses and Displacements around Deep Basements in the Sydney Area", 1990, Institute of Engineers, Australia, Australian Tunneling Conference, 1990.

4. ENEVER, J.R., "Near Surface Insitu Stress and its Counterpart at Depth in the Sydney Metropolitan Area", 1999, Australian Geomechanics, June 1999.