COMPUTER MODELLING AND ROOF SUPPORT DESIGN FOR LARGE DIAMETER ROAD TUNNELS IN SYDNEY HAWKESBURY SANDSTONE

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SUMMARY

This paper looks at the design of the roof support systems for the M2 tollway twin tunnels located at Epping in Sydney, Australia. The tunnels pass through Hawkesbury Sandstone which is subject to high insitu horizontal stresses. Making use of a finite difference computer modelling program, the tunnel excavations were simulated on computer and the results predicted that differential movements could occur along horizontal bedding planes in the sandstone, immediately above the tunnel crown. These movements, caused by the high horizontal stresses became an important factor in the design of roof rock bolts.

INTRODUCTION

Construction of the M2 Motorway in Sydney, Australia included a short underground section tunnelled through Hawkesbury Sandstone, by Peabody Resources (Australia) Pty Ltd. Douglas Partners Pty Ltd, designed the support systems for the tunnel. The writer was involved in computer modelling of the tunnels as part of the design process.

THE M2 TWIN TUNNELS

Location and Dimensions

The M2 tollway, under construction in 1995 runs from Epping Road to Old Windsor Road in Sydney, Australia. At North Epping, the tollway crosses under Norfolk Road and Epping Oval, through twin 11.7m wide tunnels. The tunnels, were commenced in September 1995 and were cut through Hawkesbury Sandstone at a depth ranging from 8.0 to 22.0 m below ground surface. The tunnels are 460 m long and are separated by 6.8 m. The arch shaped tunnels have a height of 7.8 m at their crown. Figure 1 shows the location of the tunnels.

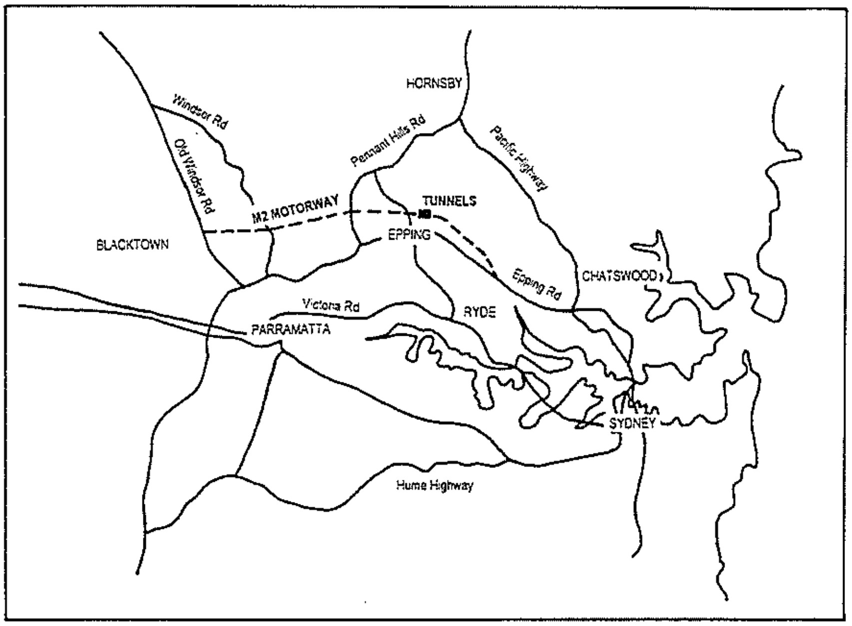

Figure 1. Location of the M2 Twin Tunnels

Geology

Test bores were drilled along the length of the tunnels by others. These indicated that the tunnels are generally located in medium strength, slightly weathered, medium grained sandstone. Features of the rock mass include horizontal bedding partings, some clay filled, spaced at 1.5 to 3.0 m and two subvertical joint sets with strike NNE and ESE, spaced an average distance of five or more metres. The tunnel itself is oriented approximately East West.

INSITU STRESSES IN HAWKESBURY SANDSTONE

The Hawkesbury Sandstone of Triassic age is characterised by high locked in horizontal stresses. The measured horizontal stresses in the rock are far in excess of those that would be expected from the weight of the rock alone, and have been measured at more than two and a half times the vertical stress. As a result, any excavations in this material involve some inward movements of the side walls caused by the elastic response of the material as it is relieved of these compressive stresses. Where bedding planes are present, these movements are concentrated along these planes of weakness. This phenomena has been observed on sites involving deep excavations in the Sydney C.B.D., and when not predicted and allowed for has resulted in disastrous effects. Parts of buildings have been literally crushed by the inwards movements of the walls of the excavation pressing against the structure. Other buildings have been literally pulled apart by stress relief that has occurred when deep excavations have been opened in adjacent blocks.

The value of horizontal stress σ_h adopted by Douglas Partners Pty Ltd for design of the M2 twin tunnels was

$$\sigma_h = 0.5MPa + 2.5\sigma_v \tag{1}$$

where σ_v is the vertical stress and is equal to the overburden pressure:

$$\sigma_v = \gamma d \tag{2}$$

where γ is the unit weight of sandstone, and d is the depth below ground surface.

The equation was based on near surface measurements obtained by over coring at the World Square site in the Sydney C.B.D. by D.J. Douglas & Partners in 1988 and measurements from other sites around Sydney. The results of the tests were plotted on a graph and a visual line of best fit applied to formulate the equation.

COMPUTER MODELLING

Computer modelling of the tunnel cross section was carried out using a commercially available program called FLAC [3]. FLAC is a two dimensional non linear explicit finite difference program that is used for stress analysis of a continuum. The program is used for rock or soil masses with a range of material behavioural models and can include interfaces such as joints or bedding planes and structural elements such as rock bolts or tunnel linings.

The computer modelling was used to model the staging of the tunnel excavations and the installation of rock bolts. As the stress distribution is path dependant, the staging of the excavation was simulated as closely as possible, with a central top heading being taken out, then the roof bolts installed before excavating out the lower bench in each tunnel. The tunnel geometry is modelled by developing a finite difference grid, an example of which is shown in Figure 2.

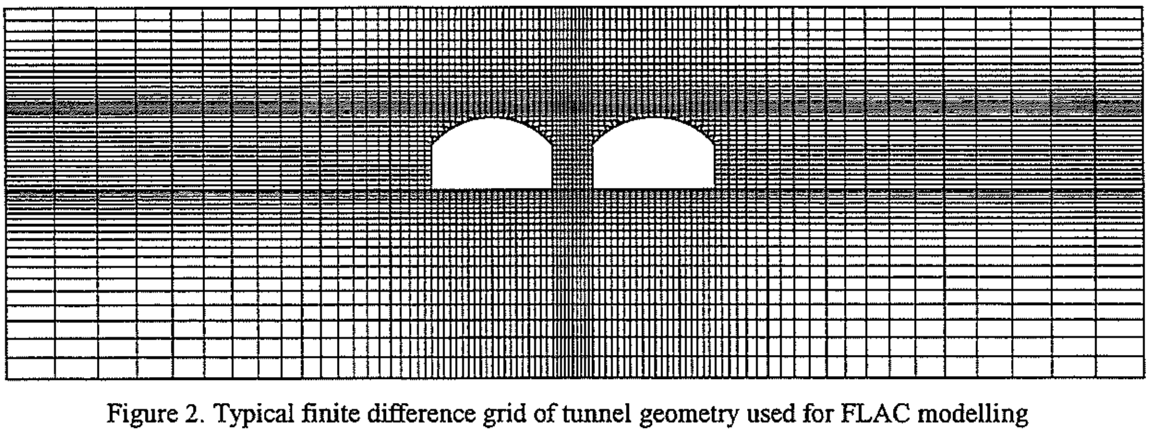

Figure 2. Typical finite difference grid of tunnel geometry used for FLAC modelling

Output from the program included the stress distribution around the tunnels and predictions of the tunnel movements and the expected loads on the rock bolts. Various models were tested that looked at different combinations of tunnel geometry and joint and bedding plane locations.

The modelling work was carried out in parallel with other analytical work to formulate the final tunnel design. This work included the use of rock mass classification systems such as the Q System [1], and the Rock Mass Rating system [2], and a beam analysis to determine the minimum bolt lengths.

Material Properties

The use of FLAC required the input of a set of material properties for the sandstone and properties of the joints and bedding planes, as well as the insitu stresses previously mentioned. The sandstone was judged to be uniformly medium strength and behaving according to a Mohr Coulomb material model. The properties used for the rock mass are summarised in Table 1. They were chosen based on conservative values and were obtained from UCS and point load tests on the rock and on the properties used for the modelling of World Square by D.J. Douglas & Partners in 1988. These properties were verified by back analysis, comparing predictions of movements with actual measurements. The properties used for the bedding planes and vertical joints are listed in Table 2.

Table 1. Assumed properties of medium strength Hawkesbury Sandstone

PROPERTY	
Unconfined Compressive Strength	15 MPa
Elastic Modulus	2000 MPa
Poisson's Ratio	0.2
Density	2300 kg/m^3
Cohesion	3 MPa
Angle of friction	45°
Tensile Strength	1 MPa
Shear Modulus	0.83 GPa
Bulk Modulus	1.1 GPa

Table 2. Assumed properties for discontinuities

PROPERTY	CLAY FILLED HORIZONTAL BEDDING PLANES	VERTICAL JOINTS
Normal Stiffness	2 GPa	20 GPa
Shear Stiffness	0.5 GPa	5 GPa
Tensile Strength	0	0
Cohesion	10 kPa	0
Angle of Friction	25°	45°

MODELLING RESULTS

The results of the FLAC modelling indicated that the tunnels would basically be self supporting in medium strength sandstone, however consideration was given to the possibility of unfavourable joint orientations or bedding plane locations causing the formation of loose blocks in the roof. For this reason, a decision was made to install 3 m long bolts in a 2.0 m grid in the roofs of the tunnels.

The models indicated that horizontal compressive stresses as high as 4 MPa could be expected in the tunnel crown and vertical stresses up to 2 MPa in the pillar between the tunnels, so there was little likelihood of large scale stress failures in the rock.

Inwards movements of the side walls of up to 8 mm and of the roof and floor of 3 mm were predicted. An interesting consequence of these movement predictions is their effect on the portal design. The design of the portals by others included a rigid steel reinforced concrete arch to be installed around the inside of the rock cutting at the portal. The curved part of the arch would be cast insitu on completion of the top heading only, then the bench would be excavated and the walls of the arch cast, however, the FLAC modelling predicted that once the arch was installed, after the bench was completed, a further 5 mm inwards movement on each side of the arch could be expected. As this movement would be enough to crush the arch, the portal had to be redesigned.

A summary of the important results is given in Figure 3.

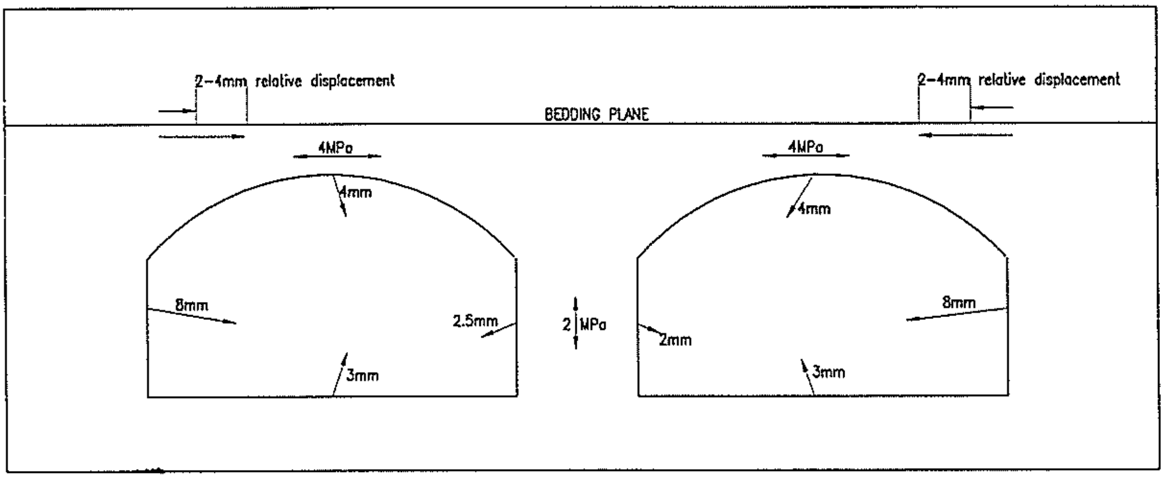

Figure 3. Summary of results from FLAC modelling

Bedding Planes

Of particular interest was the behaviour of the tunnel when there was a horizontal bedding plane above the roof of the tunnels. The log from a bore drilled near the eastern portals indicated the presence of a clay filled bedding plane only 1.6m above the tunnel crown. Modelling of the tunnels with this bedding plane indicated that the bedding plane acted as a stress "barrier", concentrating horizontal stresses that were redistributed around the top of the tunnel into the rock between the tunnel crown and the bedding plane . As a result there was a significant drop in stress immediately above the bedding plane of the order of 1 MPa. This would be likely to cause some small differential movements of the bedding plane. The rock below the bedding plane was predicted to compress some 2 to 4 mm more towards the centre of each tunnel, than the rock above the bedding plane. This should not cause any stability problems for the tunnel, but could have disastrous consequences for fully grouted rock bolts that intersect the bedding planes. Modelling indicated that these movements could cause the rock bolts to fail in shear where they intersected the bedding plane.

Design of rock bolts

The original design of the rock bolts was to install standard fully grouted passive dowels using 24 mm high strength bar. However, analysis of the possible bedding plane movements indicated shearing of the bolts. Rather than prevent the movements, it was decided to design the bolting system to allow for the movements while still supporting the rock. The bolts were required to be fully grouted for corrosion protection. Two options were considered, namely:

1) Fully grouted passive dowels with a compressible bandage adjacent to bedding planes:

> After drilling the hole for the bolt, the hole would be spoon tested to detect jointing. If the presence of any clay filled joints was detected in the first two metres, then, the dowel would be wrapped in 'Denso' tape for 0.5m either side of the joint and the bolt grouted in as normal. The 'Denso' tape would form a compressible bandage of approximately 1.5 to 2 mm around the bar, between the grout. 'Denso' tape is a grease impregnated material, and this material would be compressible enough to allow some lateral movement of the bar. If there was 2 to 4 mm movement along a bedding plane, the grout would be cracked by the shearing, but the bar would be able to bend over the one metre length of 'Denso' taping. As well as allowing lateral movement, the 'Denso' tape would maintain corrosion protection for the steel, even after cracking of the grout.

2) End anchored dowels:

> The majority of the movements associated with the relief of the horizontal stresses are caused by the elastic response of the rock, and as such, they are relatively instantaneous. The bolts would be initially installed with galvanised end anchors and not grouted. As the face of the tunnel advanced away from the location of the bolt, the horizontal stresses would be distributed around the tunnel and any slipping of the bedding planes would occur. The diameter of the bolts would be 24 mm, inside a 41 mm diameter hole, leaving a 17 mm gap to accommodate the movement. After the tunnel face had advanced at least two tunnel diameters away, the bolts could be safely grouted. By then the majority of movement would have occurred.

The first option, while having less cost in materials, would require more labour and installation time, and for this reason the second option was chosen.

CONCLUSIONS

The Hawkesbury Sandstone of the Sydney Basin is subject to high insitu horizontal stresses, and excavations in it involve various rock movements associated with the stress relief. Computer modelling of the M2 twin tunnels predicted sliding of bedding planes of sufficient magnitude to shear or over stress normal fully grouted rock bolts. Foreseeing the movements allowed for an alternate bolting design to be used that should allow for the movements without failing the bolts. The prediction of movements also affected the design of the tunnel portals, as the magnitude of the expected movements would have been large enough to crush the original reinforced concrete arch.

References

1. Barton N., Lien, R. & Lunde. J. 1974 Engineering classification of rock masses for the design of tunnel support, *Rock Mechanics.*, 6(4): 189-236.

2. Bieniawski, Z.T. 1976 Rock mass classifications in rock engineering, *Proc. Symp. on Exploration for Rock Engineering*, Johannesburg, 1: 97-106.

3. Itasca 1992. *FLAC - Fast Lagrangian analysis of continua, version 3.2; User Manual.* Itasca Consulting Group Inc., Minneapolis