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Design of Railway Cuts for Future Subsidence

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SUMMARY

In the planning of railways for new collieries the shortest rail route may pass over a proposed underground mine to be operated by another company. The alternatives in such a case are to sterilise the coal beneath the route, take a longer route through unaffected areas or design the railway to perform satisfactorily as mining subsidence occurs. The first two alternatives are expensive and the third alternative has not previously been adopted in NSW, Australia. Hence a study was undertaken to determine the effects of subsidence on the various components of the railway system. This paper discusses the part of the study concerned with the design of railway cuttings. Finite element analysis techniques were used. Failure modes predicted by the initial analyses were in reasonable agreement with observed field behaviour. Various slope profiles and treatments were then investigated to obtain preliminary designs for cut slopes subject to mining subsidence.

1. INTRODUCTION

In underground coal mining operations large areas of the land above the coal seam may be subject to subsidence. With the development of new collieries additional rail spurs are required to transport the coal to market and the most direct rail alignment may pass over an area to be mined by another company. In such a case the alternatives are to take a longer rail route through areas that will not be affected, prevent the mining of all coal beneath the railway or design the railway to perform satisfactorily during and after subsidence. The first two alternatives tend to be expensive. Hence it is desirable to develop techniques to allow design of rail projects which will result in minimal risk to the railway as subsidence occurs.

The proposed colliery is located in the western coalfields of NSW. Feasibility studies for the railway resulted in cuts up to 20 m high in the soft sandstone bedrock. This paper describes the analyses carried out to determine the behaviour of these cuts when subject to mining subsidence.

Analyses were performed for several mine layouts, rail alignments and cut locations. Data presented in this paper relate to one mine layout and two cut locations relative to that layout. Although there is some variation in the magnitude of stresses computed the general failure modes discussed are common to all mining operations and rail alignments analysed.

2. GEOLOGY

The length of railway studied passes through the gently dipping sedimentary rocks of the Narrabeen group and is located entirely in the Banks Wall sandstone of this group. These sandstones are massive, medium to coarse grained and weak to very weak in strength. Joints tend to be widely spaced and subvertical.

In areas not affected by subsidence the major concern with cut slopes is the erosion of the weak sandstone by surface runoff. In order to minimise this problem cuts are made as steep as practical. Cuts up to 20 m high with slopes of 4 to 1 are performing satisfactorily in this sandstone.

No detailed field investigations have been carried out to date as development of the mine has been postponed. Material properties have been based on data from Pells et al (1978), a preliminary field investigation and experience. A Youngs Modulus of 250 MPa, poissons ratio of 0.3 and bulk density of 1.8 t/m^3 were used in the analyses. Unconfined compressive strengths in the range 0.7 to 4 MPa and uni-axial tensile strengths in the range 0.03 to 0.3 MPa are considered likely for the sandstone.

3. SUBSIDENCE PREDICTION

Coal mining is to be carried out by the longwall technique with 150 m wide by 1500 m long panels separated by 30 m wide pillars. Vertical and horizontal ground surface movements were predicted using the methods outlined in the Subsidence Engineers Handbook of the National Coal Board of the UK, modified according to the findings of Frankham and Mould (1980) and Frankham (1981). An initially horizontal ground surface was assumed.

Computer programs were developed to calculate and plot contours of settlement and horizontal movements for the different mining situations from data given in the above references. These calculations took into account the depth of seam, thickness of seam, number of seams mined and width of longwall face. Analyses presented in this paper are for the mining of a single longwall panel 150 m wide, a seam thickness of 2 m and depth of cover of 240 m as shown on Figure 2. A typical settlement plot is shown on Figure 1.

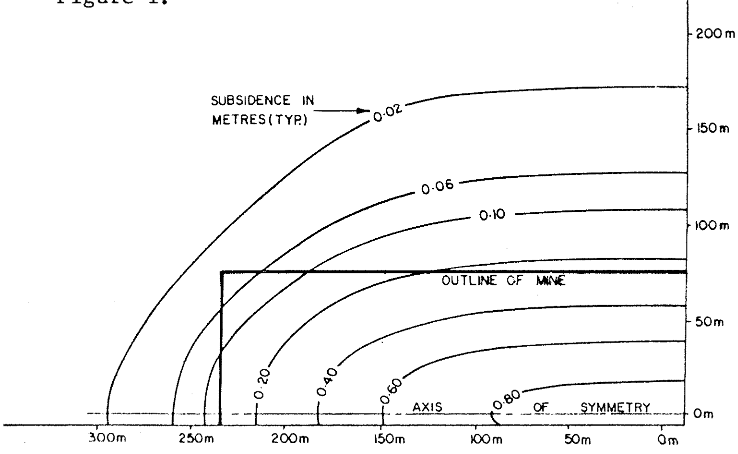


FIGURE 1 TYPICAL SETTLEMENT PLOT

4. METHOD OF ANALYSIS

4.1 General

The effects of subsidence on the stresses within an idealised rock cutting were evaluated using linear elastic finite element techniques. As assumptions made regarding ground movements, rock behaviour and rock properties are vastly simplified the analyses cannot be expected to give quantitatively accurate results. They do, however, give a good indication of qualitative behaviour which can be used to make judgement based discussions.

The analyses identified regions of compressive and tensile stress and computed the magnitude and direction of the principal stresses. Where stresses exceeded rock strength either cracking (if a tensile zone) or shear failure (if a compressive zone) were assumed to occur. In this way likely unstable regions were identified and the effects of subsidence assessed. Similar methods have been used by Kalkani (1975) and Bukovansky and Piercy (1975) to evaluate rock slope stability, although not in association with subsidence effects.

The first step in the analysis of the railway cuttings was to determine the vertical and horizontal subsidence movements for the rail alignment and the mining situation selected. Finite element analyses were then run to determine the effects of these movements on the stresses in the rock around the cut. The results presented in this paper are for the two cut locations shown in Figure 2. Other cut locations were analysed but found to be less critical.

Results of initial analyses were compared with field behaviour and found to give reasonable agreement. Analyses were then run with different cut profiles to determine the factors that were significant in the performance of cut slopes when subjected to subsidence movements.

4.2 Finite Element Analysis

Finite element analyses were two dimensional and assumed linear elastic material properties and plane strain boundary conditions. Although anisotropic material properties were used in a few analyses all results reported in this paper are based on isotropic rock properties. The computer program CEASAP was used for the analyses. CEASAP is a modified version of the Structural Analysis Program (SAP) developed by Professor Clough and Wilson of the University of California at Berkley.

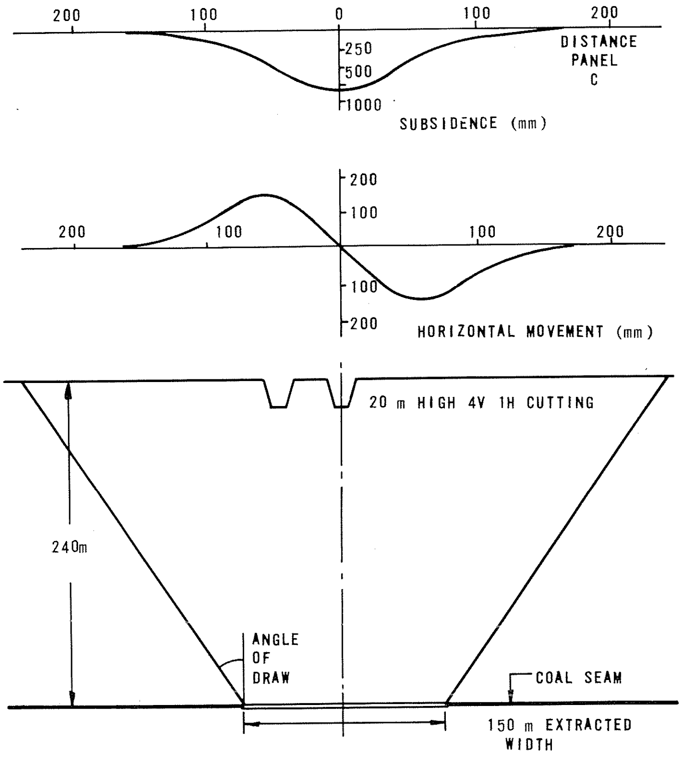


FIGURE 2 MINING ARRANGEMENT

Two finite element meshes were used in the study. A long coarse mesh extending over the full length of the subsidence profile with relatively large element sizes, as shown in Figure 3, was used to model the predicted surface movements. This mesh comprised fixed nodes at the ends and variable stiffness spring elements along the base. The spring stiffness were adjusted over a number of computer runs until reasonable agreement was obtained between the computed settlement under gravity loads and the predicted surface movements. It was found possible to closely match the vertical settlements. The distribution of horizontal surface movements computed was very close to that predicted but the magnitudes were about 20 percent higher than predicted. In view of the overall accuracy of the work this was considered acceptable as it was conservative.

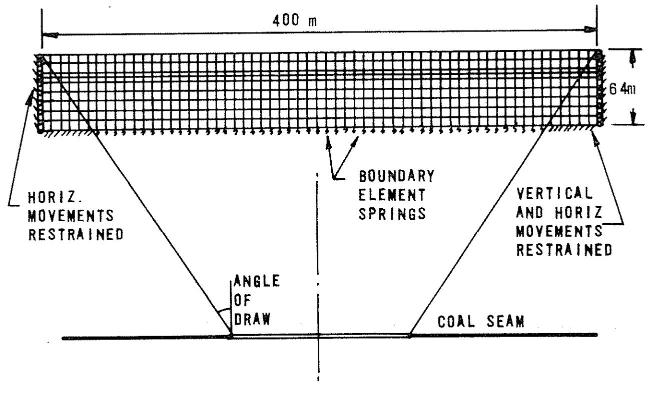


FIGURE 3 COARSE MESH

Once the spring stiffnesses were established the mesh was modified to include the 20 m high cut at the desired location. The finite element analysis using the modified mesh and the established spring stiffnesses then gave the stresses due to subsidence.

A second, finer mesh, shown on Figure 4, was used to determine detailed stresses and strains in the vicinity of the cut. This was done by imposing the displacements computed at corresponding nodes within the first mesh on the boundary nodes of the second mesh. Major and minor stress contours and vectors were computer plotted for each case analysed. Typical examples are shown on Figures 5 and 6.

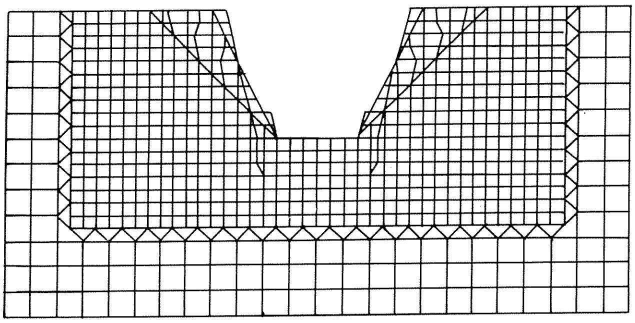


FIGURE 4 FINE MESH

5. INITIAL ANALYSES

5.1 Stresses Prior to Subsidence

The initial anlayses considered a 20 m high cut with slopes of 4 to 1 which was not subject to subsidence. Maximum tensile and compressive stresses computed were 10 and 500 kPa respectively. As noted above 4 to 1 cuttings are performing satisfactorily on nearby railway projects. Thus the results are in agreement with observed performance.

5.2 Predicted Failure Modes

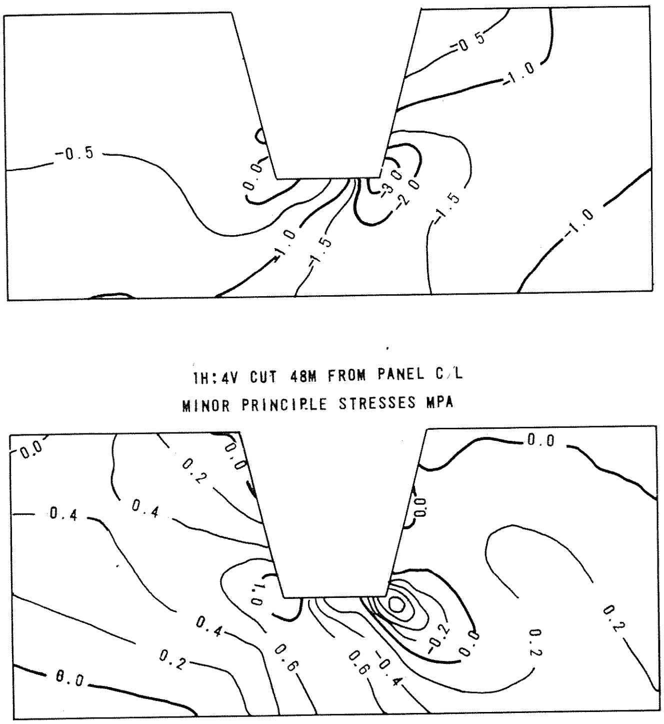
Analyses were performed for 20 m high cuts with both 4 to 1 and 2 to 1 slopes subjected to subsidence. A study of the stress contours and plots identified a number of possible ways the rock could fracture and the effect of these on overall slope stability was assessed. The stress directions and sign were used as the prime basis for the predictions of failure modes. The probability of failure was considered to increase as the predicted stresses increased, particularly once the rock strength was exceeded.

Finite element analyses deal with straight line geometry and homogeneous rock. These do not occur in practice and subsidence of 20 m high cuts will inevitably result in failure of some small blocks of rock which will accumulate at the bottom of the slope. Due allowance must be made in selecting the base width of the cut for storage of small rock falls.

All cases analysed showed significant concentrations of compressive stress developing at the base of the cuts. A typical example is shown on Figures 5 and 6. The maximum compressive stress at the base of the cut generally reached about 4 MPa, which is larger than the expected unconfined compressive strength of the sandstone. Hence shear failure would be expected at these zones.

Three possible tensile failure mechanisms (i.e. cracks) were observed as shown on Figure 7. Of these the most critical were type A cracks dipping out of the face of the cut. Typical examples can be seen on Figure 6. Generally the tensile stresses at the face of the cut were small, increasing with distance away from the

MAJOR PRINCIPLE STRESSES - MPA



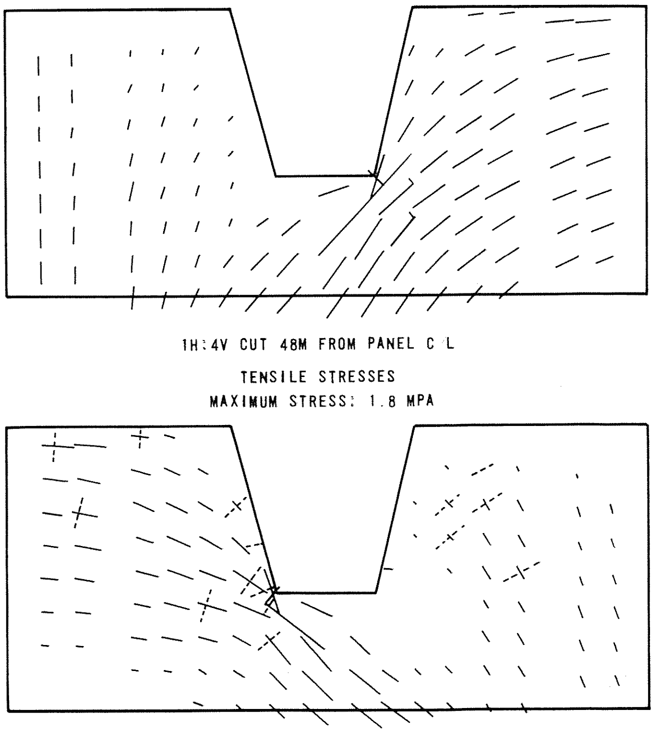
1H:4V CUT 48M FROM PANEL C/L

MINOR PRINCIPLE STRESSES MPA

NOTES 1 -VE SIGN INDICATES COMPRESSIVE STRESS
2 MINOR PRINCIPAL STRESS IS ZERO AT ALL FREE SURFACES

FIGURE 5 TYPICAL STRESS CONTOURS

COMPRESSIVE STRESSES
MAXIMUM STRESS: 3.5 MPA



1H:4V CUT 48M FROM PANEL C L

TENSILE STRESSES
MAXIMUM STRESS: 1.8 MPA

------TYPICAL LOCATION AND ORIENTATION OF LIKELY TENSION CRACK

FIGURE 6 TYPICAL STRESS PLOTS

slope. Values ranged from about 0.1 MPa near the face to 0.2 MPa about 15 m in from the face. Such stresses fall into the range of possible tensile strengths for this rock. If such cracks did form overall stability of the slope would depend on the friction angle on the failure plane, dip of the crack and internal water pressure. For the cuts analysed the dip was well in excess of 30° and failure would most likely occur.

The type B failure mode would result in cracks that dip into the cut slope. Hence these cracks would not form failure surfaces by themselves but could combine with existing joint sets to form failure wedges. As noted previously the sandstone at the site is massive and failures of this nature are not likely.

Type B and C cracks would allow the infiltration of rainwater or surface runoff to enter the rock mass thus increasing internal water pressures and promoting instability of the slope. As computed tensile stresses were as high as 12 MPa near the surface such cracks are quite probable.

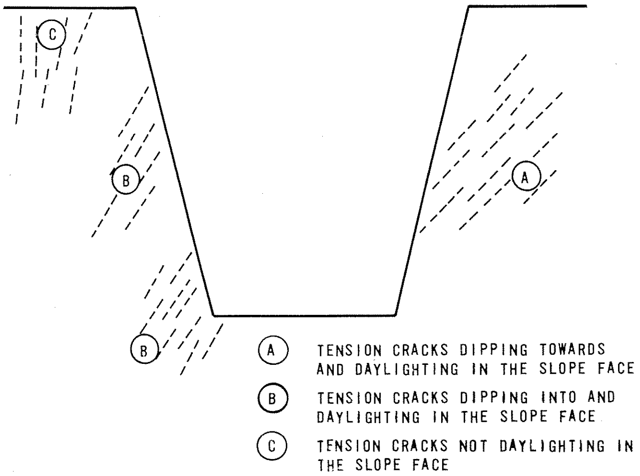


FIGURE 7 TENSION CRACKS

6. COMPARISON WITH OBSERVED BEHAVIOUR

Longwall mining proceeded under the F6 freeway near Waterfall in NSW. Performance during mining operations was monitored and results are summarised in Frankham and Mould (1980). In addition the authors inspected the area while carrying out this study.

The cuts are up to 15 m high and have a slope of about 2 to 1. The rock is sandstone, somewhat stronger than the Banks Walls sandstone. Prominent horizontal bedding joints are spaced at 2 to 4 m.

It must be emphasised that the analyses described in this paper are for longwall mining in the western coalfields of NSW and that the F6 freeway is in the southern coalfields. In addition the mining configurations are different. However, it is considered that surface strains will be of the same order of magnitude and the overall effect on slopes will be similar. Hence if predicted failure modes are observed to have occurred in the field then this gives some confidence that the analyses can qualitatively predict behaviour.

The only major distress observed in the cuts was local buckling and shear failure in the concrete kerb and gutter at the toe of the slope. This indicated that the high compressive stresses predicted by the finite element analysis did exist in this area. No compressive failure zones were noted further out into the road beyond the gutter.

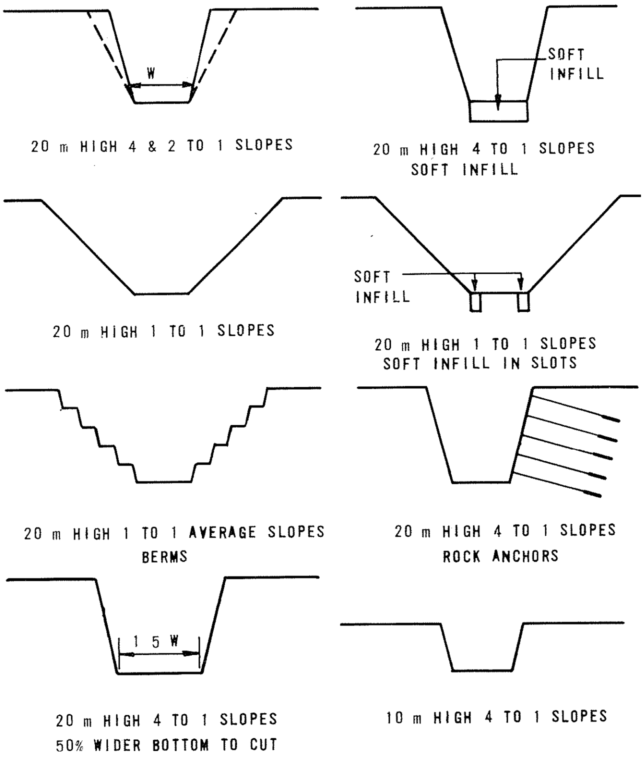
Although it appeared that local blocks of rock had fallen off the cut slopes, no cracks were observed in the slope, either dipping into or out of the face. However, slight movements had apparently occurred on the sub-horizontal bedding joints as displacements were noted on some drill hole traces. This, combined with the higher rock strength could explain the lack of such cracks.

Frankham and Mould (1980) reported that a large crack opened up parallel to and about 50 m back from the top of the slope. This is in agreement with the type C cracking shown on Figure 7.

The field observations at the freeway cut corroborate trends in behaviour indicated by the finite element analysis. Thus it was assumed that the analysis technique predicts the slope behaviour in a qualitative manner. However, considerable additional comparisons of predicted and observed behaviour of such cuts are required to confirm this assumption.

7. ANALYSIS OF ALTERNATIVE CUT ARRANGEMENTS

A series of analyses were performed in which cut geometries and support systems were varied to check the effect on possible failure modes. Details of the cuts analysed are shown on Figure 8.



20 m HIGH 4 & 2 TO 1 SLOPES

20 m HIGH 4 TO 1 SLOPES SOFT INFILL

20 m HIGH 1 TO 1 SLOPES

20 m HIGH 1 TO 1 SLOPES SOFT INFILL IN SLOTS

20 m HIGH 1 TO 1 AVERAGE SLOPES BERMS

20 m HIGH 4 TO 1 SLOPES ROCK ANCHORS

20 m HIGH 4 TO 1 SLOPES 50% WIDER BOTTOM TO CUT

10 m HIGH 4 TO 1 SLOPES

FIGURE 8 CUT ARRANGEMENTS ANALYSED

The areas of most concern were the high compressive stress zone at the bottom of the slope and the possibility of overall slope failure on cracks dipping out of the slope (i.e. type A cracks). Hence work concentrated on determining methods of reducing or eliminating such zones.

Type B and C cracks could lead to local failure if associated with adverse joint sets and infiltration of water to the rock mass. It was considered that these effects could be controlled relatively easily by local rock bolting and drainage measures respectively.

The results revealed that flattening the slope angle from 4:1 and 2:1 to 1:1 had little effect on the magnitude of the compressive stresses at the base of the cut. Also the formation of Type B and C tensile stress regions were not significantly influenced. However, flattening the slope to 1:1 considerably reduced both the magnitude of tensile stresses and dips of potential failure surfaces associated with Type A cracking. Hence, the probability of slope failure was considerably reduced.

In order to control erosion on 1:1 slopes it would be necessary to introduce berms. Analyses including the berms showed that local tensile and compressive stress concentrations would probably result in the loss of all or part of many of the berms, particularly those near the bottom of the cut.

Widening of the base of the cut had little effect on either tensile or compressive stresses.

The presence of a soft layer at the base of the cut, constructed by overexcavating and replacing with fill material, resulted in low compressive stresses at the ground surface and high stresses at the bottom of the soft layer. However, the surface strains across the base of the cut were still large and of the same order of magnitude as previously. The use of soft slots (see Figure 8) resulted in low compressive stresses and strains in the foundation between the slots. Similar slots are recommended in the Subsidence Engineers Handbook as one way of isolating buildings from horizontal strains due to subsidence. It is interesting to note that no shear failure was observed beyond the concrete gutter in the F6 freeway near Waterfall. This could be because shear failure at the edges (theoretically the area subject to the highest compressive stress) effectively formed a soft slot at this location.

Prestressing by means of rock anchors can be used to prevent the formation of excessive tensile stresses in a slope. The brief analyses carried out indicated this would be a most expensive method of achieving stability.

As the majority of the cuts along the proposed railway will be less than 10 m high analyses were run for a 10 m high cut with 4 to 1 slopes. This showed almost identical compressive stresses in the base and tensile stresses that would lead to type B and C cracking. However, the formation of failure surfaces dipping out of the face was found to be very unlikely for cuts less than 10 m high.

8. CONCLUSIONS

1. A method has been developed for analysing cut slopes subsided during mining operations that predicts behaviour similar to that observed in practice.

2. In areas that will be subjected to subsidence cuts should be widened at the base to allow storage room for local rock falls.

3. Analyses predicted excessive compressive stresses at the bottom corners of the cut slopes. The area in the centre of the excavation can be isolated from these high stresses and from high strains by constructing a soft slot at the edge of the cut. It appears as though such a soft zone may be naturally produced due to local shear failure at the corners.

4. Tensile stresses near slope faces could cause cracks dipping out of the surfaces which may lead to planar failures. The probability of this type of cracking reduces with the lowering of the cut height and the flattening of the slope angle. Although such cracking can theoretically be eliminated by prestressed cables preliminary analyses indicated that prestressing would be very expensive.

5. Where flatter slopes require berms to control runoff these berms may suffer substantial damage during subsidence due to local stress concentration effects.

6. Tensile stresses which could result in cracks dipping into the slope were predicted for all arrangements analysed. These could form unstable wedges in conjunction with existing joint sets. The presence of joints was not considered in the analyses and any case these would probably reduce tensile stresses. Local rock reinforcement may be required to avoid failures in such cases.

7. Tensile stresses that would result in cracks dipping into the slope and at the ground surface were predicted for all cases analysed. Surface and internal drainage would be required to control water pressures in all slopes.

ACKNOWLEDGEMENTS

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Computer analyses were performed on facilities provided by CEANET who also advised on computing problems.

Subsidence calculations were based on advice provided by Mr B S Frankham of the Department of Mineral Resources and Development, NSW.

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