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Shear element techniques for tunnel design

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ABSTRACT: The use of a simple shear element and associated techniques for the estimation of rock loads, ground reaction curves and failure modes in blocky rock where rock strength is dominated by weak joints and sheared zones is described. The application of these techniques is extended to estimation of the primary support requirement and performance assessment for a major rock chamber constructed in Victoria, Australia.

1 INTRODUCTION

The analysis presented demonstrates the versatility of a simple shear element which was published by Rome (1982), after it had been introduced in connection with rock slope stability analysis techniques carried out at Melbourne University under the supervision of Bamford. Further development of these techniques has been published by Rome (1986). This paper provides a further application in the analysis of rock support requirements in heavily sheared and jointed rock masses where low strength joints dominate the rock behaviour. Somewhat similar approaches have been introduced by Goodman (1976) and Desai et.al (1984) but to the Authors' knowledge have not been utilised in the manner presented.

2 SHEAR ELEMENT ANALYSIS METHOD

Briefly the analysis approach, involving the shear element, is to concentrate almost exclusively on the behaviour of joint intersection zones. The term joint is deemed to cover all rock defects such as sheared zones etc. which are concentrated on definable planes or surfaces.

The assembly of shear and block elements for the analysis and assessment of rock loading for the design of primary support systems is illustrated in Figure 1. A segment of a model based on the geological investigations carried out for a 14m diameter valve chamber for the Thomson Water Supply Scheme for the City of Melbourne in Australia is illustrated together with a detail showing the generated joint system at a typical joint intersection zone. Joint thicknesses range from 10mm to 150mm but have

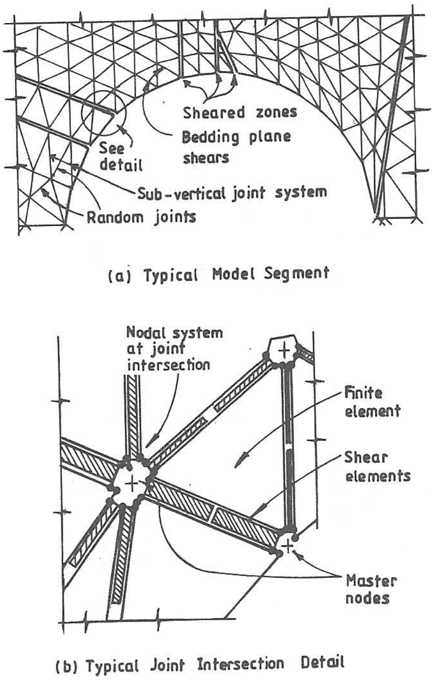

Fig 1 Typical Arrangement of Elements

been enlarged in the detail for illustration purposes.

Full details of the shear element adopted have been provided in the reference given, however the main properties will be summarised as a background to the analysis results provided.

The concept of the shear element is illustrated in Figure 2(a). It is orthogonal in behaviour with shear displacement on the joint face and shear stress being controlled exclusively by a stress/strain dependent shear modulus. Axial deformation ie. joint opening and closing, is similarly controlled by stress or strain dependent deformation moduli which may be elastic. Axial loading or stress is independent of shear displacement and shear forces are independent of the axial displacement although joint strength may be put to zero in tension.

Mohr-Columb strength assessments may thus be readily applied. Where overstress is identified, redistribution is attained by modifying shear modulus and so on.

Shear elements are generated in pairs adjacent to the edges of each face of rock blocks which are in practice defined by the joint system. Generation is achieved by the adoption of a master node system defining joint centre-lines.

To remove the possibility of "hang up" all shear elements are generated perpendicular to block faces to double precision accuracy (14 digits) hence very large shear displacements may be accomodated with negligible artificial restraint. A nodal zone concept, essential to this approach, is illustrated in Figure 2(b) whereby adjacent nodes of different co-ordinates are analysed as a zone of material having one set of freedoms only. The relative displacement between element nodes within a nodal zone is in effect considered to be zero. Displacement modes have been indicated in Figure 2(c). This approach is extended to shotcrete and rockbolt modelling.

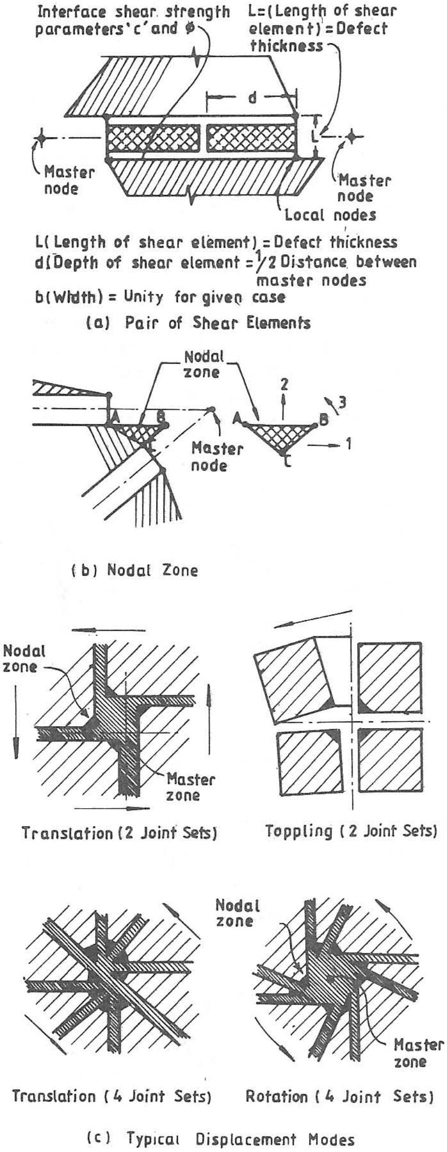

Fig 2 The Shear Element

3 GROUND REACTION CURVE DEVELOPMENT

The philosophy adopted with respect to assessing loading from the "ground reaction curve" computation for blocky jointed rock is first that the fully elastic deformation, without joint slip, would indicate a stable rock mass. The support system is therefore required to compensate for the overstress which must be transferred to it by joint relaxation. This support reaction is shown to be deformation dependent and by plotting the free elastic deflection on this curve an estimate of the maximum support requirement is obtained.

By adopting a logarithmic plot procedure the well defined "collapse" deflection and minimum support requirement is estimated.

The 'ground reaction curve' is estimated by inserting into the modelled cavity a set of radial elements. For any given stiffness of these elements, a relationship between deformation and load may be obtained at any point on the cavity circumference after all over-stress in the rock system has been released. This relationship is shown in Figure 3 to follow well defined paths.

This use of shear elements to develop ground reaction curves for a number of field stress conditions on the valve chamber illustrated has been given by Rome (1986). The ground reaction curve for the crown zone only is reproduced in Figure 3. An empirical evaluation of rock load is included for reference.

Lateral field stress is modelled by pre-stressing the rock blocks against rigid lateral supports at a suitable distance from the cavity. Vertical field stress is modelled by similarly applying a vertical prestress but it is considered preferable to provide freedom to the upper limit of the rock model and apply additional loading equivalent to the vertical field stress. All elements are given their gravitational forces. The shear elements are not prestressed and providing the volume of these elements is small they experience the field stress applied.

Pore water or hydrostatic pressure is "injected" into the shear elements where applicable, hence the stresses recorded by shear elements are the "effective" stresses between rock block faces.

The rockbolt design assumptions for the valve chamber are indicated in Figure 3 and are simplistic in nature. Visual observation of the excavation as it proceeded, indicated that the shorter 1.8 rockbolts and 75mm shotcrete might have provided adequate support without the introduction when space permitted, of the longer 4m bolts. However no adequate computational approach was available at that time and knowing that some form of full crown support was probably essential and not an insurance measure, the additional bolting was allowed to proceed.

Excavation was by road header. Crown deflections were substantially less than predicted.

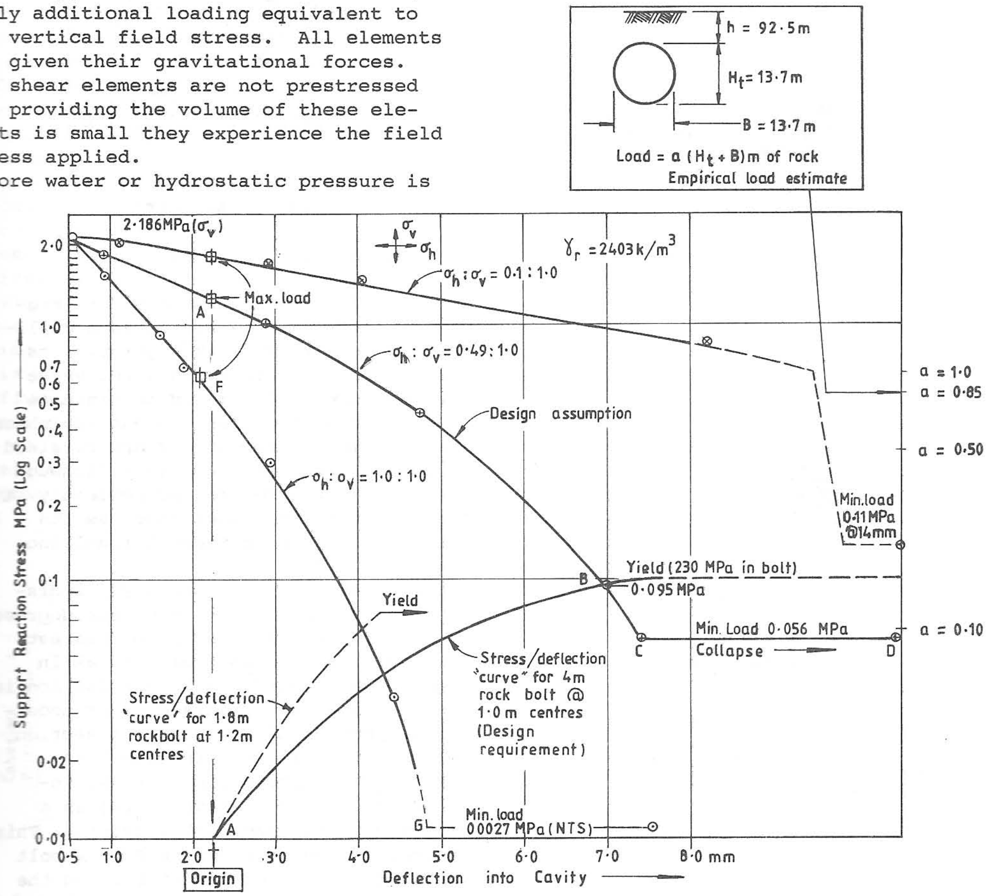

Fig 3 Ground reaction curves for crown of valve chamber

A retrospective assessment of this decision using improved techniques is now being investigated.

The major aspects now introduced into the analysis are the direct modelling of the rockbolts and the shotcrete. Field stress, joint modelling etc. are similar in form to those previously described and published.

4 SHOTCRETE AND ROCKBOLT MODELLING

To model the shotcrete, further use has been made of the shear element. A typical situation is indicated in Figure 4. For the rock type being considered the shotcrete applied to the block face will in general be weaker and more flexible than the intact rock to which it adheres. Its contribution to support in relatively undisturbed rock is consequently associated with joint strengthening and as indicated in Figure 4 it has been generated as a duplicate shear element at the joint. Its axial modulus is assigned a low value for the initial iteration to minimise its effect on field stress but its shear strength and shear modulus are retained at test or estimated values. Although the element is treated independently it occupies the same nodal zones as its corresponding shear element modelling the rock joint.

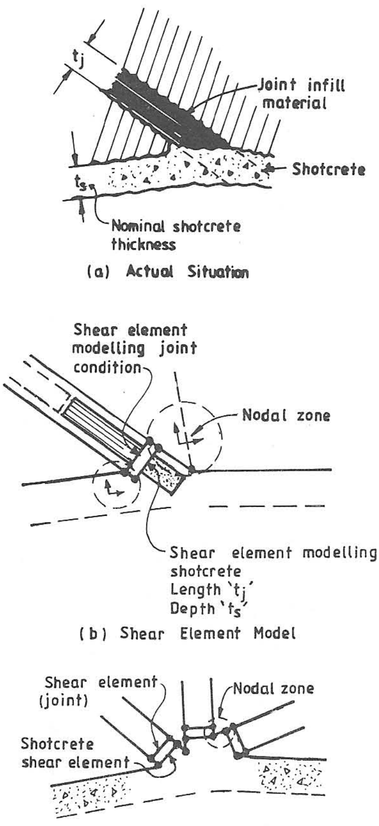

Fig 4 Shotcrete Modelling

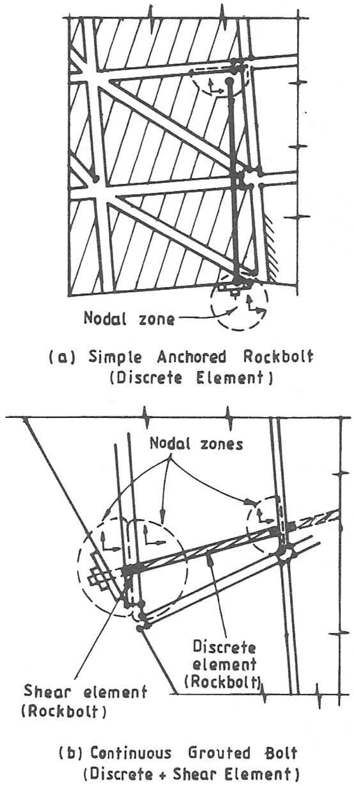

Fig 5 Rock Bolt Modelling

Rockbolts have been modelled as discrete elements which pick up the degrees of freedom of the nodal zones nearest their defined end co-ordinates as in Figure 5(a). Band width optimisation is almost essential in this type of modelling, consequently as vertical section optimisation has in this case been adopted it is desirable to treat inclined bolts, as in Figure 5(b) as a series of connected bolt segments. This becomes analogous to grouted rock bolt treatment. The segment of bolt on the joint may be treated as a shear element but unlike the shotcrete element its shear modulus in this instance is kept small. Axial properties are retained. The assumption is that the high theoretical shear stresses which might be introduced in the bolt could not be maintained by the rock fabric at the joint face and hence should be excluded from the analysis. The rockbolt both sustains tensile forces and contributes to the intrinsic rock joint strength by maintaining a state of compression.

Failure of shotcrete is treated in the same way as clay gouge in joints. It is provided with "peak" and "residual" friction and cohesion parameters. Given that at any stage in the analysis the shear modulus 'G' and shear stress 't_s' is estimated by the previous analysis iteration, the shear displacement '$\triangle$' is given by:

$$\triangle = \frac{t_s L}{G} \qquad (1)$$

where 'L' is the real or arbitrary joint thickness. The shear strength parameters are made displacement dependent with respect to overstress and joint slip is modelled by proportional reduction in shear modulus. The simple relationship adopted is indicated in Figure 6.

Rockbolt modelling is carried out using strain-dependent moduli techniques. For convenience the rock bolt is inserted in the initial model but by providing a low modulus for the 1st iteration it experiences strain with minimal stress. After the 1st iteration it is activated by introducing its true stiffness. Adopting the treatment given by Rome (1976) for stress-dependent moduli used for tunnel lining design in shattered rock, a stress vs. strain diagram is prepared as shown in Figure 7. From this a strain dependent

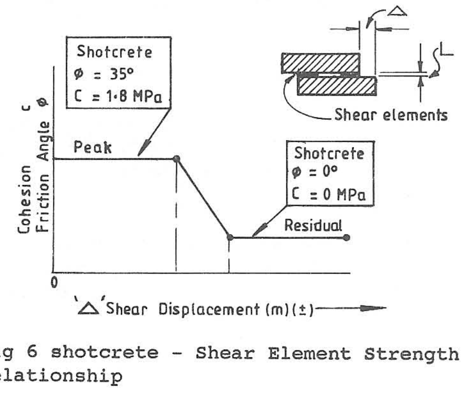

Fig 6 shotcrete - Shear Element Strength Relationship

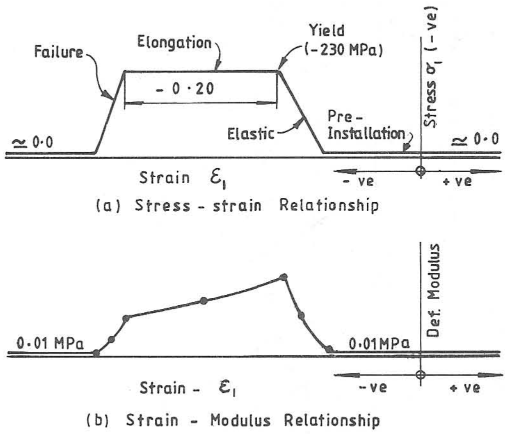

Fig 7 Strain dependent modulus for rockbolt

modulus relationship is prepared. In practice it is convenient to compute this relationship within the computer program using a preliminary (additional) iteration. Damping on rate of moduli change is necessary for both elements.

5 PRELIMINARY ANALYSIS RESULTS

The valve chamber model, as originally used for the ground reaction curve previously introduced, was refined to permit the inclusion of rockbolts as indicated in Figures Nos 1 and 8. The number of rock mass defects included was increased but apart from the major sheared zones present, defect spacing etc. in the model still greatly exceeded that of the actual rock condition.

The effect of the initially introduced 1.8m 25mm dia. rockbolts which had been installed on a 1.2m square grid was first examined. Within the limitations of the model, this rockbolt pattern was incorporated as shown in Figure 8. This Figure also provides some general data on joint strength etc. For the fully excavated cavern rapid failure was indicated, the failure mode being as illustrated. It should be noted that no attempt was made to scientifically locate rockbolts on key blocks etc. as this was not, in general feasible or reliable in practice.

Shotcrete, 75mm thickness, was then introducted into the model but stabilisation of the cavity was not achieved until a shotcrete shear strength of 3.0

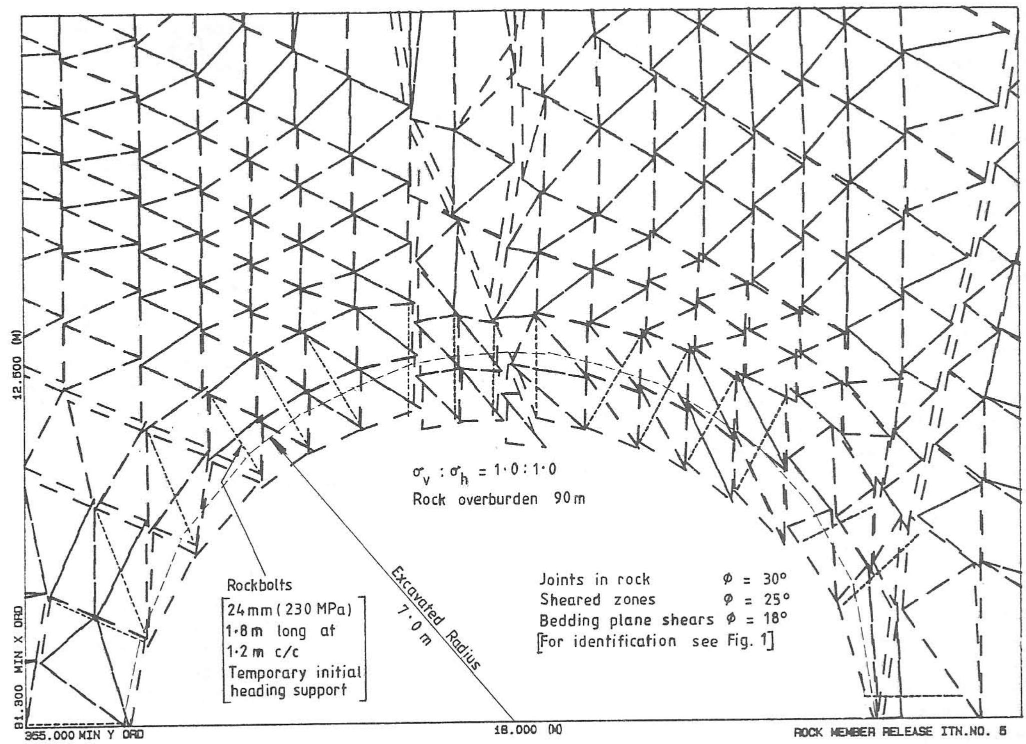

Fig 8 Possible failure mode for crown 1.8m rockbolts @ 1.2m c/c only

MPa approx. and a tensile strength of 1.5 MPa was provided. Although ultimate shotcrete strengths of this order were probably achieved, these would not have been accepted for design purposes.

Water inflow, apart from some damp patches was restricted to the invert, being largely controlled by shaft excavations and access tunnels. However water pressure was introduced into some analyses.

The design requirement called for 4m rockbolts at 1.0m centres placed as soon as space permitted after the initial shotcrete application. Although some reduction in the number of these longer rockbolts was accepted the decision to retain this general requirement appears in retrospect to have been prudent. The study is still proceeding.

REFERENCES

Desai C. S. et.al (1984). Thin layer element for interfaces and joints, Int. Jnl. for Numerical and analytical Methods in Geomechanics. Vol. 8, 19-43

Goodman R.E. (1976). Methods of geological engineering in discontinuous rocks, West Publishing Co., St. Paul.

Proctor R.V. and White T.L. (1968). Rock tunnelling with steel supports, Commercial Shearing and Stamping Co., Youngstown, Ohio.

Rome G. (1976). Equivalent rock column design system for tunnel liners and underground structures incorporating rock restaint. 2nd Australian Conf. on Tunnelling, Aust. Inst. of Mining and Metallurgy.

Rome G. (1982). Analysis of massive blocky rock slopes incorporating simple generated joint elements, Finite element methods in engineering, Proc. 4th Int. Conf. in Australia on Finite Element Methods, Melbourne University.

Rome G. (1986). Equivalent Parameter Method for rockslope dam and tunnel design, Published: Melbourne and Metropolitan Board of Works, Melbourne Australia. ISBN 0 7241 4065 4.