Design and Stability of Circular Coal Mining Tunnels

B.N. WHITTAKER
Reader, Department of Mining Engineering, University of Nottingham, UK

C.J. BONSOULL
Post Graduate Student, Department of Mining Engineering, University of Nottingham, UK

and

S.F. SMITH
Research Assistant, Department of Mining Engineering, University of Nottingham, UK

SUMMARY The study has examined the design criteria for circular mine tunnels in stratified Coal Measures rock conditions. Basic design methods are briefly reviewed and examined in relation to UK coal mine tunnel conditions. Modifications have been made to existing design procedures and improvements achieved in tunnel stability prediction. The basic data used in tunnel design have been critically assessed and their relative significance discussed. Both field and laboratory investigations have been carried out on circular tunnel stability with reference to stress and geological conditions with a view to predicting support characteristics.

1 INTRODUCTION

The tunnel design equations which are based on the concept of rock yield around the excavation, tend to utilise a large number of assumptions and simplifications to the extent that the validity of the design criteria employed are often in question. Adopting a computer based method of solution has enabled more stability variables to be included in the calculations in addition to greater refinement. Previously, to obtain tunnel design formulae, systems of equations were integrated between specified boundary limits, and when more variables were included the complexity and size of the integrals became unwieldy and cumbersome to use with the hand calculators. However, with the aid of a computer, numerical solutions to the equations are obtained which can be used to predict tunnel stability with greater speed and ease.

A major drawback to the simplified equations is that only one strata layer can be considered at any one time, therefore the calculation has to be performed a number of times depending upon the strata layers present; furthermore, only strata layers immediately surrounding the tunnel can be included and this leads to anomalies such as calculating a 20 m diameter yield zone in strata layers only 1 m thick. Floor lift is a major contributor to roadway deformation and is beyond the scope of the equations; consequently this makes the application of the equations to strata exhibiting weathered or swelling properties questionable.

It was decided to devise a computer programme which could increase the scope of the tunnel stability equations to include more complex geological situations to achieve a closer representation of realistic tunnel conditions. The method of solution used allowed other important stability effects to be examined; this included the effect of the body weight of the broken strata and the effect of rock displacement on strata loading. The latter is particularly important when deciding upon the optimum support system for an excavation.

2 METHOD OF SOLUTION

The method of solution is based on the stress equilibrium equation for plane strain which can be written in polar coordinate form as:

\[
\frac{\sigma_r}{r} = \frac{\sigma_\theta}{r} - \frac{\sigma_z}{r} = 0
\]

where

\( \sigma_r \) = radial stress

\( \sigma_\theta \) = tangential stress

\( \sigma_z \) = distance from centre of tunnel

Equation (1) describes the stress distribution acting in any material under hydrostatic stress conditions. The equilibrium equations are the basis for all mathematical models used in stress analysis.

Equation (1) calculates the stress gradient across part of the radius \( (\delta r) \), see Figure 1a. The change in stress, \( \delta \sigma_r \) over the length \( \delta r \) can then be calculated. Summing the stress changes from the tunnel wall to a point \( r \) in the rock will give the total radial stress \( (\sigma_{r_{\text{tn}}} \) at the point \( r \):

\[
\sigma_{r_{\text{tn}}} = \sigma_{r_{0}} + \sum_{i=0}^{\infty} \frac{\delta \sigma_{r_{i}}}{\delta r_{i}} \cdot \delta r_{i}
\]

\( \sigma_{r_{\text{tn}}} \), \( \sigma_{r_{0}} \) are defined in Figure 1a.

All the stresses within the yield zone are calculated using equations (1) and (2).

The advantage of using the equations in this form is that when a new rock type is reached its strength properties can be easily included without calculating specific boundary conditions for each strata layer. The deformation of the strata is calculated in a similar manner to the stress, in that the total deformation is determined as the elastic expansion plus the sum of expansion \( (\delta \sigma_{r}) \) of the length \( (\delta r) \). It has been determined experimentally that the expansion \( (\delta \sigma_{r}) \) is dependent upon the confining stress \( (\sigma_{c}) \), this incremental method of calculating both the stress and expansion enables this effect to be determined.

The computer programme treats the excavated rock mass as if it were split into mutually independent sections, see Figure 1b. Initially the strata are split into radii at 10° intervals and the deformation of the tunnel wall is considered to be the displacement of the point \( (P) \) for each radius. The amount of deformation calculated along one radius is not dependent upon the values of the adjacent
radial, thus, rather than giving an averaged closure, if any exceptionally large displacements are calculated, they are shown up as possible support failure points.

\[ \sigma_1 = k \sigma_3 + c \]  
\[ \sigma_1 = a \sigma_3 + c \]  

(3)

(4)

\( \sigma_1 \) and \( \sigma_3 \) are the major and minor principal stresses respectively and \( k \) and \( c \) are rock coefficients, or a curved Hobbs type envelope of the form.

The rock coefficients being \( a \), \( b \) and \( c \).

The failure criteria take the same form for both failure and post-failure conditions. The expansion of the material is written in equation form as:

\[ E = A \sigma_3 - B \sigma_1 + C \]  

where \( E \) is the expansion of the material when confined at a stress of \( \sigma_3 \) and \( A, B \) and \( C \), are the expansion coefficients.

In an attempt to quantify the effect of weathering upon tunnel instability a strength reduction factor is required for the weathered material, and this takes the form of a percentage loss in strength. Distinct from weathering, the swelling properties are also included in the programme; the swelling behaviour is governed by the maximum swelling pressure and maximum swelling strain.

To calculate the elastic expansion in the rock the elastic modulus and Poisson's ratio are required; the effect of the elastic displacement upon tunnel deformation is negligible and these quantities are only present for the sake of completeness.

Once all the data has been assimilated it is then stored on a file tape ready for use when required. The input data used in the programme is obtained from laboratory tests on strata samples and thus is subject to the usual sampling and testing errors.

3.2 The Computer Programme

Once the strength properties have been fixed, the operator has the opportunity to vary the mining options, namely the tunnel size and support strength. The flow chart for the programme is shown in Figure 3. A typical set of the computer print out can be seen in Figures 4, 5 and 6. Figure 4 shows the tunnel deformation and extent of the yield zone in relation to the geological sequence; from this, possible positions of failure around the support can be identified. Figure 5 shows a theoretical stress distribution along a radius from the tunnel centre. The jump in the tangential stress value at the yield zone boundary is due to assuming two distinct failure criteria for the material, one for broken rock and one for intact material. A better representation would be to introduce a transition zone between the failed and elastic zone; this situation is currently being investigated. Figure 6 is a rock support interaction diagram, the two curves (A) and (B) show the strata pressure in relation to the rock dilation. Curves (A) and (B) employed the same calculations the only difference between them being that the results from curve (A) included the body weight of the broken material, whilst for (B) body forces were not considered. The line (C) is known as the 'Characteristic Line' for a support system, it represents the resistance to movement of the support at varying amounts of distortion. The intercept between the line (C) and curves (A) or (B) will indicate the amount of deformation to be expected before the system reaches
START

INPUT NUMBER OF STRATA LAYERS

FOR EACH STRATA LAYER CONSIDERED

INPUT ROCK PROPERTIES
(i) THICKNESS OF STRATA LAYER
(ii) ELASTIC MODULUS
(iii) POISSONS RATIO

TYPE OF FAILURE ENVELOPE

LINEAR

CURVED

INPUT FAILURE COEFFICIENTS

INPUT FAILURE COEFFICIENTS

INPUT EXPANSION COEFFICIENTS

DOES THE MATERIAL HAVE ANY WEATHERING PROPERTIES

NO

YES

INPUT
(i) SWELLING STRAIN
(ii) SWELLING PRESSURE
(iii) STRENGTH REDUCTION

INPUT NAME OF STRATA LAYER

NEXT STRATA LAYER

NO

HAS ALL THE DATA BEEN COMPILED

YES

STORE DATA ON TAPE

END

Figure 2  Rock Property Data File
START

READ IN STRATA DATA FROM TAPE

INPUT
(i) DEPTH OF STRATA
(ii) DEPTH OF TUNNEL
(iii) DIMENSIONS OF TUNNEL
(iv) SUPPORT PRESSURE

FOR EACH RADII CONSIDERED

CALCULATE VIRGIN STRESS

FOR EACH STRATA ELEMENT CONSIDERED

CALCULATE IN WHICH STRATA LAYER ELEMENT IS SITUATED

TYPE OF POST AND PRE-FAILURE ENVELOPE

LINEAR

SUBROUTINE AVSTRESS

CALL AVSTRESS
Subroutine Avstress calculates the absolute stress of the element by numerical methods

CALL TANGENTIAL STRESS

SUBROUTINE YELAST

CALL YELAST
Subroutine Yelast calculates constraints necessary to determine Yield/Elastic boundary for a curved failure envelope

CALCULATE RADIAL STRESS INCREMENT

CALCULATE ELASTIC STRESS

ARE THE STRESSES IN THE FAILED REGION COINCIDENT WITH STRESS LEVELS IN THE ELASTIC ZONE

YES

CALCULATE EXPANSION IN THE ELEMENT

NO

NEXT STRATA ELEMENT

NO

DOES THE MATERIAL EXHIBIT SWELLING PROPERTIES

YES

CALCULATE EXPANSION DUE TO SWELLING

SUBROUTINE AVSTRESS

CALL AVSTRESS

CALCULATE TANGENTIAL STRESS

CALL YELAST

CALCULATE ELASTIC STRESS

Figure 3 Tunnel Stability Prediction Programme
1. Calculate total expansion in the element

2. Calculate size of the yield zone

3. Calculate radial and tangential stresses in the elastic region

4. Calculate the elastic expansion

   CALL DEFORM
   Subroutine Deform sums the expansion of the strata elements along a radius

   IS THE INFORMATION FOR ROCK/SUPPORT INTERACTION DIAGRAM
   YES

   NO

   NEXT RADIAL ELEMENT

   NO

   HAVE ALL THE RADII AROUND THE EXCAVATION BEEN EXAMINED
   YES

   PRINT OUT SIZE AND SHAPE OF THE YIELD ZONE AND THE FINAL SIZE OF THE TUNNEL IN RELATION TO THE GEOLOGICAL SEQUENCE

   PRINT OUT RADIAL AND TANGENTIAL STRESS DISTRIBUTION ALONG A PREDETERMINED RADII

   DO YOU REQUIRE A ROCK/SUPPORT INTERACTION DIAGRAM
   NO

   YES

   INPUT RADIUS ALONG WHICH STRATA PRESSURE IS TO BE EXAMINED

   SET SUPPORT PRESSURE AT ZERO

   CALCULATE THE EFFECT OF BODY WEIGHT

   INCREASE SUPPORT PRESSURE

   NO

   HAS DEFORMATION BEEN CALCULATED FOR ALL SUPPORT PRESSURES
   YES

   DISPLAY GRAPHICALLY
   (1) ROCK PRESSURE/DEFORMATION CURVE
   (11) SUPPORT PRESSURE/DEFORMATION CURVE

END
assumes a hydrostatic stress field as the applied geostatic stress, if however either the vertical or horizontal component of stress is significantly larger than the other, then equation (1) can no longer be applied and a more complex relationship is required. In the British Coal Measures strata it is commonly accepted that the stress field is approaching the hydrostatic state, this being particularly the case at depth. The exceptions to this situation will be in heavily faulted or geologically disturbed ground and at shallow depths.

Laboratory strength tests are carried out under fairly ideal conditions using samples removed from the mine. In underground conditions the material is rarely as strong, joints and small faults can significantly decrease the overall strength. Therefore, it is important to examine the strata underground with a view to appreciating the role of joints and other natural weaknesses; once a sufficiently large amount of sites has been investigated then guidelines can be drawn up to achieve closer correlation between laboratory and in situ strength values.

At present the programme only predicts stability for a circular tunnel, although the method of solution will work equally well with other shapes and it is proposed to modify the prediction model so that an arched profile will also be available. This will be an important development as arched shaped roadways are predominant in British coal mines.

5 ACKNOWLEDGEMENTS

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APPENDIX I

APPLICATION OF STABILITY PREDICTION TO CIRCULAR MINING TUNNELS

In order to investigate the validity of the predictive method, two circular tunnel sites were studied, the first being an undersea tunnel at Dawdon Colliery and the second in the moderately deep but geologically complex conditions at Cotgrave Colliery.

The Dawdon tunnel was driven in fairly competent strata throughout its length, the strata consisting mainly of sandstones and sandy siltstones. The tunnel profile was cut using a full-face tunnelling machine which gave an excellent finished rock surface allowing effective, immediate rock restraint by the circular steel support.

The Cotgrave Colliery circular tunnels are mainly characterised by the presence of a weak seatearth which forms the floor stratum for a significant length of the tunnel network. In these areas the cause of the closure was due to floorlift. The presence of water produced a detrimental effect to the material strength and caused a substantial change in its flow properties.

Table I gives geological sections for both Dawdon and Cotgrave showing the position of the tunnel in relation to the strata and the appropriate strength properties for the rock layers.

The measured and predicted values of closure for both tunnels are given in Table 2 and clearly demonstrate the degree of refinement achieved with the new treatment of geological strength data and
### TABLE I

**GEOLOGICAL SECTIONS FOR THE COTGRAVE AND DAWDON TUNNEL SITES**

<table>
<thead>
<tr>
<th>Layer</th>
<th>UCS (MPa)</th>
<th>Location</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstone</td>
<td>66</td>
<td>Cotgrave Colliery</td>
<td>270 m</td>
</tr>
<tr>
<td>Mudstone</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do</td>
<td>22.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seatearth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td>20.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>20.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siltstone/Sand</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silty Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siltstone</td>
<td>68</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Location:**
- Cotgrave Colliery: 270 m inbye
- Dawdon Colliery: 270 m inbye, 810 m inbye, 850 m inbye

*Do = Tunnel Diameter*

### TABLE II

**CIRCULAR TUNNEL STABILITY DATA**

<table>
<thead>
<tr>
<th>Site</th>
<th>Measured</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotgrave</td>
<td>1500 mm</td>
<td>603 mm</td>
</tr>
<tr>
<td>Dawdon</td>
<td>25 mm</td>
<td>14 mm</td>
</tr>
<tr>
<td></td>
<td>810 m Inbye</td>
<td>50 mm</td>
</tr>
<tr>
<td></td>
<td>850 m Inbye</td>
<td>45 mm</td>
</tr>
</tbody>
</table>

*NOTE: Wilson Formula*

\[
C = d \left[ \frac{1+\nu}{E} \right] \left[ \frac{(K-1)q \sigma_f}{(K+1)} \right] \left[ \frac{2q \sigma_f}{(P+P')^2} \right] - \frac{2+e}{K+1}
\]

- C = diametric closure
- d = driven diameter
- \( \nu \) = Poisson's ratio
- E = modulus of elasticity
- K = triaxial stress factor
- q = corer load
- \( \sigma_f \) = uniaxial compressive strength
- P = lining resistance
- \( P' \) = strength reduction factor
- \( \varepsilon \) = post failure strength property

**BIBLIOGRAPHY**