Nonlinear Numerical Simulation for Concrete Hinges of TBM Tunnels

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Abstract

One of the influencing factors affecting the stresses induced in the lining, which is often ignored in design, is the effect of hinges or joints of TBM tunnels. It is clear for whom dealing with tunnels that, there is a moment should be transmitted across the joint of tunnel, although it is considered as a concrete hinge in the analysis and design of tunnels, but for the concrete hinge it should be no moment transmitted across it. Therefore, the objective of this study is to find a good simulation for the TBM tunnel joint considering its real properties. In the present study five finite element models for tunnel joint were performed, to serve most of tunnel diameters, curves based on normal force and bending moment are drawn for presenting the rotational stiffness of joint and hence the joint can be dealt with, in the analysis of tunnel, as a spring connecting each two segments. The results are directly coupled with the finite element program FINAL (Swoboda 2007). Based on the results of these curves, a FORTRAN program ‘Joint’ was made for calculating the rotation of joint Φ, and the rotational stiffness Cmn representing the spring, for any expected values of bending moment and normal force, also the program can expect the type of deformation in the joint, however is elastic or plastic.

Keywords: Longitudinal joint, Hinge, Rotation, Segment, Spring.
1 INTRODUCTION AND LITERATURE REVIEW

In most cases of tunnel design, conventional modelling ignores the influences of the assembling of segments, the construction method, nonlinear effects, grouting, type of joint, etc. For TBM tunnels there are two types of joint [1];

1) Longitudinal joint is the longitudinal interaction between the segments, its behaviour is considered as hinge with characteristics of the concrete.

2) Lateral joint is the lateral interaction between rings, which is modelled by springs, generally with linear behaviour.

According to the shape of the joint, there are many types of tunnel joints the present paper will deal with the flat-flat type. For the determination of the rotational stiffness of the longitudinal joints usually formula of Janssen (1983) [3], based on the investigation of Leonhardt and Reimann (1966) [4], is used. For linear stresses, the rotational stiffness $C_m$ is constant and can be described as:

\[ C_m = \frac{E \cdot c}{12} \]  \hspace{1cm} (1)

It depends only on the young's modulus $E$ and the width of the contact area $c$. If the bending moment $M$ exceeds the boundary bending moment ($M_{bou} < \frac{N c}{6}$) [2], the rotational stiffness will depend on the normal force $N$, and can be described as:

\[ C_m = \frac{9 E \left(2 M - N \cdot c\right)}{32 \left(N^3 \cdot c\right)} \]  \hspace{1cm} (2)
2 THE FINITE ELEMENT MODELS OF TUNNEL LINING JOINT

The model of tunnel joint in the present study consists of two parts representing the segments, the gap between the segments represents the joint and has a width equals zero, the width of the contact area \( c \) equals to half of the thickness of the segment \( t \), the steel reinforcing was taken from the design of the segment according its thickness. The finite element model adopted for the analysis of TBM joint is shown in Figure 2.

![Figure 2: The finite element model adopted for the analysis of TBM joints.](image)

The model consists of the Linearly Strain Triangular (LST) element to simulate the concrete part of the tunnel segments, (BEAM 2) element to simulate the reinforcing bars of the segments, and an interface element was chosen to simulate the joint or the longitudinal interaction between segments. Table 1, shows the main dimensions of models of TBM joint, performed in the study. Under the effect of normal force and bending moment on the model of joint, a relation between rotation \( \Phi \), moment \( M \), at a constant normal force \( N \), can be represented in figures from 3 to 7. The calculations of the generated model are performed using FINAL package.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of Segment (( t ))</td>
<td>20 cm</td>
<td>30 cm</td>
<td>40 cm</td>
<td>50 cm</td>
<td>60 cm</td>
</tr>
<tr>
<td>Width of the Contact Area (( c ))</td>
<td>10 cm</td>
<td>15 cm</td>
<td>20 cm</td>
<td>25 cm</td>
<td>30 cm</td>
</tr>
</tbody>
</table>
Figure 3: Relation between rotation \( \Phi \), moment \( M \), for Model (I).

Figure 4: Relation between rotation \( \Phi \), moment \( M \), for Model (II).

Figure 5: Relation between rotation \( \Phi \), moment \( M \), for Model (III).
Figure 6: Relation between rotation $\Phi$, moment $M$, for Model (IV).

Figure 7: Relation between rotation $\Phi$, moment $M$, for Model (V).

Figure 8: Limit between elastic and plastic deformation of joint.
3  SPRING STIFFNESS PROGRAM “JOINT”

Based on the curves represented in figures from 3 to 7, a new spring stiffness program ‘Joint’ was made for calculating the rotation of TBM joint.

3.1  Input Data of Program Joint

The input data, needed for program Joint are:

1) Length of the contact area c

2) Value of the maximum expected normal force N affecting on the joint

3) Value of the maximum expected bending moment M affecting on the joint

3.2  Output Data of Program Joint

The output data of the program Joint are:

1) Value of the rotation Φ, and the rotational stiffness C_m for the spring

2) Also the program gives notations about the type of the deformation in the joint, if it is elastic or plastic, which can help the designer to choose the suitable thickness for the lining. Figure 8, represents the limit between elastic and plastic deformation at the joint.

3.3  Using of Program Joint in Modelling of Segmental Lining

To simulate tunnel segments, the BEAM 6 element developed by Swoboda [6], can be used, this element provides an acceptable solution for the finite element modelling problem of tunnels because it considers all possible deformations of the lining. The advantage of this element is that, it can describe the real behaviour of the lining as curved beams, with an acceptable accuracy. Each BEAM 6 element has a 6x6 stiffness matrix, to simulate the joint as a spring it will be as a truss element has 2x2 stiffness matrix, its elements equal the rotational stiffness C_m, which can be known by solving the tunnel as non jointed tunnel to know the maximum expected bending moment and normal force affecting on the suggested place of the joint in the lining, then using program Joint to calculate C_m. For a tunnel consists of n segments, between each two segments there is a joint, which will be dealt with in the present study as a spring, the global stiffness matrix for each segment and spring will be 7x7 and by a method of condensation it can be transformed to 6x6 stiffness matrix.
3.3.1 Condensation of Beam Stiffness

Przemieniecki’s formula [5] was used in condensing the stiffness matrices of BEAM 6 and spring, where, if Eqn. (3) and (4) represent the complete set of equilibrium equation for BEAM 6, and spring, respectively, the global stiffness matrix for the whole structure will be as it appears in Equ. (5)

\[ K_b \cdot U_b = F_b \]  
\[ K_s \cdot U_s = F_s \]

where \( K_b \) and \( K_s \) are the stiffness matrices of Beam 6 element and spring respectively, \( U \) represents a column matrix of displacements, and \( F \) is the effective external loads.

\[ \begin{bmatrix} K_{bb} & K_{bs} \\ K_{sb} & K_{ss} \end{bmatrix} \begin{bmatrix} U_b \\ U_s \end{bmatrix} = \begin{bmatrix} F_b \\ F_s \end{bmatrix} \]

(5)

The formula of condensation as it is described by Przemieniecki will be as follows:

\[ K_c = K_{bb} - K_{bs} \cdot K_{ss}^{-1} \cdot K_{sb} \]

(6)

If the spring lies at the end of the beam as in figure 10, the global stiffness matrix for the beam connected with a spring can be derived by applying Equ. (6), where \( k_C \) stands for elements of the condensed stiffness matrix.

\[ \begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix} \]

(7)

Figure 9: Modelling of segmental lining according to program Joint.

Figure 10: Freedom displacements for beam connected with a spring.
4 APPLICATION ON TUNNEL

An application of the spring stiffness program Joint has been performed on a tunnel has the following data: number of tunnel segments \((n) = 6\), thickness of the segment \((t) = 40.0\) cm, external diameter of the tunnel \((\text{De}) = 4.80\) m, the tunnel is at depth \((H) = 2\text{De}\), the water level is 7.0 m above the upper surface of the tunnel, the water pressure inside the tunnel is 1 bar. Figure 11; (a), shows the finite element model for the tunnel, where element BEAM 6 represents the segmental lining and element LST represents the soil surrounding the tunnel. Figure 11; (b), represents the bending moment and normal force affecting on the tunnel lining for three cases; non jointed tunnel lining, jointed tunnel; considering the joints as concrete hinges (conventional method), and jointed tunnel, considering the joints as joints with spring, by using the results of program Joint.

![Finite element model of tunnel](image)

**Figure 11:** (a) The finite element model of the tunnel, (b) M & N for different methods.

Figure 11 : (b) shows that, the maximum bending moment induced in the lining in case of dealing with the joints as springs is 40% greater than that in case of joints as concrete hinges for tunnel has 6 segments, but the effect on normal force is negligible.

5 CONCLUSION

A numerical study was performed to introduce a new numerical simulation for TBM tunnel by considering the longitudinal joint of tunnels as a spring, its rotational stiffness can be calculated from a FORTRAN program ‘Joint’ introduced in the present paper.
REFERENCES


