Effect of Joint Attributes on Water Tunnel Lining

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Abstract

A numerical study was carried out using the finite element analysis program FINAL to investigate the effect of joint attributes on the maximum bending moment induced in the segmental tunnel lining, the analysis has been performed with different combination of segments number, joint orientation, tunnel depth, and the ground coefficient at rest k_o. The model used in the analysis was for a water tunnel exposed to an internal and external water pressure, The results show that, the orientation of hinges has a significant effect on the moment induced in the lining in case of number of segments equals four, and it has a maximum value if the angle between the vertical axis of tunnel and the first joint is 45°, in this case it is preferable to erect the segments by keeping the angle between the axis of the tunnel and the first joint not more than 20° for the economic design. Also the orientation of joints on the moment of the lining decreases when the number of segments is five, and it is nearly no effect for the orientation if the number of segments is seven, or more. The number of joints has a greater effect on the maximum bending moment induced in the lining, where as the number of segments increases the bending moment decreases. However, beyond a number of joints equals ten the increase of number of joints has a little influence on the values of stresses induced in the lining, and for the economical design, the number of segments is preferred to be more than four, and the most economical design can be obtained if the number of joints is seven. For the effect of k_o on the moment induced in the lining it was found that, the moment is nearly zero if k_o equals 1.0, however the value of moment increases in the both cases, if K_o increases or decreases than 1.0.

Keywords: Longitudinal joint, Rotation, Orientation, Segmental lining.
Introduction

Most of world countries nowadays suffer from a lack of fresh water which represents the main source of life, that fact occupied the attention of many investigators in recent decades to find solutions for keeping and protecting the available quantity of water. One of the main reasons of wasting water is the method of water transportation. Where in Egypt, as one of those countries, to develop new areas away of the River Nile, it needs to transport the water to those areas, such transportation may be faced by many obstructions such as mountains, valleys, water ways, housing areas, etc., so tunnelling is the most suitable solution to overcome such obstructions, and to keep the water quantity and quality, besides the possibility to use those tunnels in generating of the electrical power.

It is clear for whom dealing with TBM tunnels (Tunnel Boring Machine) that, an amount of moment should be transmitted across tunnel joint to the segments, although it is considered as a concrete hinge in the analysis and design of tunnel, but in the concrete hinge it should be no moment transmitted across the hinge, this reason makes the designers of tunnel neglecting the effect of joints in the design.

In this study an application on a water tunnel has been performed to compare the results of the design of tunnel joint as a spring, by using the stiffness of the spring from the non linear spring stiffness program ‘Joint’ [1], with the conventional method of tunnel design in which the joint is considered as a concrete hinge.

Numerical Simulation

A two dimensional plane strain elastoplastic soil model based on Moher-Coulomb failure criterion has been developed. The finite element model for the analysis is shown in Figure 2. The numerical modelling is based on the Linearly Strain Triangular (LST) elements, to simulate the soil, and (Beam 6) elements to simulate the segmental lining of the tunnel. The calculation of the generated model is performed using finite element program FINAL (Swoboda 2007).

Dimensions of the Tunnel Model and Geotechnical Conditions

The model is based on the following data and conditions:

- Internal diameter of the tunnel $D_i = 4.0 \text{ m}$
- The thickness of the segments $t_s = 40.0 \text{ cm}$
- Number of segments per a ring $n = 6$ segments, the first joint lies at $30^\circ$ from the vertical axis of the tunnel
- The tunnel is at depth $H = 2D_e$, where $D_e$ is the external diameter
- The water level is 7.0 m above the surface of the tunnel
- The water pressure inside the tunnel is 1 bar
- Parameters of soil which had been used in the present analysis are: modulus of elasticity ($E$) 50 MPa, Poisson’s ration ($\nu$) 0.25, cohesion ($C$) 15 kPa and angle of internal friction ($\phi$) $35^\circ$. Ground Coefficient at Rest ($k_o$) = 0.8
- Parameters of concrete which had been used in the present analysis are: modulus of elasticity ($E$) 30,000, MPa, Poisson’s ration ($\nu$) 0.3.

Figure 1: Dimensions of the model of tunnel and geotechnical conditions

Figure 2: Finite Element Mesh adopted for model of tunnel
Comparison between Considering Tunnel Joint as a Concrete Hinge and as a Spring in the Analysis of TBM Tunnels

Figure 3 : (a) shows the normal force and bending moment for the lining in case of non jointed tunnel lining, in this case the tunnel is designed as a circle without joints, the tunnel was redesigned as a segmented tunnel consists of 6 segments, and the joint between each two segments was designed in two ways; as a concrete hinge as in Figure 3 : (b), and another design as a spring by using the rotational stiffness of the spring from program ‘Joint’ [5], as in Figure 3 : (c). Figure 3 clears that the design of joint as spring has a significant effect on the values of bending moment, where the bending moment is larger than that obtained from joints as a concrete hinge, and less than that obtained from non jointed tunnel lining. For tunnel has 6 segments, 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 but the effect on normal force is negligible.

Figure 3: Bending moment and normal force for different solutions.
Attributes of Jointed Tunnel Lining

A numerical study to investigate the effects of joint number (n), orientation, tunnel depth (H), and ground coefficient at rest (Ko) on the maximum bending moment induced in a jointed tunnel lining, has been performed. For the same 2D plane strain elastoplastic soil model shown in figure 2, has been performed by using the finite element program FINAL [4]. But the differences between the two models will be in n, H, Ko, and orientation of joints, the analysis also will be done for two cases, case where tunnel joints are considered as concrete hinge, and the case of joints as spring which depends on the program ‘Joint’ to compare the results of the two solutions.

Effect of Orientation of Joints

In figure from 5 and 6, the relation between the maximum bending moment induced in the lining and the orientation of the joint was drawn, the solution was done for two cases, first for a joint as a spring by using the results of the spring stiffness program Joint and the other solution is the conventional method by dealing with the joint as a concrete hinge, the orientation of joints can be defined, as the angle between the first joint and the vertical axis of the tunnel, from those figures it is clear that The orientation of joints has a significant effect on the moment of tunnel lining in case of the number of joints equals 4 as shown in figure 4, and in this case it is preferable to erect the segments by keeping the angle between the axis of the tunnel and the first joint not more than 20° for the best design. The effect of orientation of the joints on the moment induced in the lining decreases if the number of segments greater than 5, and has nearly no effect if the number of segments is 7, or more. Those results are accepted with the previous work dealing with attributes of tunnel joints [2], [6].

Effect of Number of Joints

Figure 7, shows the effect of number of segments on the maximum bending moment induced in the lining for case of Ko = 0.8, and it can be seen that, solving the joints as a spring gives a maximum bending moment greater than solving joints as a concrete hinge especially if the number of segments is greater than 4, and in both solutions. Figure 7 also shows that, the effect of number of segments or number of joints has small effect on the bending moment in it is greater than 7, and it is negligible if it is greater than 9 segments, therefore for the best economic design, the number of tunnel segment can be taken 7.
Figure 4: Effect of joint orientation on moment in 4-joints tunnel lining

Figure 5: Effect of joint orientation on moment of tunnel lining by using spring stiffness
Figure 6: Effect of joint orientation on moment of tunnel lining by using joints as R.C. hinges

Figure 7: relation between moment and number of segments at critical orientation
**Effect of Ground Coefficient at Rest $k_o$**

Figures from 8, to 10, show the effect of the ground coefficient at rest $k_o$ on the maximum bending moment induced in the lining in case of number of segments equals 4, 6 and 8, respectively, it can be seen that, for the number of segments $n = 4$ $k_o$ has no effect on the maximum bending moment, where the maximum bending moment in case joint as a concrete hinge or as a spring are the same as it is in non jointed tunnel design, but the effect appears if $n > 4$, also for $k_o = 0.5$, 1.0 and 2.0, there is no effect for the results obtained from the spring stiffness program on the maximum bending moment however the number of joints is, where the maximum bending moment has the same value if the joints were designed as a spring or as a concrete hinge, but the effect appears clearly if $k_o$ value is between 0.5 and 1.0 or between 1.0 and 2.0 and the big effect can be found if $k_o = 0.8$ or 1.35, in those cases the maximum bending moment in the lining designed with a joint as a spring is between 40% to 80% greater than that of designed considering the joint as a concrete hinge, where the percentage increases with the increase of joint number. For $k_o = 1.0$, the bending moment induced in the lining is nearly zero for all cases of design and for a tunnel has any number of joints.

![Graph](image_url)

**Figure 8: Effect of the ground coefficient at rest $k_o$ ($n = 4$)**
Figure 9: Effect of the ground coefficient at rest $k_o$ ($n = 6$)

Figure 10: Effect of the ground coefficient at rest $k_o$ ($n = 8$)
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Figure 11: Effect of the ground coefficient at rest $k_o$ ($n = 4$, $6$ and $8$)

Figure 12: Effect of tunnel depth (H/De)

Effect of Tunnel Depth

Figure 12, shows the relation between the maximum bending moment induced in the lining and the ratio H/D where H is the tunnel depth and D is the external diameter of
the tunnel as it appears in figure 1, Figure 12 clears that the maximum bending moment increases linearly with the increase of tunnel depth ratio H/D.

From the discussion of all figures, it can be seen that the spring stiffness program has a big effect on the maximum bending moment if the number of segments exceeds than 4 and if the ground coefficient at rest $k_o$ is between 0.5 and 1.0, or between 1.0 and 2.0.

References: