Shahrood
University of
Technology

Iranian Society
of Mining
Engineering
(IRSME)

Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

THOMSON
REUTERS

Vol. 10, No. 4, 2019, 1031-1043.
DOI: 10.22044/jme.2019.8581.1738

Effect of segmental joint stiffness on tunnel lining internal forces under static conditions

G. Ranjbar[1], K. Shahriar[2*] and K. Ahangari[1]

1. Department of Mining Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
2. Department of Mining and Metallurgy Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

Received 14 June 2019; received in revised form 26 August 2019; accepted 6 September 2019

Keywords

Segmental Lining

Joint Stiffness

Internal Forces

Static Loading

Numerical Analysis

Abstract

According to the wide application of segmental lining in mechanized tunneling, recognizing the behavior of segmental lining joints is important in tunnels designing. In the structural analysis of the tunnel segmental lining, segmental joints can be considered as elastic joints, and their stiffness characteristics are affected by the rotational, shear, and axial stiffness. The purpose of this work is to investigate the effect of the rotational, shear, and axial stiffness of segmental lining joints on the internal forces (bending moment and axial force) under the static conditions. For this purpose, a 3D numerical analysis was carried out using the ABAQUS software. The results obtained show that by increasing the rotational stiffness of the segmental joint, the bending moment increases, and for lower values of rotational stiffness, the bending moment variations are higher, while the axial force variations are very slight in comparison with the bending moment. By increasing the axial and shear stiffness of the segmental joint, changes of the bending moment and axial force in segmental lining are negligible.

1. Introduction

Most tunnels to be excavated by tunnel boring machines in poor geotechnical conditions, precast concrete is used to support the tunnels. These support systems include a number of precast concrete pieces called segments. By putting these segments together, segmental rings are made. Segmental tunnel linings have two types of joints: the joints between the segment pieces of a ring are called the longitudinal or radial joints and the joints between the segment pieces of two adjoining rings are called the circumferential joints. The joint between segments is the main characteristic of segmental linings. Not only the characteristics of concrete segments affect the behavior of segmental lining, but also the geometrical and mechanical characteristics of joints strongly affect that [1]. Thus, one of the most important factors involved in designing the tunnel segmental lining is the effect of segmental joints on its behavior. The segmental joints are usually disregarded in designing and analyzing the tunnel segmental lining and they are modeled as a continuous lining with a constant bending stiffness. Therefore, the displacement values are underestimated and the internal forces of the tunnel lining are overestimated and increase the safety factor of the support system. Considering the fact that stiffness of segmental joints is very different from stiffness of the segment, not considering it will affect the results of the structural analysis of the tunnel lining. Therefore, for a realistic simulation of the tunnel segmental lining and also for a correct prediction of the structural internal forces and displacements, segmental joints of the lining should be considered in modeling [2]. The effects of segmental joints on the tunnel lining behavior by analytical methods are usually considered in both the direct and indirect methods. In indirect methods, the tunnel structure is perceived as a

---

✉ *Corresponding author: k.shahriar@aut.ac.ir (K. Shahriar).*

rigid lining ring embedded on a continuous ground model. The effect of joints is usually shown through reduction of the tunnel lining stiffness. These simplified analytical methods can not consider any complexity of the joint characteristics including stiffness and joint distribution or displacement and stress state of soil ground tunnel. In the direct methods, segment joints are directly added to the tunnel lining element. Most direct methods consider the joint behavior through rotational springs in joints [3].

Generally, the presence of joints leads to a decreased stiffness of the tunnel segmental lining. In other words, flexibility of the segmental lining is more than continuous lining. One solution in utilization of designing methods for designing the tunnel segmental lining based on the continuous lining is to consider segmental lining as a continuous ring with decreased stiffness and decrease factor η in bending stiffness of the tunnel lining.

$$\eta = \frac{(EI)_{eq}}{EI} \tag{1}$$

where $(EI)_{eq}$ is the bending stiffness of the segmental lining and EI is the bending stiffness of the continuous lining without joints.

Although simple designing methods, like when the tunnel lining is considered continuously, can be used for determining the internal force in segmental lining using the decrease factor η, they have a few problems, as follow, which should be considered [3]:

-Effect of the joint location on the internal forces induced in the tunnel lining is not considered.

-Dependence of the lining behavior on characteristic variations such as rotational stiffness (K_R) between joints in a ring could not be considered.

Therefore, it is more accurate to use the designing methods, which directly consider the presence of the tunnel lining joints.

Lee *et al.* have presented an analytical solution to predict displacements and internal forces of segmental lining of the circular tunnel. The effects of joint stiffness on the tunnel segmental lining have been analyzed, and laboratory tests have been done to confirm the suggested analytical solution. This method has been developed based on the force method to study the effects of joint stiffness, joint distribution, joint numbers, and unbalanced stiffness of joints. The results obtained have shown that in the model, the bending moment in segmental lining is considerably affected by stiffness of segmental joints. Harder joints produce higher values of bending moment in segmental lining, while the axial force is not affected by joint stiffness [4].

Blom has proposed an analytical method that takes into account both the interaction between the successive rings composed of elastic jointed segments and the soil-structure interaction. The longitudinal joints are modelled using rotational spring stiffness K_R, while the radial joints between successive rings are modelled with shear springs. The bending moment in the lining has been determined by superposition of moments caused by the effects of longitudinal joints and ring joints [5].

Naggar *et al.* have developed a simplified analytical solution, which considers joints in the tunnel lining. Segment joints are simulated through rotational stiffness. The results of analyzing jointed lining show that the presence of joints results in the moment of the tunnel lining to decrease by 50% compared with the continuous lining, although the effect of joints on the created axial force in the lining is not remarkable (10% or less) [6].

Limitation of analytical methods and quick development of computer codes have resulted in the increased use of numerical methods in designing the tunnel lining.

Teachavorasinkun has carried out a numerical research work to investigate the effect of the joint rotational stiffness, number of joints, and ground modulus on the bending moment using the bar-spring method. The results obtained have shown that when the joints are stiff (with a high value of K_R), the maximum bending moment of the jointed lining both for the higher and lower values is close to the value of continuous lining [7].

Ding *et al.* have suggested a numerical method in which the joint behavior is simulated by three types of joint stiffness including rotational stiffness, axial stiffness, and shear stiffness, although the details of the effect of joint stiffness have not been studied [8].

Do *et al.* have presented a 2D numerical analysis of the segmental tunnel lining behavior in which the effects of the joint stiffness, Young's modulus of the ground, and the lateral earth pressure factor are taken into consideration using a 2D finite difference element model. The longitudinal joint between segments in a ring has been simulated through double node connections, with six degrees of freedom, represented by six springs. The influence of certain characteristics including the rotational stiffness, axial stiffness, and radial stiffness of longitudinal joints on the tunnel behavior with respect to the effect of the packing material is considered in details. The presented model is used for the parametric analyses of a shallow tunnel in conditions in which the ground loads increase in depth due to the effect of the gravity field. The numerical results show a significant reduction in the bending moment induced in the tunnel lining as the joint number increases. It has been seen that the influence of joint rotational stiffness, the reduction in joint rotation stiffness under the negative bending moment, the lateral earth pressure factor, and the Young's modulus of ground surrounding the tunnel should not be neglected. On the other hand, the results obtained have also shown an insignificant influence of the axial and radial stiffness of the joints on the segmental tunnel lining behavior [9].

Henfy *et al.* [10], Chow *et al.* [11], Arnau & Molins [12], Klappers *et al.* [1], and Sliteen [13] have carried out a few studies about the effects of joint number, joint orientation, tunnel depth, lateral earth pressure factor, interaction among the segment, and packers between rings. Also Yan & Shen [14], Cavalaro & Aguado [15], and Salemi *et al.* [16] have done laboratory research works to study the tunnel segmental joints and to determine joint stiffness, in which the effect of joint stiffness on the lining behavior during the tunneling process has not been analyzed in details.

Considering the previous studies, the effect of stiffness of segmental lining joint on the behavior and bearing capacity of the tunnel segmental lining by the 3D numerical method has not been completely practiced. As a result, more research works are required to study the bearing capacity of the segmental lining under static loading. In the present work, the joint behavior was applied to the numerical model using the three parameters of rotational, axial, and shear stiffness. Considering the geometrical and mechanical parameters of segments and segmental joints of the tunnel lining, the numerical model of a segmental lining was simulated in an elastic environment. A numerical method was used by applying the ABAQUS software and information from the Mashhad subway tunnel (line 2) in order to analyze the effect of segment joints parameters on the bearing capacity of the tunnel segmental lining.

2. Mashhad subway tunnel (line 2)

For the numerical modeling in this work, the geotechnical parameters of Mashhad subway tunnel (line 2) were used as the input data to analyze the results. The location of Mashhad subway tunnel stretches from northeast to southwest (from Tabarsi Boulevard to Fakuri Boulevard). This line with an approximate length of 14.3 km has 12 stations. The soil of the tunnel route mainly includes layers of fine clay and coarse sand. The underground water height differs only under the roof of tunnel, and the tunnel depth differs from 13.5 m to 21.65 m along the route. Line 2 of Mashhad subway tunnel is mechanically excavated by TBM. The tunnel support lining is a precast type of segments with 35 cm thickness and 1.5 m width which is assembled at the back of TBM, and in one ring of the tunnel lining, seven segments and one key segment are used. The mechanical parameters used are shown in Table 1.

Table 1. Mechanical parameters of segmental lining [17].

Elasticity modulus (GPa)	Poisson ratio	Specific weight (kg/m^3)
35	0.2	2400

3. Monitoring and choosing tunnel section to study

Uncertainty in the geological and geotechnical characteristics affects the tunnel excavation and designing methods. The realistic conditions of the project during the tunneling process, the tunneling method, and the design can be modified by monitoring. Designing and installing the monitoring instruments to prevent the negative influences of excavation and to recognize the ground and tunnel support system behavior will help the standard permitted range and will provide the required safety [18].

Considering the fact that in the excavation of urban railway tunnels the amount of ground surface subsidence is very important, due to the safety of constructed buildings in the area around the excavation, the measurement pins of the ground surface subsidence are used to measure this parameter in Mashhad subway tunnel line 2. The subsidence measurement includes operations of installation of pins, surveying, and data processing. After checking the tunnel route and data from the instruments installed in sections, the section 6.98 km, between the F2 and G2 stations were chosen to study. The overburden of this tunnel section was 14.1 m, and included three soil layers: upper fine clay layer, middle coarse sandy layer, and bottom fine clay layer. The geomechanical parameters of these layers are shown in Table 2. In this section, the pins are installed on ground surface at the right and left sides of the tunnel axis in a ten m distance from the tunnel axis, and for each two pins, the amount of subsidence was recorded to be 7 mm [19].

Table 2. Mechanical parameters of the understudied section soil layers [17].

Type of soil	Layer diameter (m)	Dry density (kg/m^3)	Cohesion (kg/cm^2)	Friction angle (degree)	Elasticity module (kg/cm^2)	Poisson ratio
Upper fine clay	6	1600	0.2	24	300	0.3
Middle coarse sand	2	1900	0.11	40	1000	0.3
Bottom fine clay	12	1630	0.25	20	300	0.3

4. Numerical modeling and validation by monitoring data

The ABAQUS software is one of the most powerful commercial softwares with the finite element method, which has provided a wide range of the required instruments for analyze of geomechanical problems, as follow:

-Using a variety of methods including the implicit finite element method (able to analyze the problem of small strain), explicit finite element method (to solve problems of medium with a large strain), and synthetic method of Oilrian-Lagrangian.

-Presence of behavioral models for soils and rock medium like plasticity of Mohr-coulomb, developed plasticity of Draker-Prager, modified model of Draker-Prager, and clay plasticity.

-It is able to define different boundary conditions. In dynamic simulations, infinite elements and absorbent boundaries can be used.

-It provides the ability to apply the initial conditions (like the initial stress condition, initial pore pressure, and saturation ratio) in geomechanical problems [20].

In this work, the finite element method was used by the ABAQUS software. The first step in numerical modeling is to determine the model dimensions. Dimensions of a model are determined with the purpose of minimizing excitement in the numerical model boundaries due to the underground excavation. Primary idea in this context is related to the accurate mathematical dissolve in an elastic environment by the Kirsch equations, in which the maximum distance, affected by an underground space, is estimated to be double to triple of its diametric, and after this distance, stresses get to their first status. As it is shown in Figure 1, the model dimensions are 200 m in the horizontal dimension and 70 m in the vertical dimension.

In the finite element method, the element is the smallest geometrical unit, for which changes of a parameter are evaluated by changing the situation (like stress by strain). These elements are used to construct the model geometry. In modeling of the surrounding soil in the ABAQUS software, 20 node continuous 3D stress quadratic brick elements (C3D20R) are used, which have 3 freedom degree for nodes and are suitable for the soil and rock environment (Figure 2).

The tunnel concrete lining is modeled by shell element due to its thin thickness compared to the tunnel diametric. For the segments, eight node quadratic shell elements (S8R) are used (Figure 3).

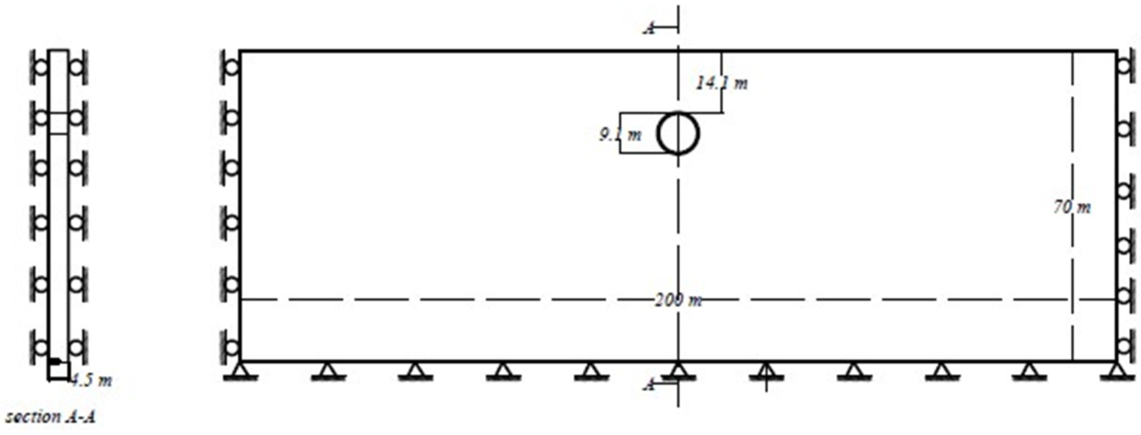

Figure 1. Dimensions and boundary conditions of the numerical model.

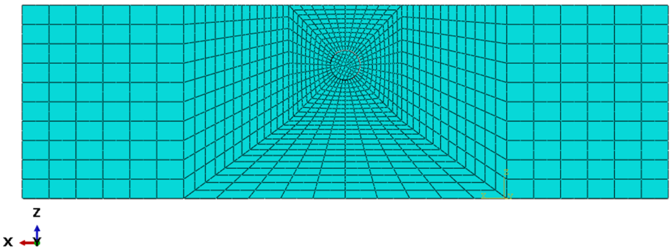

Figure 2. Elements used for modeling the surrounding soil.

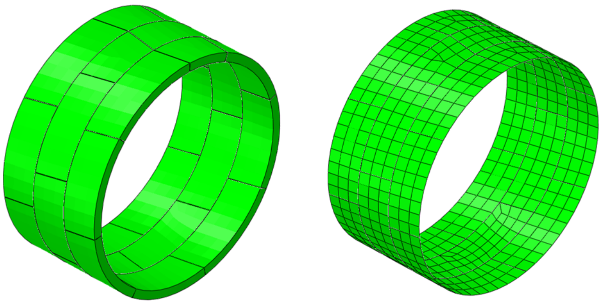

Figure 3. Shell elements for segmental modeling.

In the structural analysis, the segmental joint can be considered as an elastic pin, and its stiffness characteristics can be simulated by rotational or revolving stiffness (K_R), axial or normal stiffness (K_A), and radial or shear stiffness (K_S) (Figure 4). The value of K_R is defined as the bending moment-per-unit length, which is required to make the unit revolving angle along with the segmental joints. Similarly, the axial stiffness (K_A) and the radial stiffness (K_S) are, respectively, defined as axial force and shear force of the length unit, which are required to make the unit axial and radial movements in the assumed joint [9].

In the numerical method, the segmental joints are defined as the connector elements between the shell elements. The connector element functions as a link between two shell elements, in which, segments are allowed to move toward each other. Considering the type of connector element, different freedom degrees can be defined for rotating and displacement of these links, which could be stiff as either spring with non-linear, linear elastic behavior. As it is shown in Figure 5, the connector elements are used for segmental joint modeling. The behavior of these linear elastic elements is modeled by rotational stiffness EI, axial stiffness EA, and shear stiffness GA, and by considering the cylindrical coordinate system to apply the behavioral characteristics of these joints.

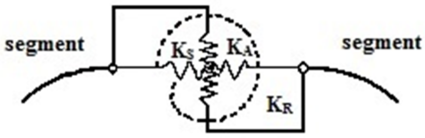

Figure 4. Shear (K_S), axial (K_A), and rotational stiffness (K_R) of the joint [9].

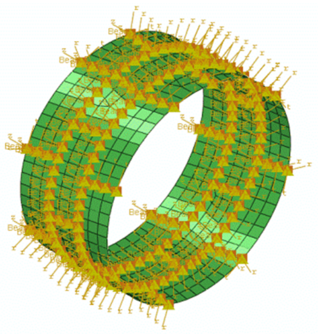

Figure 5. Connector elements for segment joint modeling.

Considering the problem condition and the surrounding soil and lining type of tunnel, different behavioral models existing in the ABAQUS software can be used. The behavioral model of Mohr-Coulomb has been used for modeling the surrounding soil of tunnel. The behavior of segmental lining and joints was considered as linear elastic. The initial condition includes *in situ* stress (vertical $\sigma_v = \rho g h$ and horizontal $\sigma_h = k\sigma_v$, in which $k = 1 - \sin\phi$, ρ is specific weight, g is gravity acceleration, h is depth of soil, ϕ is friction angle of soil, and k is ground stress ratio), which is applied to the model. The boundary condition includes roller support (horizontal movements equal zero) in the right and left boundaries and the boundaries along with the tunnel axis and the joint support (horizontal and vertical movements equal to zero) at the bottom boundary of the model (Figure 1). The implicit analysis includes two resolution steps. The first one is geostatic, which is usually the first step in analyzing the geotechnical problems to ensure that the *in situ* stress is in balance with the forces and boundary condition that are applied to the model, and the second step is static-general, which is used for excavation and installing the support system and analyzing movements and forces induced to the soil and tunnel support system. The monitoring data was used for verifying and calibration of the numerical model. Contours of the ground surface subsidence, as outputs of the ABAQUS software, are shown in Figure 6. Comparing the subsidence result of the numerical method and the monitoring data (Figure 7) shows that the computed subsidence using the software is equal to the subsidence data from the monitoring data. Therefore, the tunnel modeling is correct.

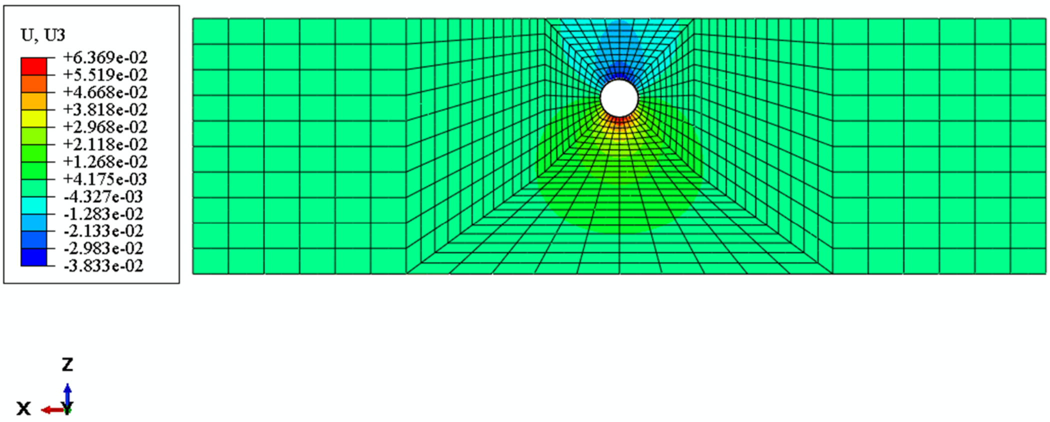

Figure 6. Computed contours of the ground surface subsidence in ABAQUS software.

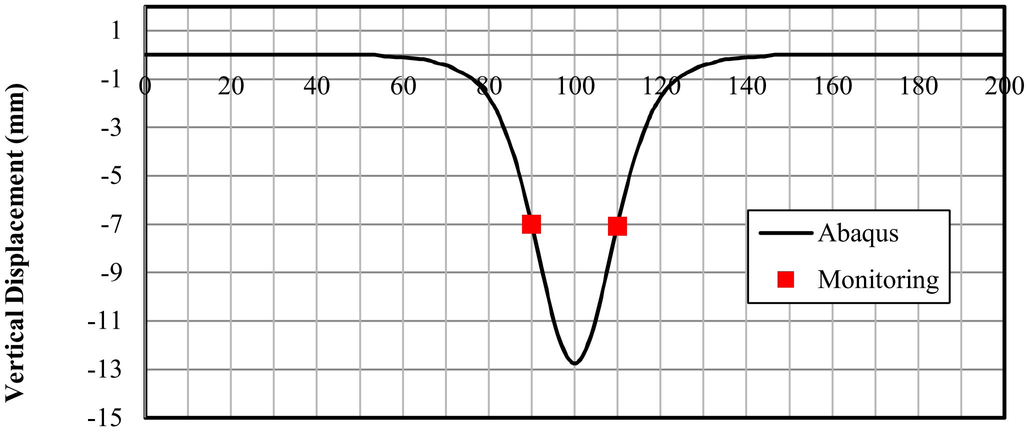

Figure 7. Comparing subsidence of calculated by the numerical method and the monitoring data.

5. Effect of segmental joint stiffness on internal forces of tunnel lining

Applying stress on the ground surface and the gradual increase of this stress up to a fixed value are used to study the effects of segmental joint stiffness on internal forces of segmental lining. This behavior can be modeled in the ABAQUS software by explicitly applying the constant velocity to upside boundary nodes of the model in a specific time. Therefore, the following modification was applied to the model, which was used for validation to investigate the effect of joint stiffness on the internal forces of segment lining:

1- The explicit dynamic analysis is used.

2- Applying velocity to the upside level of the model during a specific time (by analyzing a few models and applying velocity and different times to them, velocity of 0.05 meter-per-second during 10 s showed the optimized time and conclusions of analysis to study the internal forces of segmental lining).

3- Considering the fact that the purpose of this research work was to study the effects of the rotational, axial, and shear stiffness of segmental joints on the segmental lining behavior, and the behavior of the soil around tunnel is not studied, modeling of the tunnel surrounding setting is only for applying the charge on the segmental lining, and therefore, the tunnel surrounding setting is considered as linear elastic.

Dimensionless parameters of rotational joint stiffness ratio ($\lambda_R = k_R l / EI$) and the axial joint stiffness ratio ($\lambda_A = k_A l / EA$) and the shear joint stiffness ratio ($\lambda_S = k_S l / GA$), which were introduced by Lee in 2001 [4], were used to show the relationship between the structural forces and displacements with the rotational, axial, and shear stiffness of segmental lining joints. The length of segmental lining is usually considered to be the unit length in calculations (l = 1 m). Considering the previous studies, the main variation in segmental lining forces, moment, and displacement belong to the joint stiffness ratio between zero and one. Therefore, the values of 0.1, 0.2, 0.3, 0.5, 0.8, and 1 were considered as the values of segmental joint stiffness ratio in the analyses. For simplicity, the rotational, axial, and shear stiffness of all joints were considered in one similar ring. The bending moment ratio (R_M) is defined as the relation of maximum bending moment of segmental lining to maximum bending moment for $\lambda = 1$, and axial force ratio (R_N) is defined as the relation of maximum axial force of segmental lining to maximum axial force for $\lambda = 1$, and the tunnel diametric deflection (R_d) is defined as the relation of diametric deflection of segmental lining to diametric deflection for $\lambda = 1$. Thus after applying the joint stiffness ratio to the model and performing the model, the results are as follows:

5.1. Effect of rotational stiffness

After applying the joint rotational stiffness ratio (λ_R) for various values in the numerical model, figures were drawn. As shown in Figure 8, by increasing the rotational stiffness ratio of the segmental joint, the bending moment in segmental lining increases. When the rotational stiffness ratio is less than 0.5, the bending moment variation is more remarkable. The bending moment variation in the tunnel wall is more in the roof. The joint rotational stiffness ratio has no effect on the axial force of the segmental lining (Figure 9). As it is shown in Figure 10, by increasing the rotational stiffness, displacement decreases. Variation in vertical and wall displacements are approximately equal for rotational stiffness ratio upper than 0.5. By increasing the rotational stiffness of the segmental joints, the rotational displacement decreases. The greatest rotational displacement in segmental lining occurs in the angle of 45 degrees with the tunnel vertical axis (Figure 11). By increasing the rotational stiffness of segmental joints, the bending moment of segmental lining increases. The stiffness effect is more remarkable in spots of the tunnel segmental lining in which the moment is maximum, and maximum moment occurs in the tunnel wall, roof, and floor (Figure 12). Figure 13 shows the rotational displacement contours calculated by the ABAQUS software in segmental lining. Figure 14 shows the contour of bending moment counted by the ABAQUS software in segmental lining.

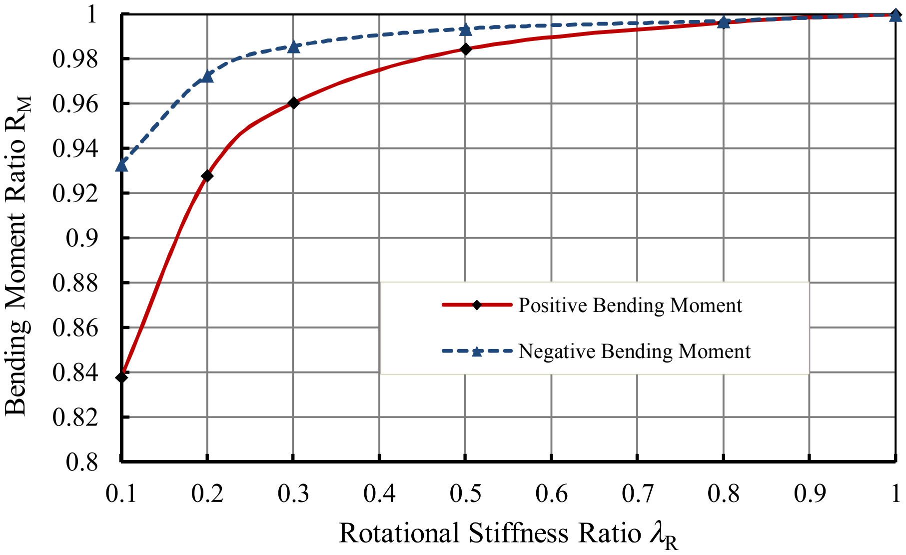

Figure 8. Effect of joint rotational stiffness on bending moment.

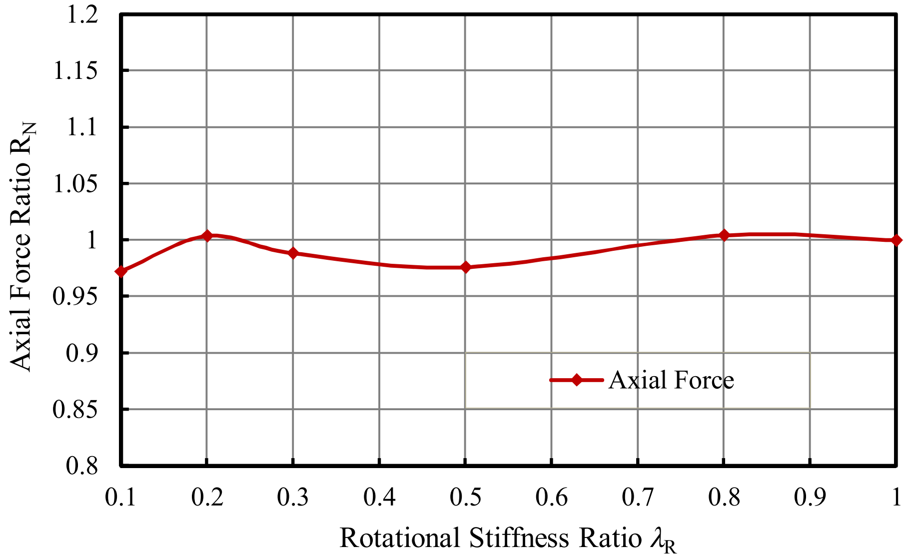

Figure 9. Effect of joint rotational stiffness on axial force.

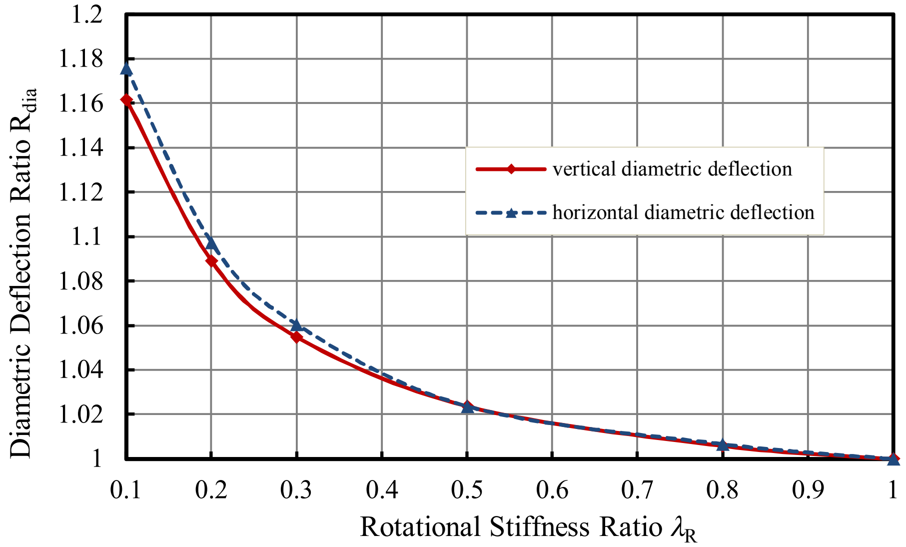

Figure 10. Effect of joint rotational stiffness on the tunnel diametric deflection.

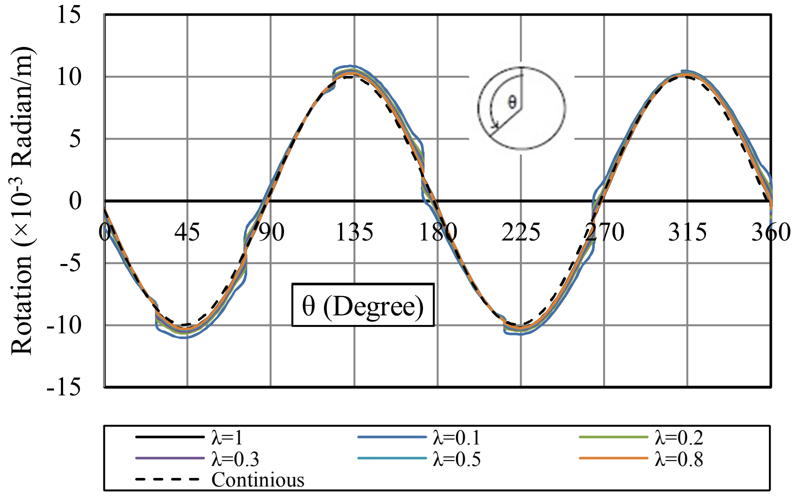

Figure 11. Graph of rotational displacement in the tunnel segmental lining.

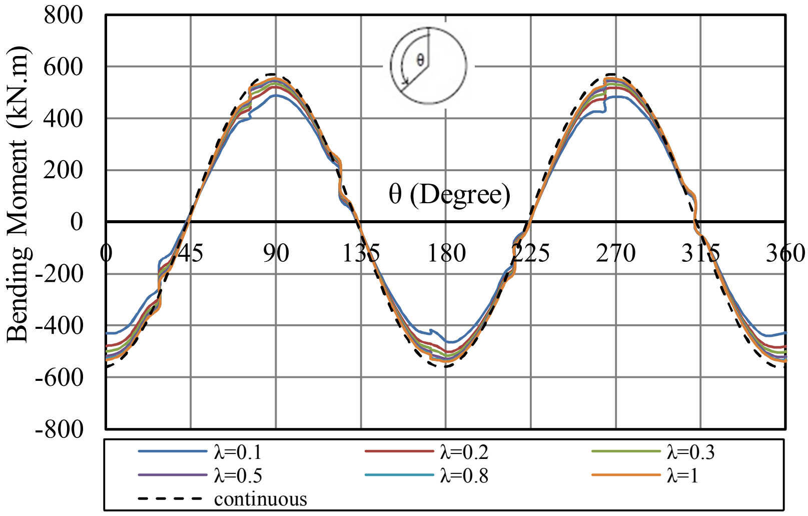

Figure 12. Graph of bending moment in the tunnel segmental lining.

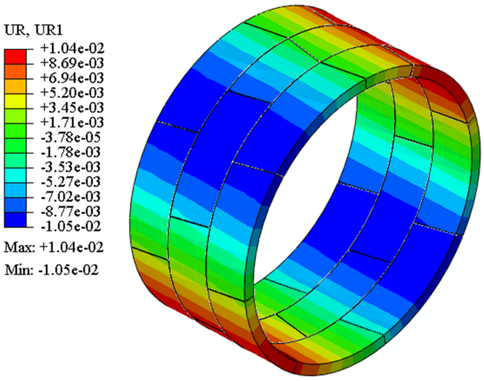

Figure 13. Rotational displacement contour in segmental lining $(\lambda_R = 1)$.

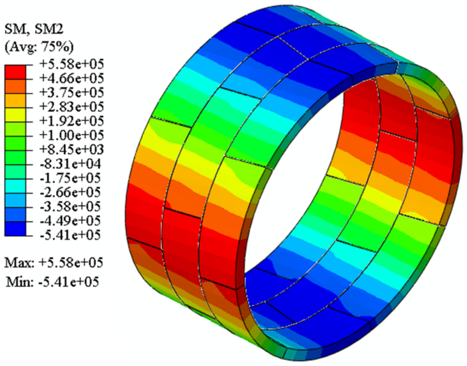

Figure 14. Bending moment contour in segmental lining $(\lambda_R = 1)$.

5.2. Effect of axial stiffness

After applying the joint axial stiffness ratio (λ_A) for different values to the model, figures were drawn. As it is shown in Figure 15, by increasing the axial stiffness of the segmental joint, variation of bending moment in segmental lining is very partial, which can be ignored. By increasing the joint axial stiffness ratio from 0.1 to 0.5, the axial force decreases, and by increasing it to more than 0.5, the axial force does not change (Figure 16). According to Figure 17, by increasing the axial stiffness ratio of the segmental joint, the vertical diametric deflection decreases and the horizontal diametric deflection of the tunnel increases, and variation in vertical and horizontal diametric deflection for axial stiffness ratio more than 0.5 is approximately equal.

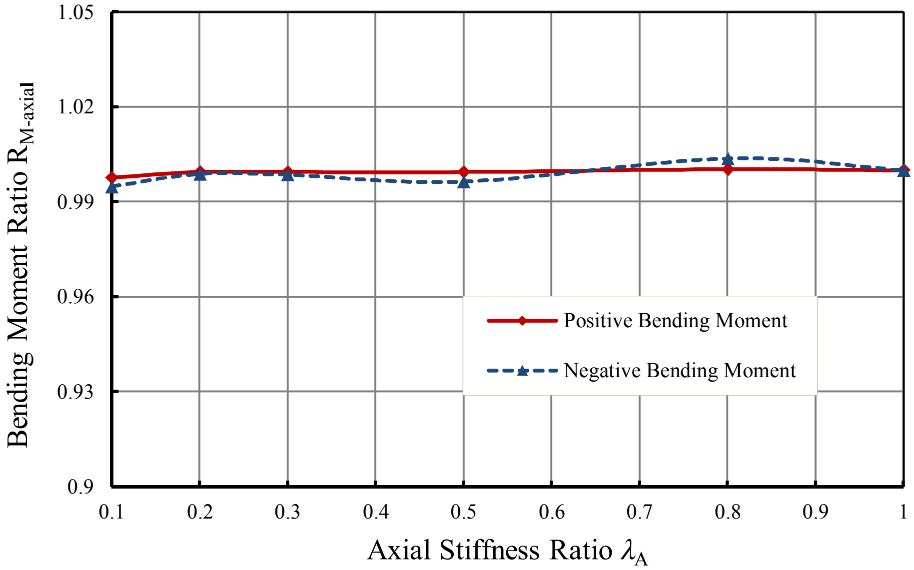

Figure 15. Effect of the joint axial stiffness on bending moment.

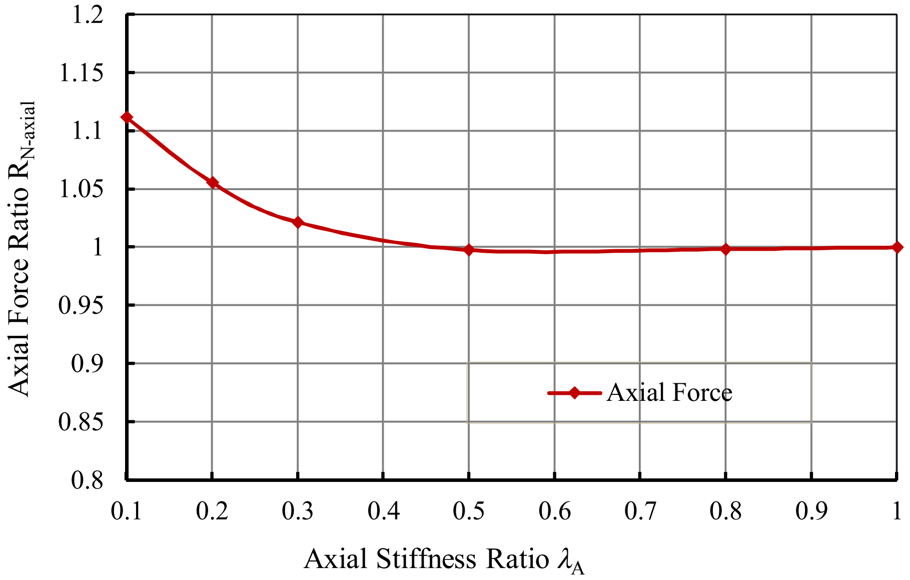

Figure 16. Effect of the joint axial stiffness on axial force.

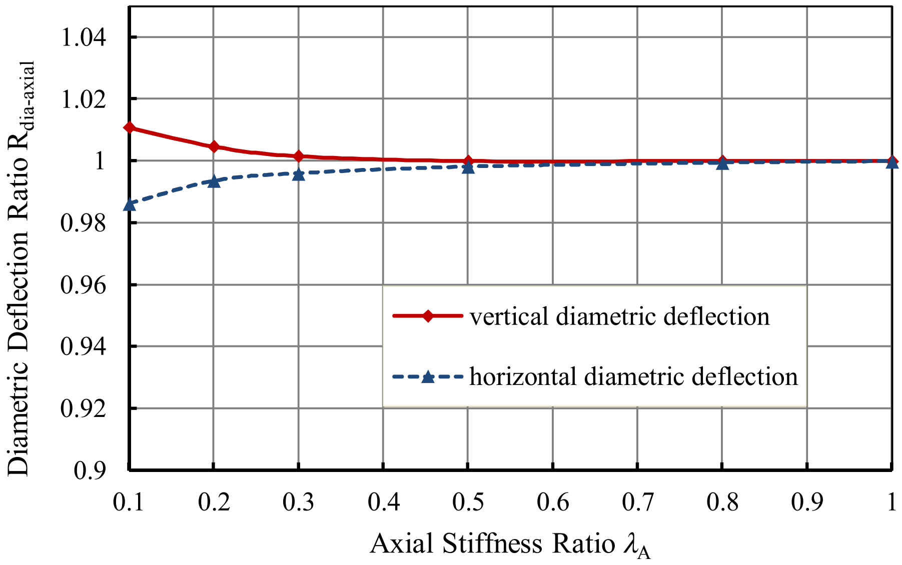

Figure 17. Effect of the joint axial stiffness on the tunnel diametric deflection.

5.3. Effect of shear stiffness

After applying the joint shear stiffness ratio (λ_S) for different values to the model, figures were drawn. As it is shown in Figure 18, by increasing the shear stiffness ratio of the segmental joint, variation of bending moment in segmental lining is very partial, which is ignorable. By increasing the joint shear stiffness ratio, variation in the axial force is partial (Figure 19). According to Figure 20, by increasing the shear stiffness ratio of the segmental joint, variation in vertical and horizontal diametric deflection of the tunnel is partial.

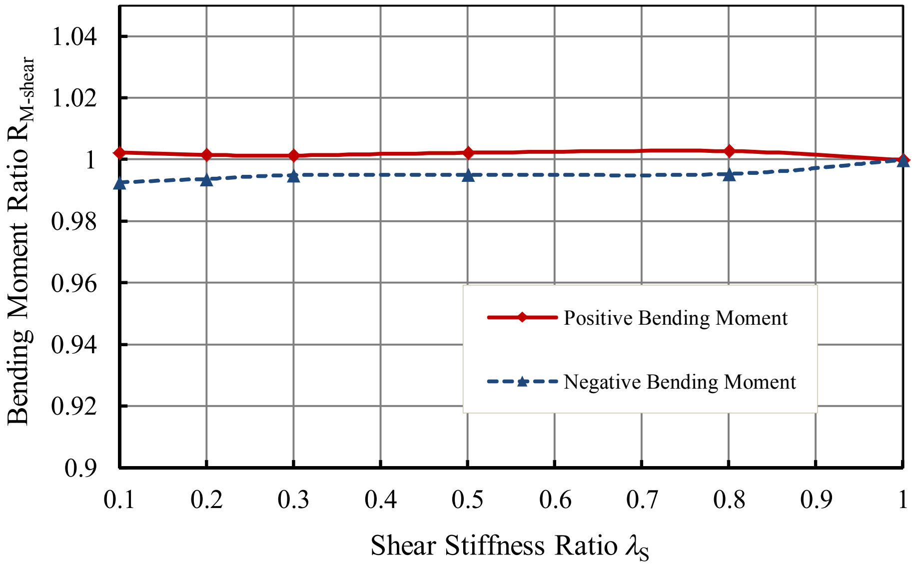

Figure 18. Effect of the joint shear stiffness ratio on bending moment.

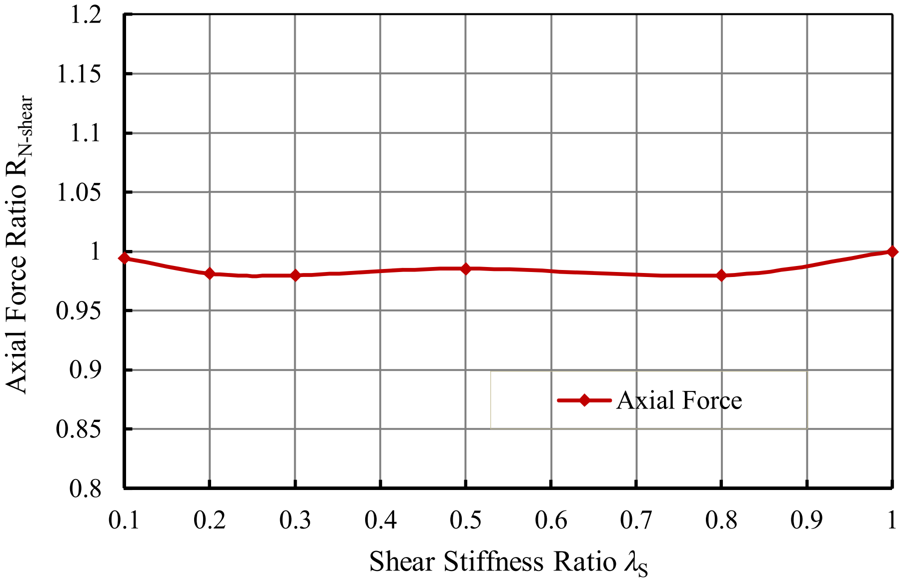

Figure 19. Effect of the joint shear stiffness ratio on axial force.

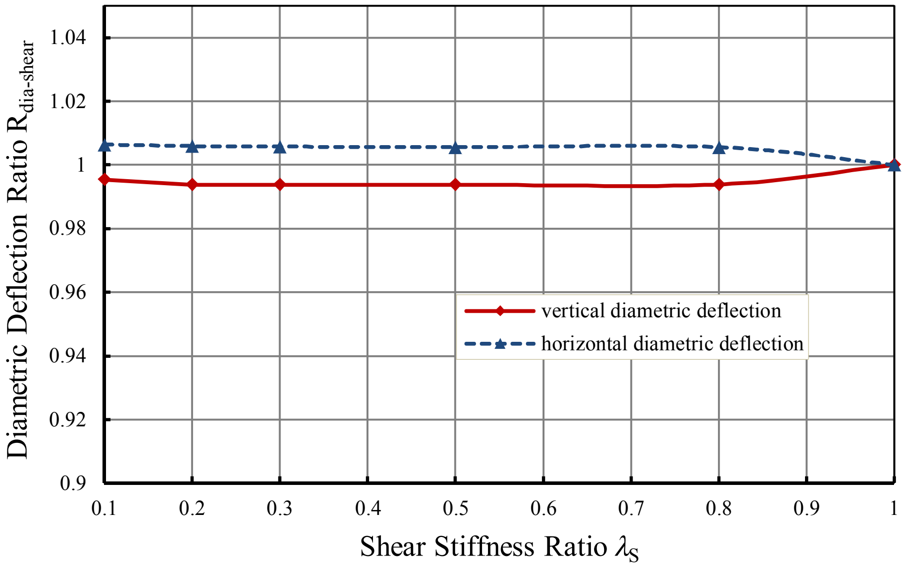

Figure 20. Effect of the joint shear stiffness ratio on the tunnel diametric deflection.

6. Conclusions

By increasing the rotational stiffness of the segmental lining, the bending moment in segmental lining increases. When the joint rotational stiffness ratio is less than 0.5, the bending moment variation is more remarkable. The bending moment variation in the tunnel wall is more in the roof. The joint rotational stiffness does not affect the axial force of the segmental lining. By increasing the rotational stiffness, the diametric deflection decreases. Variations in wall and vertical diametric deflection for rotational stiffness ratio more than 0.5 are approximately equal.

By increasing the axial stiffness of the segmental lining, the bending moment in segmental lining changes partially; by increasing the joint axial stiffness ratio from 0.1 to 0.5, the axial force decreases; and by increasing it to more than 0.5, the axial force does not change. By increasing the axial stiffness ratio of the segmental joints, the vertical diametric deflection decreases and the horizontal diametric deflection of the tunnel increases, and for the axial stiffness ratio more than 0.5, variation in vertical and horizontal diametric deflections are approximately equal.

By increasing the shear stiffness of the segmental lining, variations in the bending moment and axial force are partial. By increasing the shear stiffness of the segmental joint, the vertical and horizontal diametric deflection of the tunnel change partially.

References

[1]. Klappers, C., Grübl, F. and Ostermeier, B. (2006). Structural analyses of segmental lining-coupled beam and spring analyses versus 3D-FEM calculations with shell elements. Tunnelling and Underground Space Technology. 21: 254-255.

[2]. Rashiddel, A., Rahmannejad, R., Hadei, M. and Haji hasani, M. (2016). A review of longitudinal joints modeling methods of segmental tunnel lining, 3th International Conference on New Reaserch Achievements in Civil, Architectural & Urban Management, International Confederation of Inventors of the World (IFIA), University of Applied Science and Technology.

[3]. Do, N. (2014). Numerical analyses of segmental tunnel lining under static and dynamic loads. PhD thesis. Civil Engineering. University of Lyon. France.

[4]. Lee, K.M., Hou, X.Y., Ge, X.W. and Tang, Y. (2001). An analytical solution for a jointed shielddriven tunnel lining. International Journal of Analytical and Numerical Methods in Geomechanics. 25: 365-390.

[5]. Blom, C.B. (2002). Design philosophy of concrete linings for tunnel in soft soils. PhD thesis. Delft University. Netherlands.

[6]. Naggar, H.E., Hinchberger, S.D., Hesham, M. and Naggar, E.I. (2008). Simplified analysis of sesmic in-plane stresses in composite and jointed tunnel linings. Soil Dynamics and Earthquake Engineering. 28 (12): 1063-1077.

[7]. Teachavorasinskun, S. and Chub-Uppakarn, T. (2010). Influence of segmental joints on tunnel lining. Tunnelling and Underground Space Technology. 25: 490-494.

[8]. Ding, W.Q., Yue, Z.Q., Tham, L.G., Zhu, H.H., Lee, C.F and Hashimoto, T. (2004). Analysis of shield tunnel. International Journal for Numerical and Analytical Methods in Geomechanics. 28: 57-91.

[9]. Do, N. and Dias, D. (2015). 2D numerical investigation of segmental tunnel lining under seismic loading. Soil Dynamics and Earthquake Engineering. 72: 66-76.

[10]. Hefny, A. and Chua, H. (2006). An investigation into the behavior of jointed tunnel lining. Tunnelling and Underground Space Technology. 21: 428.

[11]. Chow, W.L., Tang, S.K. and Tong, S.Y. (2009). Design of segmental tunnel lining in an earthquake zone. ITA-AITES World Tunnel Congress 2009, Safe Tunnelling for the City and Environment. Budapest.

[12]. Arnau, O. and Molins, C. (2015). Theoretical and numerical analysis of the three-dimensional response of segmental tunnel linings subjected to localized loads. Tunnelling and Underground Space Technology. 49: 384-399.

[13]. Sliteen, L., Mroueh, H. and Sadek, M. (2013). Three-dimensional modeling of the behaviour of shallow tunnel under seismic load. 20th Congress Rock Mechanics, France.

[14]. Yan, Z. and Shen, Y. (2016). Experimental study of tunnel segmental joints subjected to elevated temperature. Tunnelling and Underground Space Technology. 53: 46-60.

[15]. Cavalaro, S.H. and Aguado, A. (2011). Packer behavior under simple and coupled stresses. Tunnelling and Underground Space Technology. 28: 159-173.

[16]. Salemi, A., Sereshki, F., Esmaeili, M. and Jalali, M. (2014). Study of shear and normal stiffness of segmental joints by laboratory method. 5th Iranian Rock Mechanics Conference, Tehran, Iranian Society of Rock Mechanics, Tarbiat Modares University.

[17]. Munsterman, W.P. and Brugman, M.H.A. (2009). Determination of final geotechnical parameters for calculations. Mashhad Urban Railway Line 2, Rahab Engineering Establishment, Document No: MUR2-ART-RE-01R04-01.

[18]. Sarikhani, M. (2012). Analysis of geomechanical parameters and *in situ* stress of rock mass in the Isfahan-Shiraz railway tunnel using back analysis based on displacement monitoring. MSc thesis. Department of Mining Engineering. Isfahan University of Technology.

[19]. Rijke, Q.C. (2010). Monitoring. Mashhad Urban Railway Line 2, Rahab Engineering Establishment, Document No: MUR2-ART-RE-E.08R01-00.

[20]. Pichler, T., Pucker, T., Hamann, T., Henke, S. and Qiu, G. (2015). High-performance abaqus simulations in soil mechanics reloaded–chances and frontiers. Institute of Geotechnical Engineering and Construction Management. Hamburg University of Technology. Germany.

تأثیر صلبیت درزه سگمنت بر روی نیروهای داخلی پوشش تونل در شرایط استاتیکی

غلامحسین رنجبر[1]، کوروش شهریار[2]* و کاوه آهنگری[1]

۱- گروه مهندسی معدن، دانشگاه آزاد اسلامی، واحد علوم و تحقیقات، تهران، ایران
۲- دانشکده مهندسی معدن و متالورژی، دانشگاه صنعتی امیرکبیر، ایران

ارسال ۲۰۱۹/۶/۱۴، پذیرش ۲۰۱۹/۹/۶

* نویسنده مسئول مکاتبات: k.shahriar@aut.ac.ir

چکیده:

با توجه به کاربرد وسیع پوشش سگمنتی در تونل‌های با حفاری مکانیزه شناخت رفتار درزه‌های پوشش سگمنتی در طراحی تونل اهمیت دارد. در تحلیل سازه‌ای پوشش سگمنتی تونل، درزه‌های سگمنتی را می‌توان به صورت مفصل الاستیک در نظر گرفت و خصوصیات صلبیت آن از صلبیت چرخشی، برشی و محوری متأثر است. هدف از این پژوهش، بررسی تأثیر صلبیت‌های چرخشی، برشی و محوری درزه‌های پوشش سگمنتی بر روی نیروهای داخلی (ممان خمشی و نیروی محوری) پوشش سگمنتی تونل به روش عددی تحت بارگذاری استاتیکی است. برای این منظور تحلیل عددی سه‌بعدی با استفاده از نرم‌افزار آباکوس انجام شد. نتایج به دست آمده نشان می‌دهد که با افزایش صلبیت چرخشی درزه سگمنتی ممان خمشی افزایش می‌یابد. تغییرات ممان خمشی برای مقادیر صلبیت‌های چرخشی پایین‌تر، بیشتر است. در صورتی که تغییرات نیروی محوری نسبت به صلبیت چرخشی درزه‌ها بسیار ناچیز است. با افزایش صلبیت محوری و برشی درزه سگمنتی تغییرات ممان خمشی و نیروی محوری در پوشش سگمنتی جزئی است.

کلمات کلیدی: پوشش سگمنتی، صلبیت درزه، نیروهای داخلی، بارگذاری استاتیکی، تحلیل عددی.
