Modeling of joints of segment linings under complex relation between lining and ground conditions

Kyeung-hye Ahn
Laboratoire Navier (Université Gustave Eiffel, CNRS, ENPC), Ecole des Ponts ParisTech, Marne-la-Vallée, France

Amade Pouya
Laboratoire Navier (Université Gustave Eiffel, CNRS, ENPC), Ecole des Ponts ParisTech, Marne-la-Vallée, France

Gye-Chun Cho
Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea

ABSTRACT: This study has been attempted to do segment lining modeling by researching the effects on joints between segments. There were limitations in modeling analysis considering complex ground conditions along with joins. For example, it is often used to analyze the lining behavior due to joints in elastic ground like the beam-spring model or to analyze intensively the ground behavior by simplifying it. However, since consideration of elasto-plastic ground conditions and behavioral analysis of segment by joints are both important parts that influence each other, it can be said that modeling analysis is appropriate when analyzed together. To this end, the numerical analysis (FEM-code Disroc) was performed on the relationship of the interface between the ground and the lining by applying the segment joint as a nonlinear elastic model (Bandis). It is also reminded of the need for analysis depending on the presence or absence of joints in ever more complex ground.

Keywords: Joint, interface, tunnel, nonlinear elastic.

1 INTRODUCTION

Segmental joints are the weakest points in the tunnel, and their design must be carefully considered to ensure that they can withstand the loads imposed by the tunneling process and must be designed to resist the loads from ground pressure, water pressure, and other external forces. Therefore, it is essential to analyze joints in segment tunnel design to make sure that they are able to withstand the loads imposed by the tunneling process and prevent potential damage.

Since consideration of complex ground conditions (ex: fault, earthquakes, water pressure) and behavior analysis of segment by joints are both important parts that influence each other, it can be said that modeling analysis is appropriate when analyzed together. And then, if it is possible to analyze the segment lining behavior including joints and even the complex ground, it will be possible to model various ground, such as fault zone conditions, fracture zones, or seismic impact ranges. The segmental joint of infrastructures is characterized by several rings composed of precast segments in contact. So, the mechanical response of this type of lining is significantly influenced by the behavior of the joints (e.g. Lee & Ge 2001; Blom 2002; Do et al. 2013; Li et al. 2015; Zhang et al. 2019 and Andreotti et al. 2020).

Segment joints can be divided into two parts and named regarding the direction of the segment surfaces in contact. There are interring joints in the circumferential direction of the tunnel in Figure 1. This part analyzes the three-dimensional response of the lining by increasing the interaction between adjacent rings due to the force that advances in the transverse direction of the TBM (Tunnel Boring Machine) during construction. However, long-term stress behavior analysis tends to significantly reduce the axial force in the joint (Arnau & Molins 2011 and Zhang et al. 2019), so the interaction between adjacent rings becomes less important than radial loading. Under these conditions, a two-dimensional analysis is also reasonable because the mechanical behavior of the segment lining is affected by the solution of the radial joint (Figure 1) (Luttikholt et al. 2008; Li et al. 2015 and Zhang et al. 2019).

The preexistence indirect methods (Hinges model, Reducing liner rigidity model, Effective moment of inertial model, Rotational springs model) simplify the tunnel lining into a ring of uniform stiffness and apply a reduction factor to the bending stiffness of the tunnel lining. Although this is computationally cost effective, it cannot reliably evaluate relative rotation and quantification of joint openings. In the direct method, each precast segment and joints are explicitly modeled. Further, classical interface models for longitudinal joints were developed by Gladwell (1980) and Janssen (1983) (Zhang et al., 2019; Andreotti et al., 2020). The fundamental assumptions of both models are linear material behavior of concrete and unreinforced interfaces. However, it is necessary to structurally apply and analyze the limit-damage model following the contact area of the segment joint and the transmitted load.

Therefore, in this part, an attempt was made to evaluate the effect of the nonlinear behavior joint model in addition to the case studied in the previous part (evaluation of the interface effect of lining and ground). So, first, after finding a clear relationship between the stiffness and normal stress of the interface in contact with the joints, the behavior of the segment was simulated by applying Bandis Elastic to a nonlinear interface element (DISROC-Fracsima 2016).

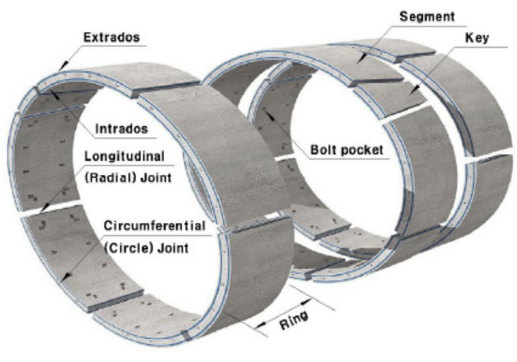


Figure 1. Illustration of segments and joints (Woo &Yoo, 2016).

2 NUMERICAL ANALYSIS METHOD

2.1 Joint model as non-linear interface

Since the lining of the segment tunnel has longitudinal joints, it is unreasonable to assume that it is a continuous ring-beam. Therefore, in order to approach the actual internal force displacement values of these joints, the effect of the segment joint material properties must be evaluated.

In the study of Salemi A et al. (2015), the mechanical behavior of longitudinal joints in segmental lining was researched so as to find a definite relationship between stiffness of contact points and normal stress in contact of locations. In other words, their research is tried to develop a precise contact model based on experimental direct shear tests on the concrete samples of contact points in segments. We focus here on the results of the experimental tests they performed on concrete samples. Their experimental results are a good source to be applied to our numerical joint model.

In that research, the relation of the contact shear and normal reaction module in compression normal condition is found (Figure 2).

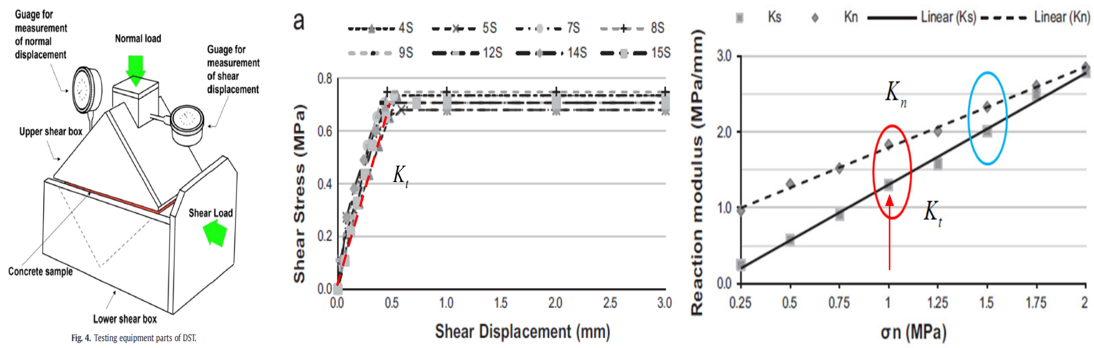
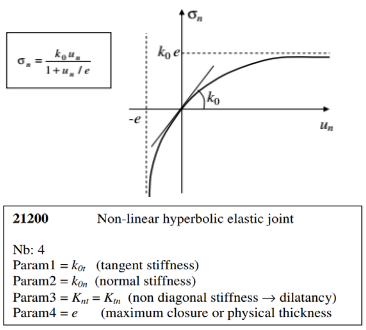


Figure 2. Experimental data on segment join properties by Salemi A et al. (2015)
(Case -condition: the normal stress 1MPa without gasket).

The contact shear and normal reaction modules K_t and K_n were related to contact normal stress via two linear regression equations. The joint stiffness formula required for our joint model is as Eq (1).

$$\begin{bmatrix} K_n = 730100 + 1106380\sigma_n \;\; kPa/m \\ K_t = \pm 168400 + 1472500\sigma_n \;\; kPa/m \end{bmatrix} \quad (1)$$



Bandis(1981,1983)

$$\begin{bmatrix} K_n = \dfrac{k_0}{1+u_n/e} \\ \sigma_n = -K_n u_n \\ K_n = \dfrac{k_0}{1-\dfrac{\sigma_n}{K_n e}} \\ K_n = k_0 + \dfrac{\sigma_n}{e} \end{bmatrix} \begin{bmatrix} K_t = \dfrac{k_{0t}}{1+u_n/e} \\ \sigma_t = K_t u_t \\ K_t = \dfrac{k_{0t}}{1+\dfrac{\sigma_t}{K_t e}} = k_{0t}(1-\dfrac{\sigma_n}{k_{on} e}) \\ K_t = k_{0t} - \dfrac{\sigma_t}{e} \end{bmatrix} \Leftrightarrow \begin{bmatrix} K_n = 730100 + 1106380\sigma_n \;\; kPa/m \\ K_t = \pm 168400 + 1472500\sigma_n \;\; kPa/m \\ e = 9E-7m \end{bmatrix}$$

Figure 3. Transformation process of relational form of shear and normal stress according to reaction coefficient of joint concrete sample test and Bandis nonlinear elasticity model (Disroc-FEM).

After referring to the research data by SALEMI, Akbar et al. (2015), in order to apply to our joint model, Bandis nonlinear elastic model (Figure 3), the initial stiffness value, which is a parameter of the joint, is requested. To do so, if Eq (1) is replaced with the Bandis nonlinear model, initial stiffness parameter and "e"(gap of joint) are obtained.

The final total parameters applied to the numerical analysis performed in this section are shown in Tables 1. The interface G-L model in Table 1 is the interface between the segment lining and the ground. When installing the tunnel lining, the grouted part between the ground and the lining was simulated with shear, normal stiffness, and gap "e".

In practice, since the convergence stress applied to the outer wall of the tunnel during tunnel excavation is different even in the ground under the same conditions, the resulting lining's behavior was examined for the stress depending on the convergence confinement method.

In convergence confinement method, to analyze the problem of near the face 3D during excavation as a plan-strain problem, a radial stress is adapted to the tunnel wall and is reduced from an initial value equal to the initial stress to zero without support when interpreting these conditions. The radial stress induces this face effect and this fictitious temporary support is given by Sulem et al. (1987).

Table 1. Properties applied to rock classification and interface between Ground-lining for comparative analysis in this study.

Classification	Unit Weight (kN/m3)	Elastic modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (□)	Earth pressure coefficient K_0
Rock Grade 4	23.2	1,500	0.27	200	27	0.5
Segment Lining	23.0	30,000	0.2			
	ES/1000 (kN)		EI/1000 (kNm2)			
	15000		312			
Interface G-L	kt (kPa/m)	kn (kPa/m)	Gap (e1) (m)		Gap (e2) (m)	
Case N5	1E+5	2E+5	0.1		0.01	
Case N6	1E+4	2E+4	0.1		0.01	
Joint		kt0 (kPa/m)	kn0 (kPa/m)	e (m)		
		730100	168400	9E-07		

$$\sigma_{rr} = (1-\lambda)\sigma^0 \tag{2}$$

Where the parameter(Load ratio*0.1) □ is increased from 0 to 1

Figure 4 shows different geometries according to the presence or absence of joints in the numerically analyzed segment lining. Except for the joint part, all other dimension conditions are the same.

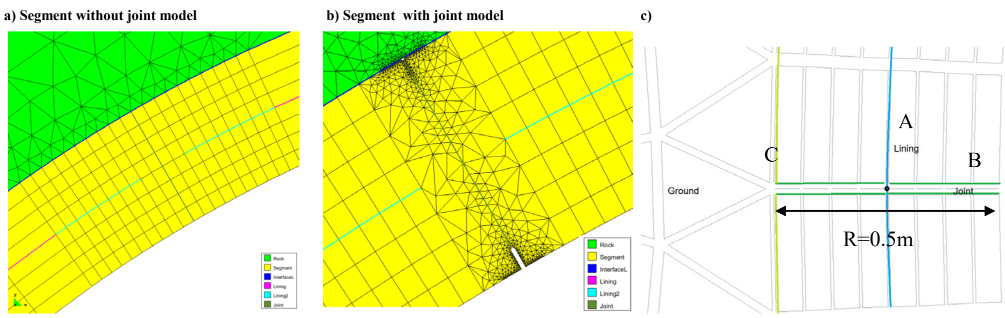


Figure 4. Segment Lining Geometry By GID: a) Segment Lining Geometry without Joints, b) Geometry with Joints in actual segment lining design c) A: Phantom beam element, B: Interface joint between each segment longitudinal, C: Interface between ground and lining.

3 ANALYSIS OF RESULTS

3.1 Numerical results

The results of the radial displacement of the lining according to the initial stress of the load ratio (convergence confinement method) are shown in Figure 5. The results of a) and b) where there is the displacement of the 45 degree point in the clockwise direction of the circular tunnel have few differences in accordance with joints or without. However, the lower the stiffness value of interface b)-Case N6 and the larger the gap between the existing interfaces (e1), the more different point is shown depending on whether or not there is a joint. In particular, it can be seen that the section where the difference is visible is made under a certain tunnel convergence stress condition (load ratio 5 to 9).

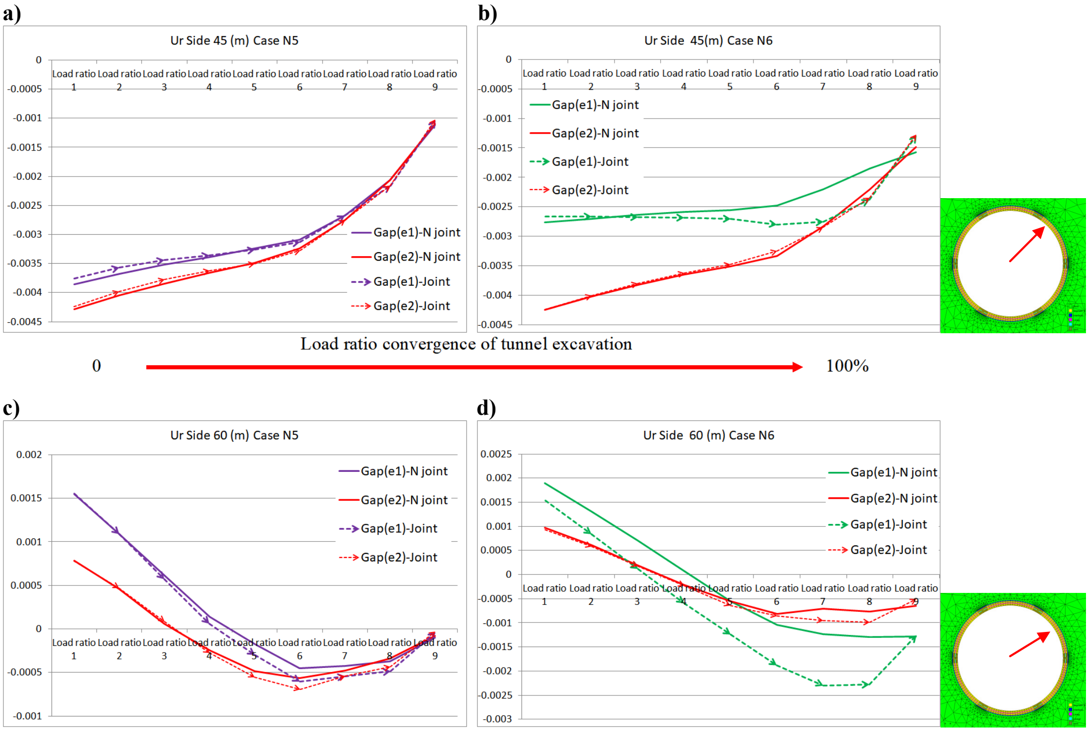


Figure 5. Radial displacement of linings with and without joint: a) interface case N5, b) N6 at 45 degree clockwise point, c) interface case N5, d) N6 at 60 degree clockwise point.

c) and d) show the radial displacement values at the 60 degree point in the clockwise direction of the tunnel where the plastic deformation of the ground progressed more than at the 45 degree point. Therefore, comparing results b) and d) when the interface gap is e1, the result of d) can show a large difference in the presence or absence of a joint.

4 CONCLUSION AND PERSPECTIVE

Instead of indirectly modeling and analyzing segment joints, which are often used in the past, we tried direct joint modeling to model under complex geotechnical ground that can be analyzed together.

As a result of numerical analysis regarding the presence or absence of segment joints, it was found that the difference increased as the stress on the inner wall of the tunnel decreased, that is, as the inner hole displacement converged (increased load ratio), and then it decreased again at an appropriate convergence point. These results remind us of the need for numerical analysis of tunnel modeling due to the effect of segment joints in various complex ground conditions, such as when the ground around the tunnel is plasticized or when the grouting part between the ground and the lining is not yet hardened.

If it is possible to analyze the segment lining behavior including joints and even the complex ground, it will be possible to model various ground, such as fault zone conditions, fracture zones, or seismic impact ranges. As an example of this, in this study, as shown in Figure 5, the numerical analysis of the tunnel passing through the fault zone was performed as a hydraulic-mechanics couplage model. As shown in this result, it can be seen that the result according to the presence or absence of the joint appears clearly.

However, there are still improvements to be made to accurately model segment joints. In our study, the joint gap “e” obtained here is 9E-7m, so it is very small. Looking at the non-linear hyperboic graph in Figure 1, a very small "e" means a very large stiffness value. This has no discriminative power in evaluating the effect of the presence or absence of a joint. Therefore, there is a need to further investigate improvements in the joint model.

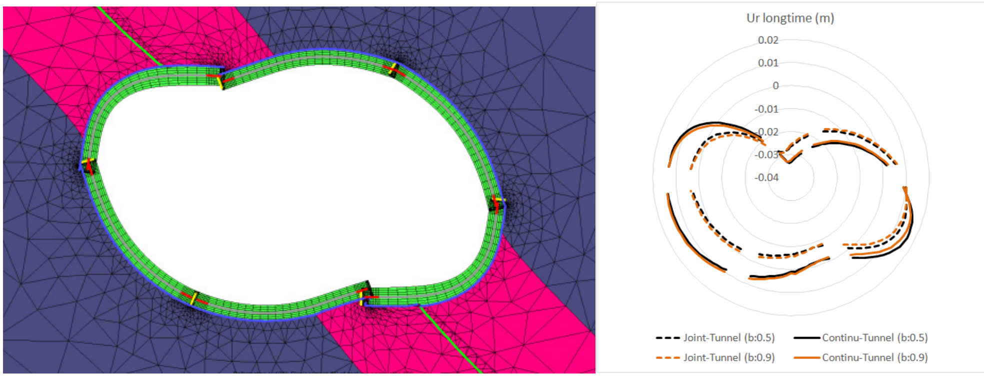


Figure 5. Radial displacement of the lining with (Joint-Tunnel) or without (Continu-Tunnel) joints under complex ground in the hydraulic-mechanical couplage analysis according to the Biot coefficient (b=0.5 or 0.9).

REFERENCES

Andreotti, G. et al. (2020) ‘Cyclic model with damage assessment of longitudinal joints in segmental tunnel linings’, Tunnelling and Underground Space Technology, 103(July), p. 103472. doi: 10.1016/j.tust.2020.103472.

Arnau, O. and Molins, C. (2011) ‘Experimental and analytical study of the structural response of segmental tunnel linings based on an in situ loading test. Part 2: Numerical simulation’, Tunnelling and Underground Space Technology, 26(6), pp. 778–788. doi: 10.1016/j.tust.2011.04.005.

Blom, C. B. M. (2002) Design philosophy of concrete linings for tunnels in soft soils, Structural Concrete, Journal of the fib.

Do, N. A. et al. (2013) ‘2D numerical investigation of segmental tunnel lining behavior’, Tunnelling and Underground Space Technology, 37, pp. 115–127. doi: 10.1016/j.tust.2013.03.008.

Fracsima Disroc 2016: A Finite Element Code for modelling Thermo-Hydro-Mechanical processes in fractures porous media. Available at: http://www.fracsima.com/DISROC.

Lee, K. M. and Ge, X. W. (2001) ‘The equivalence of a jointed shield-driven tunnel lining to a continuous ring structure’, Canadian Geotechnical Journal, 38(3), pp. 461–483. doi: 10.1139/cgj-38-3-461.

Li, X. et al. (2015) ‘Experimental and analytical study on longitudinal joint opening of concrete segmental lining’, Tunnelling and Underground Space Technology, 46, pp. 52–63. doi: 10.1016/j.tust.2014.11.002.

Luttikholt, A. J. T., Vervuurt, A. H. J. M. and den Uijl, J. A. (2008) ‘Ultimate limit state analysis of a segmented tunnel lining’, Proceedings of the International FIB Symposium 2008 - Tailor Made Concrete Structures: New Solutions for our Society, 1998, p. 267. doi: 10.1201/9781439828410.ch195.

Salemi, A., Esmaeili, M. and Sereshki, F. (2015) ‘Normal and shear resistance of longitudinal contact surfaces of segmental tunnel linings’, International Journal of Rock Mechanics and Mining Sciences, 77, pp. 328–338. doi: 10.1016/j.ijrmms.2015.04.014.

Sulem, J., Panet, M. and Guenot, A. (1987) ‘An analytical solution for time-dependent displacements in a circular tunnel’, International Journal of Rock Mechanics and Mining Sciences and, 24(3), pp. 155–164. doi: 10.1016/0148-9062(87)90523-7.

WOO, Seungjoo, CHUNG, Eunmok, et YOO, Chungsik. Development of optimized TBM segmental lining design system. Journal of Korean Tunnelling and Underground Space Association, 2016, vol. 18, no 1, p. 13-30.

Zhang, Q. et al. (2019) ‘A numerical large strain solution for circular tunnels excavated in strain-softening rock masses’, Computers and Geotechnics, 114(May), p. 103142. doi: 10.1016/j.compgeo.2019.103142.