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Influence of segmental joints in lining and ground deformability on surface settlements above tunnels

Anh Ngoc Do[1,*], Daniel Dias[2]

[1]Faculty of Civil Engineering, Hanoi University of Mining and Geology, Vietnam

[2]Department of Geotechnical Engineering, Grenoble Alpes University, France

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ABSTRACT

The development of transportation in large cities requires the construction of tunnels. In many tunnelling projects, surface settlements have been observed. Most of the cases reported in the literature focus on considering the effect of ground conditions, tunnel size, depth, surface loads, and construction process on the ground surface settlement. However, the effect of joints between segments is not considered in the precast concrete lining in these cases. A numerical study of the settlements above a tunnel at the Bologna metro project is performed which made it possible to include the influence of joint characteristics such as joint number, joint distribution, joint rotational stiffness and deformability of ground on the surface settlement. Analysis is carried out using a two-dimensional finite difference element model. The results show a negligible influence of joint distribution, joint number and joint rotational stiffness on the surface settlement. On the other hand, the Young's modulus of the ground must be well known due to its significant influence.

1. Introduction

The development of transportation in large cities requires the use of underground space for transportation infrastructures and facilities. While underground construction has certain advantages, it could have undesirable effects on the surface structures. The tunnel boring machine (TBM) advances through a prescribed design route creating a cylindrical cavity. As a result, the cavity would then cause the surrounding ground to move towards the tunnel space to reach a new state of equilibrium. In many tunnelling projects, surface settlements have been observed. Apart from the TBM selection and the behaviour estimation of the tunnel structure, the problem of determining vertical settlements due to tunnelling process is therefore one of three main aspects on which a special attention must be paid .

*Corresponding author
E-mail: dongocanh@humg.edu.vn

For the construction of urban underground tunnels in soft ground, shield-driven tunnelling method is widely adopted due to its flexibility, cost effectiveness and its minimum impact on ground surface. Segmental concrete lining is commonly used in most shield-driven tunnels which generally comprises a sequence of rings placed side-by-side (Gruebl, 2006). These rings are divided into sectors and each of these elementary units is called a segment.

The main difference between a segmental lining and a continuous one is the existence of joints in the lining. Under the influence of the joints, the behavior of the tunnel structure and the surrounding ground will be different from the ones induced by a continuous lining.

There are current numerical and analytical studies conducted to estimate settlement as the tunnel boring machines advances (ITA, 2007). In addition, tunnel settlements can be also estimated with empirical methods (Peck, 1969; Attewlle et al., 1986; Lee and Rowe et al., 1992). Most of the cases reported in the literature focus on considering the effect of ground condition, tunnel size, depth, surface load, and construction process on the ground surface settlement. However, these cases do not consider the effect of joints between segments in the precast concrete lining (Maranha and Neves, 2000; Melis et al., 2002; Jenck and Dias, 2003; Barla et al., 2005; Phienwej et al., 2006; Chehade and Shahrour, 2008; Afifipour et al., 2011; Hossaini et al., 2012; Mirhabibi and Soroush, 2012).

In this paper, a numerical study of the settlements induced on the ground surface above a tunnel which belongs to the Bologna metro project is performed which made it possible to include the influence of joint characteristics such as joint number, joint distribution, joint rotational stiffness and deformability of ground on the surface settlement. Analysis is carried out using a two-dimensional finite difference element model.

The results show a negligible influence of joint distribution, joint number and joint rotational stiffness on the surface settlement.

On the other hand, Young's modulus of ground must be taken into account.

2. Numerical modelling

A tunnel excavation and the support structure application induce a three-dimensional phenomenon. When tunnelling process is performed in 2D plane strain model, one must adopt assumptions, which take into account the displacement of ground surrounding the tunnel prior to installation of structural support elements. The available approaches include convergence-confinement method, gap method, disk calculation method, progressive softening method, volume loss control method, hypothetical modulus of elasticity, soft lining method and grouting pressure method (Möller 2006; Karakus 2007). Karakus (2007) compared various ways of modelling tunnel excavation, taking into account the three-dimensional effects in a two-dimensional model (except the gap method and grouting pressure method). He concluded that the convergence-confinement method (Panet, 1995), which is used in this study, allows the best agreement with experimental results.

The determination of ground convergence when the support system becomes active is an essential element of the convergence-confinement method. This method is also known as "λ_d method". Choosing the value of the stress release before the lining installation corresponding to the de-confinement ratio λ_d of the surrounding ground is one of the difficulties when applying this method. In this study, for the purpose of the numerical investigation, a λ_d value of 0.3 is adopted (Karakus, 2007).

Figure 1 depicts the two-dimensional numerical model assuming plane-strain conditions. It will be used to quantify the settlement on the ground surface. For the reason of arbitrary joint distributions along the tunnel circumference, the whole tunnel is simulated. Parameters of Bologna-Florence Italian Railway high speed line tunnel project were adopted in this numerical modeling

(Croce, 2011; Do et al., 2013a, 2013b). This case is named the reference case.

The behavior of the tunnel structure is assumed to be linear elastic. The ground behavior is assumed to be governed by a linear elastic perfectly-plastic constitutive relation based on the Mohr-Coulomb failure criterion. The properties are given in Table 1.

In this study, numerical simulations are performed by means of the finite difference element program FLAC (Itasca, 2009). The segmental joint is simulated using double node connections. In this study, only the influence of rotational stiffness is considered. All other stiffness parameters of the joint are neglected. Typical parameters of tunnel lining are summarized in Table 1.

The numerical model presented in Figure 2 is 240m wide (X direction), and 60m high (Z direction) and consists of approximately 13,800 zones and 27,765 grid points.

Modelling of the tunnel construction is carried out in the following steps:

(a) For the numerical excavation process, the first calculation step corresponds to the setup of the model, the assignment of the plane strain boundary conditions and the initial stress state taking into consideration the influence of the gradient of vertical stress with depth under the effect of gravity;

(b) Deactivating the excavated ground and simultaneously applying a stress relaxation ratio λ_d to the excavation circumference. The boundary conditions of the tunnel walls in this case follow a force-reduction approach (see Figure 3).

(c) Activating the segments in a ring on the tunnel boundary, assigning the joints link condition and applying the total relaxation.

Finally, it should be mentioned that the average computation time of each numerical analysis is approximately to 4 hours when using a portable computer with 2.67GHz Core i5 CPU.

Table 1. Details of the reference case

Parameter	Symbol	Value	Unit
Properties of clayey sand			
Unit weight	γ_S	17	kN/m^3
Young's modulus	E_S	150	MPa
Poisson's ratio	υ_S	0.3	-
Internal friction angle	φ_S	37	degrees
Cohesion	C	0	kPa
Lateral earth pressure factor	K_0	0.5	-
Overburden	H	20	m
Properties of tunnel lining			
Young's modulus	E_l	35	GPa
Poisson's ratio	υ_l	0.15	-
Lining thickness	t_l	0.4	m
External diameter	D	9.1	m

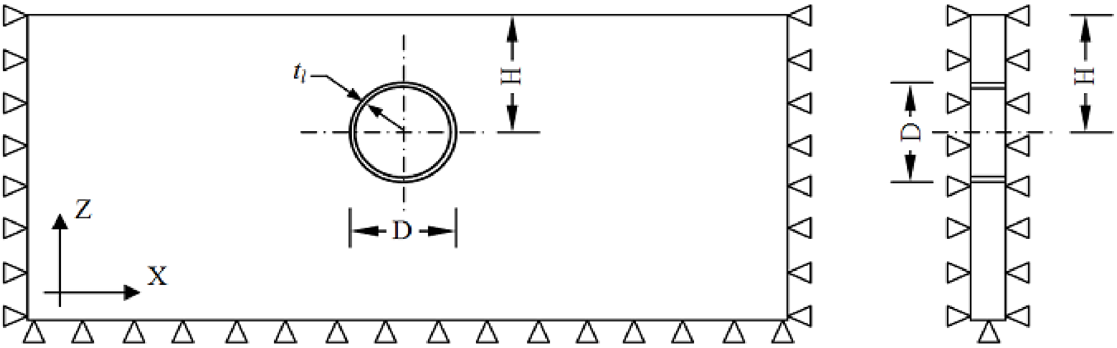

Figure 1. Plane strain model under consideration

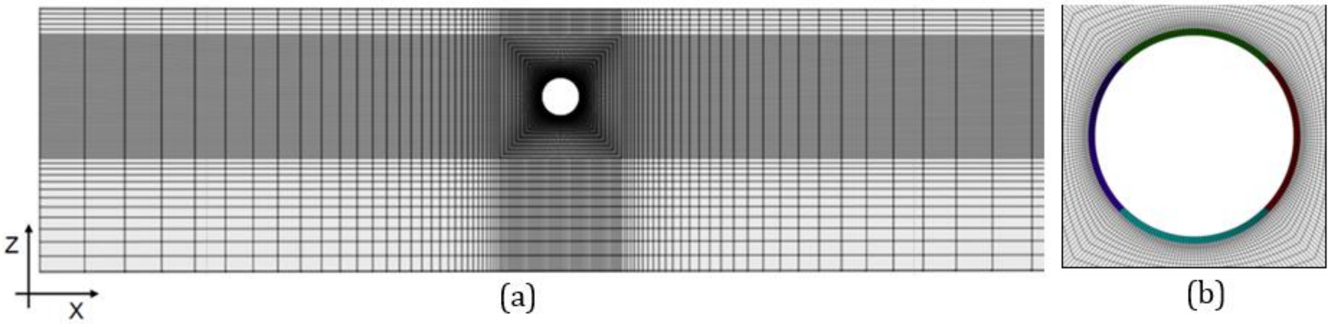

Figure 2. Two-dimendional numerical model (a) and zoom of the tunnel (b)

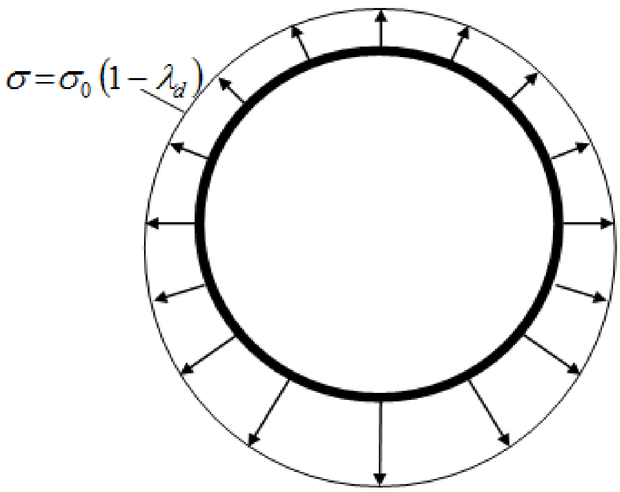

Figure 3. Tunnelling simulation by the λ_d method (Hejazi et al., 2008; Do et al., 2013b)

3. Parametric investigations

3.1. Influence of segment joint

3.1.1. Influence of joint distribution

The influence of joint distribution on the settlement developed on the ground surface is estimated by the change of joint number and joint orientation in a ring along the tunnel circumference. Location of joints in a ring is represented by the reference joint defined as the one which is located closest to the tunnel crown respecting the clockwise rotation from the tunnel crown. Joint distribution is assumed to be uniform along the tunnel circumference.

In this study, a simplified bilinear relationship between the bending moment and

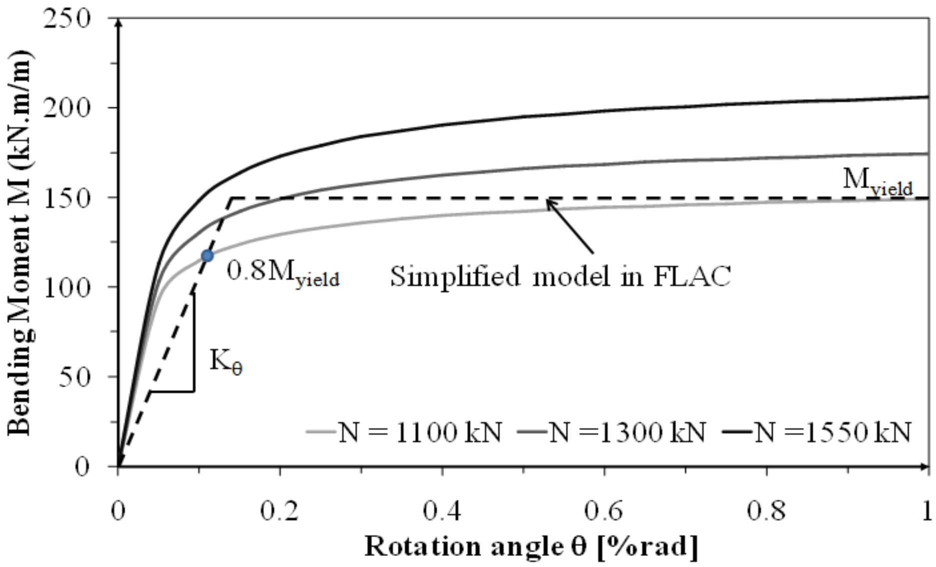

Figure 4. Bending moment - rotation relationship of the longitudinal joint

the joint angular rotation is used. This type of relation has been used by (Zhong et al., 2006) and it has been demonstrated that it can fit well the nonlinear behavior of joint rotation. For this purpose, a preliminary calculation is first performed based on the input data of the reference case (Table 1) with a full hinge and a thickness at the narrowest part of joint of 30cm. From the average normal force of the tunnel lining, the maximum limit bending moment M_{yield} is calculated for an angle of rotation of 0.01 radian (≈ 1%), which is assumed as an approximation for the maximum permissible rotation. The rotational stiffness of K_θ = 0.8 M_{yield}/θ are derived as a simplification for all joints in lining ring (Thienert et al., 2012). For the determination of the rotational stiffness of the formulas (Janssen, 1983) based on the investigation (Leonhardt and Reimann, 1966; Gruebl, 2006) are used. Using the input parameters presented in Table 1, the rotational stiffness of joint K_θ which equals to 98,410 kN.m/rad/m is adopted (Figure 4) (Do et al., 2013).

A comparative study is performed for the tunnel lining with number of joints varying from 4 to 9. The numerical results show a negligible influence of joint distribution on the magnitude of settlement induced on the ground surface as can be seen in Figure 5. It should be noted that the settlements caused by the excavation of tunnel supported by segmental lining is always higher than the settlement induced by the one supported by continuous lining. In this study, the maximum difference of settlement between two above cases is 1.73%. This indicates that the segment joint has a certain influence on the maximum settlements developed on the ground surface.

Figure 5a shows that the settlement magnitudes are negligibly affected by the joint location. However, the increase of joint number will result in a slight increase of the maximum settlement induced on the ground surface (Figure 5b). It could be explained by the fact that when the joint number in a lining ring increases, the higher flexibility of tunnel structure is. As a consequent, it will result in a larger deformation of tunnel structure and then may be followed by larger movements of surrounding ground. Nevertheless, as we can see in Figure 5b, the change of maximum settlement under the influence of joint number is in a negligible range of 1.712 ÷ 1.724 cm, corresponding to the increase of 1.05 ÷ 1.73% compared to the one induced by the excavation of tunnel supported by continuous lining.

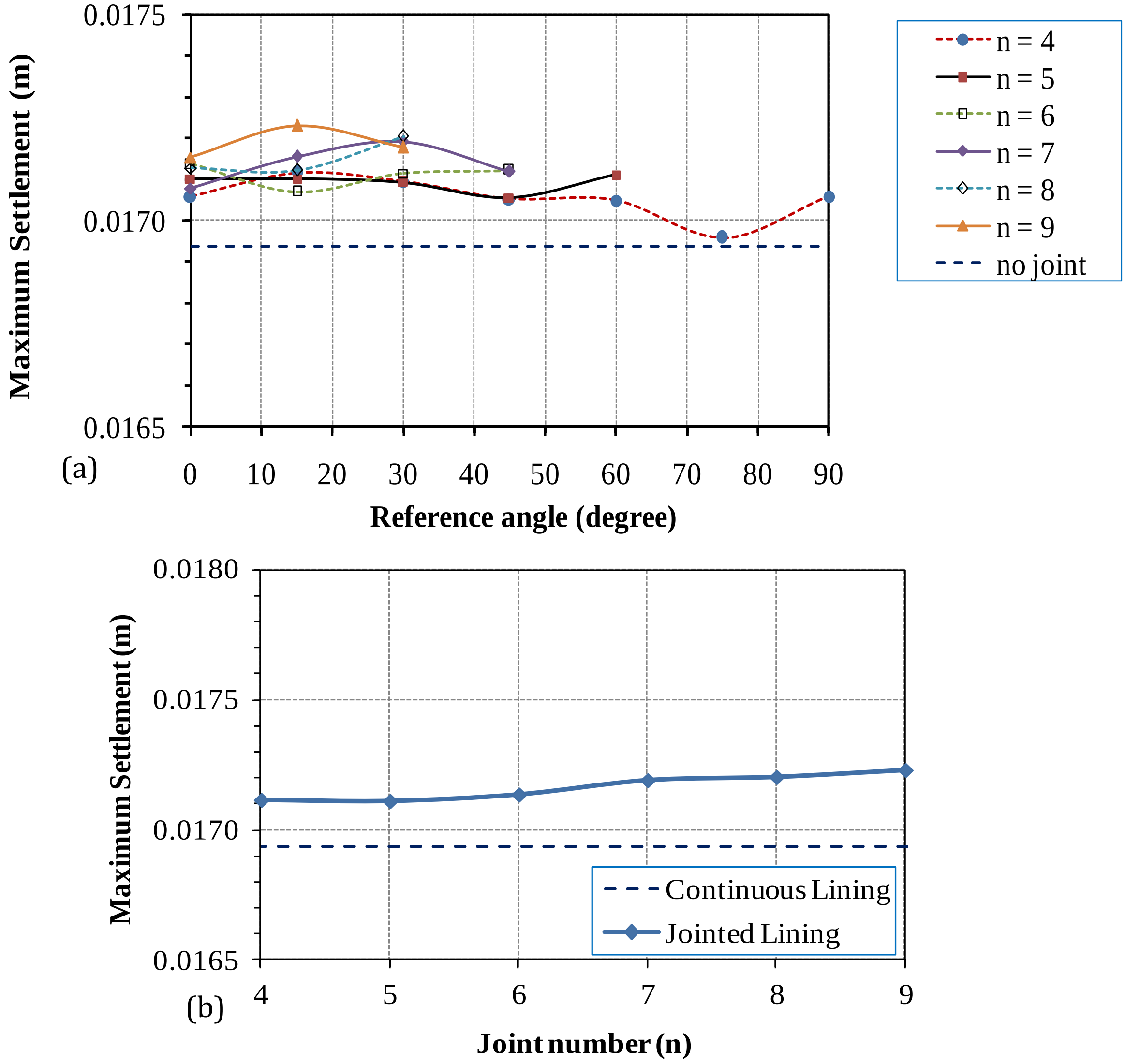

Figure 5. Influence of joint distribution (a) and joint presence (b) on the maximum settlement

3.1.2. Influence of joint rotational stiffness

In order to illustrate the relationship of settlement against joint rotational stiffness, the dimensionless factor called rotational stiffness ratio, $\lambda = K_\theta l/E_l I_l$, proposed by (Lee et al., 2002) is adopted to represent the relative joint stiffness over the lining segment bending stiffness. The calculation length, *l*, is usually taken as 1 m to present a typical unit length of a lining segment.

The reference case (Table 1) with a joint number equal to 6 is adopted in this study. Joints are located at angles of 0^0, 60^0, 120^0, 180^0, 240^0, 300^0 measured in counter-clockwise with respect to the right spring line. The settlement ratio, R_S, is defined as the ratio of maximum settlement value induced on the ground surface during the excavation of a tunnel supported by segmental lining to the one developed in a tunnel supported by continuous lining.

Figure 6 shows the dependence of settlement ratios predicted on the rotational stiffness ratio. For a given value of Young's modulus of ground (E_S = 150 MPa), the development of maximum settlement is clearly affected by the rotational stiffness ratio, λ. A higher rotational stiffness ratio will result in a

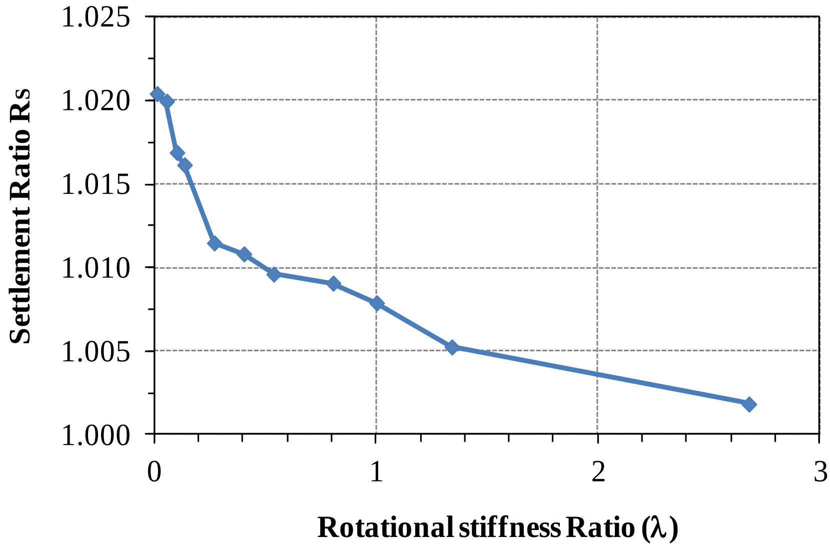

Figure 6. Influence of joint rotational stiffness on the settlement ratio

lower settlement ratio. This is attributed to the fact that the increase of rotational stiffness of joints will result in an increase the rigidity of lining ring leading to a lower deformation of the tunnel structure. Consequently, it will be followed by a smaller settlement. However, as we can see in under the influence of rotational stiffness of joint the settlement ratio changes within a negligible range of 1.002 to 1.021.

3.2. Effect of ground deformability

To investigate the effect of the ground deformability surrounding the tunnel, represented here by the Young's modulus of ground, E_S, for each given value of stiffness ratio $\lambda = 0.01$, 0.1, 0.5 and 1, the change of maximum settlement predicted on the ground surface will be investigated in a range of Young's modulus of ground varying from 10 MPa to 500 MPa, corresponding to a range which contains soft soils to soft rocks, respectively. For a given rotational stiffness ratio, λ, the development of the maximum settlement is significantly affected by the change of Young's modulus of ground surrounding the tunnel. A higher E_S value will result in a lower magnitude of the settlement (Figure 7a). The maximum settlement developed on the ground surface is sensitive to the Young's modulus of ground, especially at low range of E_S from 10 to 75 MPa. Beyond a Young's modulus of 75 MPa, the changes of the maximum settlement become more gradual and approach the values of about 0.5 mm.

We can also see that at the same value of Young's modulus of ground, the higher the rotational stiffness is, the lower the settlement ratio R_S is (Figure 7b). It agrees well with the results presented in Figure 6. Except at low range of Young's modulus of ground (E_S = 10 MPa) the influence of stiffness ratio (λ) on the maximum settlement is, however, insignificant when the Young's modulus of ground changes (Figure 7a).

4. Conclusion and respective

This paper presents a numerical study to investigate the influence of a tunnel construction process supported by segmental lining on the settlement induced on the ground surface. 2D numerical simulations have been conducted to highlight the influences of joint distribution, joint rotational stiffness and ground deformability.

In comparison with the settlement caused by the excavation of a tunnel supported by a continuous lining, the settlement induced in cases of using segmental lining is always higher.

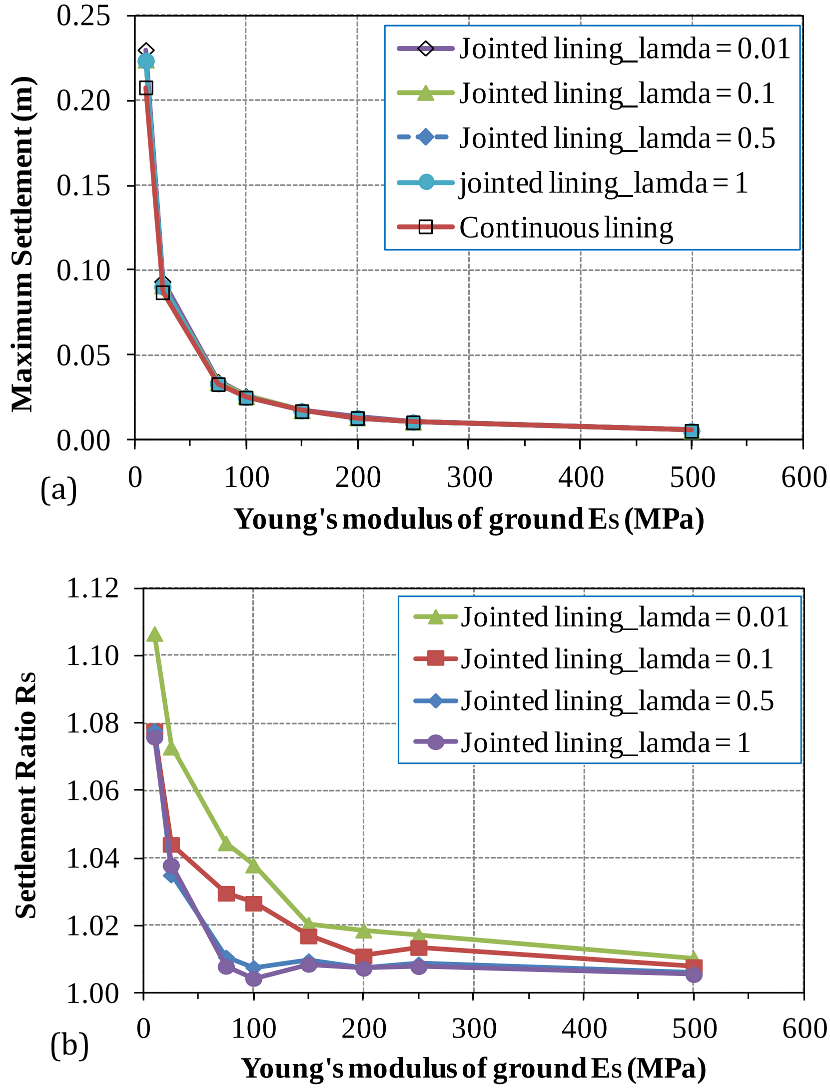

Figure 7. Influence of ground deformability on the maximum surface settlement (a) and settlement ratio R_S (b)

The number and orientation of segmental joints in tunnel lining have an insignificant influence on the maximum settlement. Generally, the higher the joint number is, however, the higher the maximum settlement is.

A higher rotational stiffness will result in a lower value of settlement ratio. However the change of settlement caused by various rotational stiffnesses is very small. In other words, the development of settlement is not affected by the rotational stiffness of joints.

For a given rotational stiffness ratio, λ, the development of the settlement is considerably affected by the change of Young's modulus of ground surrounding the tunnel. A higher E_S value will result in a lower magnitude of the settlement. The settlement developed on the ground surface is sensitive to the Young's modulus of ground, especially at low range of E_S varying from 10 to 75MPa. For a given E_S value, the maximum settlement does almost not depend on the rotational stiffness, λ.

In future, considering the effect of segment joints, further complementary calculations should be carried out to study the influence of:

- Other stiffness parameters of joints such as axial stiffness, radial stiffness;

- The interaction between two tunnels excavated at close proximity ;
- Other more sophisticated constitutive models of ground.

In addition, comparisons with experimental data obtained from a real tunnel excavations should be made in order to improve the quality of the numerical simulation.

References

Afifipour, M., Sharifzadeh, M., Shahriar, K. and Jamshidi, H., 2011. Interaction of twin tunnels and shallow foundation at Zand underpass, Shiraz metro, Iran. *Tunnelling and Underground Space Technology* 26, 356-363.

Attewell, P.B., Yates, J., Selby, A.R., 1986. *Soil movements induced by tunnelling and their effects on pipelines and structures.* Glasgow and London: Blackie.

Barla, G., Barla, M., Bonini, M., Gamba, F., 2005. Two and three dimensional modelling and monitoring of the Metro Torino. *11th International Conference of Iacmag*, Turin, Italy.

Chehade, F., and Shahrour, I., 2008. Numerical analysis of the interaction between twin-tunnels: Influence of the relative position and construction procedure. *Tunnelling and Underground Space Technology* 23, 210-214.

Croce, A., 2011. *Analisi dati di monitoraggio del rivestimento della galleria del passante ferroviario di Bologna.* Unpublished PHD thesis. Polytechnics of Turin, Italy.

Do, N.A., Dias, D., Oreste, P.P. and Djeran-Maigre, I., 2013a. 2D numerical investigation of segmental tunnel lining behavior. *Tunneling and Underground Space Technology* 37, 115-127.

Do, N.A., Dias, D., Oreste, P.P. and Djeran-Maigre, I., 2013. 2D tunnel numerical investigation: the influence of the simplified excavation method on tunnel behaviour. *Geotechnical and Geological Engineering* 32 (1), 43-58.

Gruebl, F., 2006. Modern design aspects of segmental lining. *CPT-ITA Congress*, Iguacu, Brazil.

Hejazi, Y., Dias, D., Kastner, R., 2008. Impact of constitutive models on the numerical analysis of underground constructions. *Acta Geotechnica* 3, 251-258.

Hossaini, S.M.F., Shaban, M. and Talebinejad, A., 2012. Relationship between twin tunnels distance and surface subsidence in soft ground of Tabriz metro - Iran*. 12th Coal Operator's Conference*, University of Wollongong & the Australasian Institute of mining and Metallurgy, 163-168.

ITA/AITES WG "Research", 2007. Settlement induced by Tunnelling in SoftGround. *Tunnelling and Underground Space Technology* 22, 119-149.

Itasca Consulting Group, Inc., 2009. FLAC *Fast Lagrangian Analysis of Continua, Version 4.0.* User's manual. <http.itascacg.com>.

Janssen, P., 1983. Tragverhalten von Tunnelausbauten mit Gelenktübbings, *Report-No*. 83-41, Department of civil engineering, Institute for structural analysis, University of Braunschweig.

Jenck, O., Dias, D., 2003. Numerical analysis of the volume loss influence on building during tunnel excavation. *Third Int, FLAC Symp. - FLAC and FLAC3D Numerical Modelling in Geomechanics*, Sudbury, Canada.

Karakus, M., 2007. Appraising the methods accounting for 3D tunnelling effects in 2D plane strain FE analysis. *Tunnelling and Underground Space Technology* 22, 47-56.

Lee, K.M., Rowe, R.K., and Lo, K.Y., 1992. Subsidence Owing to Tunnelling I-

Estimating the Gap Parameter. *Canadian Geotechnical Journal* 29, 929-940.

Lee, K.M., Hou, X.Y., Ge, X.W., Tang, Y., 2001. An analytical solution for a jointed shield-driven tunnel lining. *International Journal for Numerical and Analytical Methods in Geomechanics* 25, 365-390.

Leonhard, F., Reimann, H., 1966. Betongelenke. *Der Bauingenieur* 41, 49-56.

Maranha, J. R. and Neves, E. M., 2000. 3D analysis of ground displacements due to the construction of Lisbon underground. *Proceedings of the International Conference on Geotechnical & Geological Engineering* (Geo. Eng 200), Melbourne.

Melis, M., Medina, L., Rodriguez, J.M., 2002. Prediction and analysis of subsidence induced by shield tunnelling in the Madrid Metro extension. *Canadian Geotechnical Journal* 39, 1273-1287.

Mirhabibi, A. and Soroush A., 2012. Effects of surface buildings on twin tunnelling-induced ground settlements. *Tunnelling and Underground Space Technology* 29, 40-51.

Möller, S., 2006. *Tunnel Induced Settlements and Structural Forces in Linings.* Unpublished PhD Thesis, Stuttgart University.

Panet, M., 1995. Le calcul des tunnels par la méthode convergence-confinement. *Presse de l'ENPC*, Paris, French.

Peck, R.B., 1969. Deep excavations & tunnelling in soft ground. *Proc. 7th Int. Conf. on Soil Mechanics and Foundation Eng*. Mexico 1969, IV (State of the Art), 225-290.

Phienwej, N., Hong, C. P., & Sirivachiraporn, A, 2006. Evaluation of ground movements in EPB-shield tunnelling for Bangkok MRT by 3D-numerical analysis. *Tunnelling and Underground Space Technology* 21(3-4), 273.

Thienert, C. and Pulsfort, M., 2011. Segment design under consideration of the material used to fill the annular gap. *Geomechanics and tunnelling* 74, 665-679.

Zhong, X., Wei, Z., Zhengrong, H., and Yuewang, H., 2006. Effect of joint structure on joint stiffness for shield tunnel lining. *Tunnelling and Underground Space Technology* 21, 406-407.