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Numerical investigation of segmental tunnel linings-comparison between the hyperstatic reaction method and a 3D numerical model

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Abstract. This paper has the aim of estimating the applicability of a numerical approach to the Hyperstatic Reaction Method (HRM) for the analysis of segmental tunnel linings. For this purpose, a simplified three-dimensional (3D) numerical model, using the $FLAC^{3D}$ finite difference software, has been developed, which allows analysing in a rigorous way the effect of the lining segmentation on the overall behaviour of the lining. Comparisons between the results obtained with the HRM and those determined by means of the simplified 3D numerical model show that the proposed HRM method can be used to investigate the behaviour of a segmental tunnel lining.

Keywords: hyperstatic reaction method; lining response; numerical method; segmental tunnel lining; three-dimensional model

1. Introduction

The presence of segmental joints in the tunnel lining is the main reason which causes the difference in the behaviour of segmental linings and that of continuous linings. In the literature, the effects of segmental joints on tunnel lining behaviour have usually been considered using analytical, empirical and numerical methods. A summary of the design methods used for segmental tunnel linings was given by Do *et al.* (2014a, b, c). They showed the limitation of current solutions on the evaluation of segmental tunnel lining behaviour and that it is necessary to develop new design methods which allow one to taken into consideration in a more precise way the effect of segmental joints.

Segmental tunnel lining is a 3D structure (Do *et al.* 2013a, 2014d, Oreste 2012, 2013) and therefore 3D models are the only manner to take into consideration in a rigorous way the problem (Jenck *et al.* 2004). A numerical approach to the HRM for the analysis of segmental tunnel lining was developed by the same authors of the present paper (Do *et al.* 2014a) (Fig. 1). In this work, the influence of segmental joints was added directly in the HRM, using a fixity ratio that is determined on the basis of the rotational stiffness. This method is able to consider the 3D effect of segment joints in successive rings on the tunnel lining behaviour and it also allows an arbitrary distribution of segment joints in the lining rings to be taken into account. Three assumptions on the 3D effect of segmental lining were proposed. Do *et al.* (2014a) made a comparison between the numerical results obtained with the HRM and the experimental data obtained from a shield-driven tunnel project. They showed that the proposed HRM can be used to estimate the behaviour of a segmental tunnel lining in short calculation time. However, it should be noted that the effect of the connecting condition in successive lining rings and the applicability of the assumptions on the 3D effect are still not yet estimated in this work using a rigorous comparison with 3D analyses.

In the present paper, a simplified 3D numerical model, using the $FLAC^{3D}$ finite difference software (Itasca 2009), has been developed, which allows analysing in a rigorous way the influence of the connecting condition between successive lining rings on the overall behaviour of the tunnel lining. On the basis of the comparison with 3D

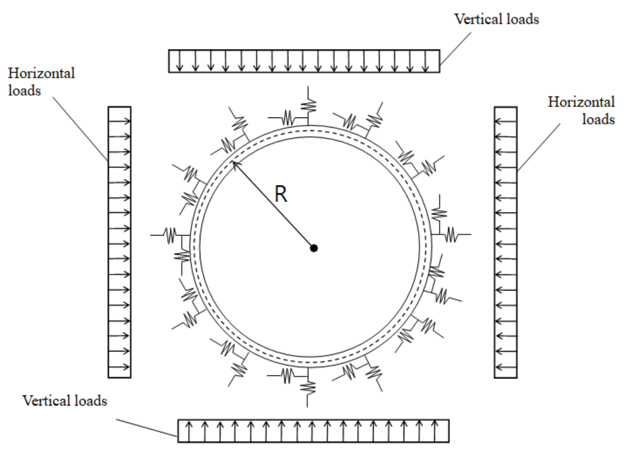

Fig. 1 Scheme of support structures adopted in the hyperstatic reaction method (from Do *et al.* 2014a)

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numerical analyses, using the simplified 3D numerical model, the suitability of assumptions on the 3D effect proposed in the HRM has been estimated.

2. The HRM method

On the basis of the work by Oreste (2009) and Do *et al.* (2014b), Do *et al.* (2014a) developed a numerical HRM approach for the analysis of tunnel linings in which the influence of segmental joints was considered directly using a fixity ratio that is determined on the basis of the rotational stiffness. The details of the HRM model are presented in Do *et al.* (2014a).

Real joint connections in a segmental lining are intermediate between the following two extreme cases: a pinned-joint connection and a rigid-joint connection. They are therefore considered as semi-rigid connections with a moment transmission capacity and a continuous change in the rotational stiffness under the action of the loads (Kartal *et al.* 2010).

A typical approach was used to incorporate the joint connections into numerical analysis foresees beam elements with lengthless rotational springs attached at each end (Burn *et al.* 2002). In this way the number of freedom degrees of the system is the same as for the conventional system with ideally rigid-connections.

As far as the rotational stiffness is concerned, the single-stiffness linear model for the semi-rigid joint connection is generally used in analytical methods (e.g., Lee *et al.* 2002, Naggar and Hinchberger 2008). The bilinear models are usually used in the numerical analyses of tunnels and provided better approximations (Zhong *et al.* 2006, Van Oorsouw 2010, Thienert and Pulsfort 2011).

A nonlinear behaviour (Janssen's formulation (Groeneweg 2007)) was instead adopted in the HRM (Do *et al.* 2014a) to simulate the segmental joint behaviour, continuously updating the rotational stiffness values during the analysis process. According to this formulation, the contact area can be represented by a concrete beam with a depth equal to the width of the joint contact area (segment width) and a height equal to the contact height of the joint. Two stages are distinguished for an increasing rotation of the joint or beam (Groeneweg 2007): Closed joint and Opened joint (Fig. 2). For each stage the rotation stiffness is obtained on the basis of the geometrical parameters of the contact, the concrete elastic modulus and the normal force and the bending moment values in the joint (Groeneweg 2007).

Using this approach, Monforton and Wu (1963) defined a "fixity factor" (r_j) in order to represent the rotational stiffness of the joint with respect to the bending stiffness (Kartal *et al.* 2010, Burn *et al.* 2002, Filho *et al.* 2004, Pinheiro and Silveira 2005, Xu 1991, Sekulovic and Salatic 2001, Csébfalvi 2007, Kaveh and Moez 2008, Hasan *et al.* 2011)

$$r_j = \frac{1}{1+\dfrac{3E_S J_S}{K_\theta L}} \quad (1)$$

where K_θ is the end-connection rotational spring stiffness, and $E_s J_s/L$ is the bending stiffness of the attached member (beam).

For a semi-rigid joint connection the r_j value changes in a range from 0 to 1 (pinned connection r_j = 0; fully-rigid connection r_j = 1). In order to consider the presence of the joints in a segmental lining, only minor modifications to the member stiffness matrix of a continuous lining are necessary (Do *et al.* 2014a). The elastic stiffness matrix of a semi-rigid member *i* (K_i^{SR}), with two semi-rigid end-connections can be represented by the stiffness matrix of the member considered to have rigid end-connections (Z_i) modified by a semi-rigid correction matrix (C_i) (Burn *et al.* 2002, Chen 2000)

$$K_i^{SR} = Z_i.C_i \quad (2)$$

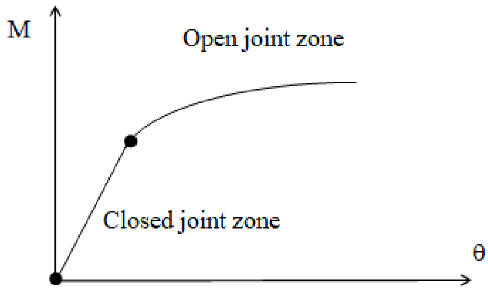


Fig. 2 Relationship between the bending moments (M) and rotations (θ) in a Janssen joint (from Groeneweg 2007)

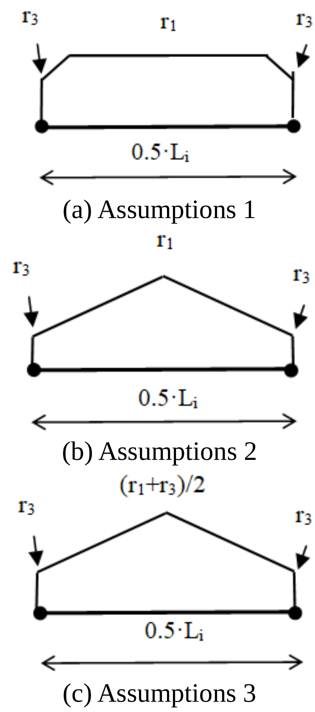


Fig. 3 Three assumptions adopted for the simulation of a segmental tunnel lining: the fixity factor changes along each segment of the lining (from Do *et al.* 2014a). Key: r_1 is the fixity factor of the concrete section and equal to 1 (completely rigid connection); r_2 is the fixity factor of the true joints; r_3 the average value of r_1 and r_2; L_i: length of the lining segment

All the other calculations are performed in the same way as for a rigid frame using the "displacement method", described by Oreste (2007) and Do *et al.* (2014b). Due to the fact that the stiffness of the semi-rigid connection is not constant, an iterative procedure is used in order to modify the K_i^{SR} matrix at each iteration (Do *et al.* 2014a). The necessary time for each calculation using Matlab program, is very short: about 5 seconds for a numerical model including 360 beam elements per lining ring divided by 6 segmental joints.

In reality, segment joints in successive lining rings have not the same positions. This staggered distribution of the joints has an important effect on the behaviour of segmental linings and need to be taken into consideration (Do *et al.* 2013a). In the HRM, this 3D effect can be studied considering three assumptions on the segmental joint simulation, which allow modelling the interaction between segment joints in successive rings (Do *et al.* 2014a). The number of numerical joint inserted in the calculation is equal to double of the true joint number that is present along the lining ring. The analysed model considers the behaviour of a fictitious ring constituted by two successive half rings along the tunnel axis (Do *et al.* 2014a) (Fig. 3).

3. 3D numerical model description

A simplified 3D model has been developed using the FLAC^{3D} software (Itasca 2009), which is based on the generalized finite difference method (Fig. 4). The analyses have been performed using small strain calculations.

In the simplified model, a 3D simulation of a tunnel supported by means of segmental lining has been modelled. The influence tunneling process such as the shield machine and the construction loads (face support pressure, grouting pressure, jacking force loads, etc.) was however not taken into consideration. The main purpose of the simplified model is to estimate in a rigorous way the effect of the tunnel lining segmentation.

In this numerical model, the ground is assumed to be linear elastic and a massless material is used which corresponds to the conditions applied in the HRM method. The in-situ stresses are calculated in the soil mass, and also applied as external loads acting on the far-field boundaries (Fig. 4). The vertical load σ_v is determined as the weight of the underlying layers above the tunnel centre. The horizontal load σ_h is the product of the vertical load σ_v and of the lateral earth pressure factor K_0.

In order to verify the performance of the FLAC^{3D} proposed model, computed internal forces values induced in the tunnel lining obtained using the numerical model under plane-strain conditions have been compared with the analytical solution of Einstein and Schwartz (1979). In these two models, continuous lining without segmental joints has been adopted. Following the good agreement of the results between the two models, the 2D numerical model was then extended into a 3D model considering the presence of segmental joints in the tunnel lining.

As in the works by Do *et al.* (2013a, c, d), the tunnel segments have been simulated using linear-elastic embedded liner elements. Embedded liner elements are

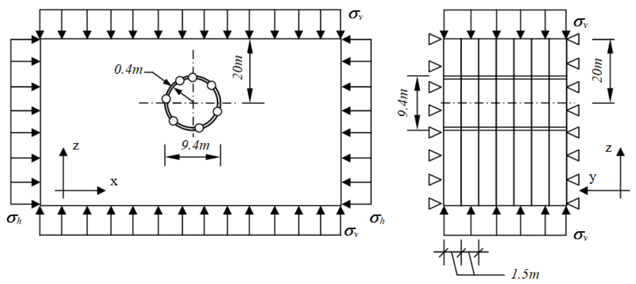


Fig. 4 Simplified 3D model under consideration

attached to the zones on the tunnel boundary. The liner-zone interface stiffness (normal stiffness k_n and tangential stiffness k_s) are set to one hundred times the equivalent stiffness of the stiffest neighboring zone (Itasca 2009).

The segment joints in a ring have been simulated using double node connections (Do *et al.* 2013a, 2014d). In this study, the stiffness characteristics of the joint connection have been represented by a rotational spring (K_θ). The influence of radial and axial stiffness has not been considered and assigned to be rigid, which allows producing the same connecting condition of the joints as that applied in the HRM. The rotational stiffness of a segment joint was modelled by means of a bi-linear relation. The values of the spring constants used to simulate the segment joints can be determined on the basis of the simplified procedures presented by Thienert and Pulsfort (2011) and Do *et al.* (2013b). The attachment conditions of the translational components and two rotational components around the *x* and *z* directions were assumed to be rigid for all the investigated cases.

In the same way as for the segment joint, the ring joints between successive lining rings have also been simulated using double connections. In this study, like the assumption that has been adopted in the HRM method, connections between lining rings have been assumed to be rigid. In other words, the rotational, axial and radial stiffnesses of the ring joint connection have been assumed to be infinite. A discussion on the influence of this assumption on the tunnel behaviour is mentioned in the following section.

The first calculation step of the numerical process consists in setting up the model, and assigning the boundary conditions. The nodes at the sides of the model on the *x*-*z* planes were fixed in the horizontal directions. In the second step, the ground inside the tunnel is deactivated. Segmental lining rings have set on the excavation surface and connecting conditions of the joins are then assigned.

A parametric analysis has been performed in the present study in order to determine the minimum dimension of the numerical model along the *y*-direction (parallel to the longitudinal axis of the tunnel) which allows the influence of the model boundaries on the behaviour of the monitored lining to be reduced. The numerical results have showed that a model with seven rings, which corresponds to 10.5 m length in the y-direction, is sufficient to determine the structural behaviour of the middle lining ring (ring 4) without the effect of the model boundaries (Fig. 4). The time requested for the FLAC^{3D} analysis of the model presented in Fig. 4 is about 15 minutes when using a 2.67GHz core i7 CPU computer.

4. Evaluation of the FLAC^{3D} model

Parameters from the Bologna-Florence high speed railway line tunnel project in Bologna (Croce 2011) have been adopted in this numerical modelling for the evaluation purpose. It is assumed that the behaviour of the soil and the tunnel structure is linear-elastic. The input properties of the soil mass and of the tunnel lining for the FLAC^{3D} numerical model are given in Table 1 (Do *et al.* 2013a, b).

Table 1 Parameters of the section at lining ring 582 (Croce 2011, Do *et al.* 2013a)

Parameter	Symbol	Value	Unit
Properties of the soil			
Unit weight	γ	17	kN/m^3
Young's modulus	E	150	MPa
Poisson's ratio	ν	0.3	-
Internal friction angle	ϕ	37	degrees
Lateral earth pressure factor	K_0	0.5	-
Overburden	H	20	m
Properties of the tunnel lining			
Young's modulus	E_s	35,000	MPa
Poisson's ratio	ν_s	0.15	-
Lining thickness	t	0.4	m
External diameter	D	9.1	m
Joint connection			
Rotational stiffness	K_θ	100	MN.m/rad/m
Maximum bending moment at the segment joint	M_{yield}	150	kN.m/m

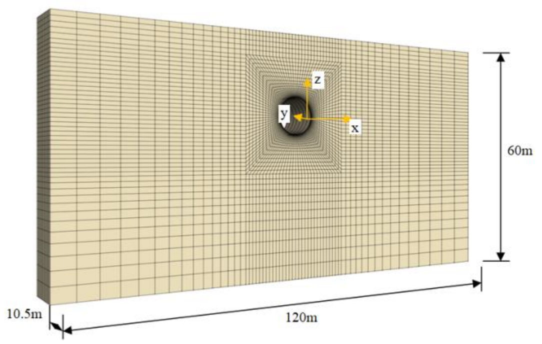
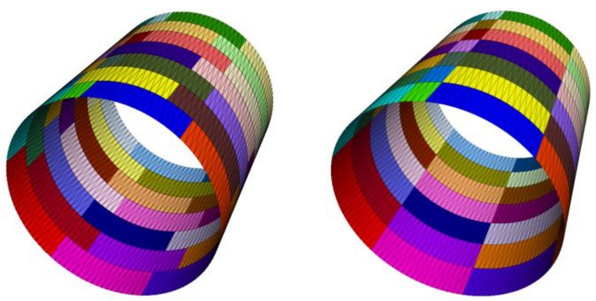
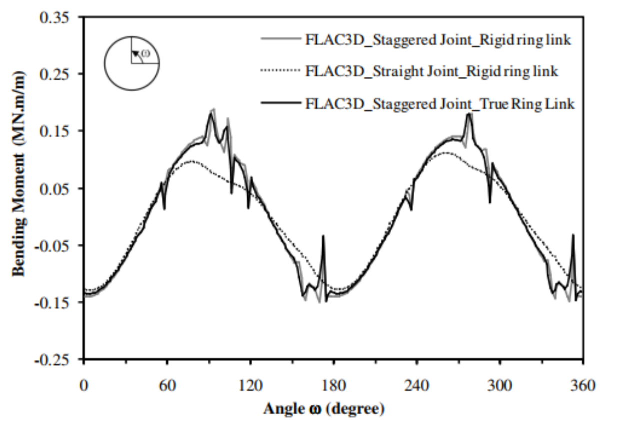


Fig. 5 FLAC^{3D} numerical model

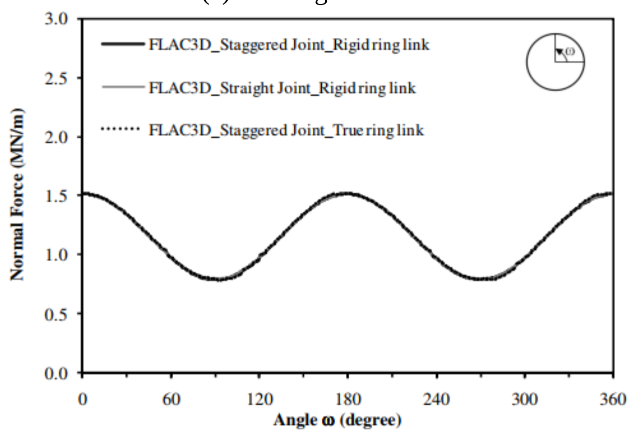


(a) (b)

Fig. 6 Segmental lining patterns, (a) staggered lining and (b) straight lining



(a) Bending moment



(b) Normal forces

Fig. 7 Structural forces in the tunnel lining

The 3D numerical model (Fig. 5) is 120 m wide in the x-direction, 10.5m thick in the y-direction, 60 m high in the z-direction and consists of approximately 42,000 zones and 55,000 grid points. Two lining joint patterns, that are staggered and straight patterns (see Fig. 6), have been simulated. Obviously, a staggered pattern allows the tunnel lining to be simulated in a more realistic way in case of the Bologna-Florence tunnel. However, the straight pattern has also been simulated in order to highlight the effect of tunnel lining segmentation on the lining behaviour.

Fig. 7 illustrates the structural forces determined using the simplified 3D model. It can be seen that the segmentation in the tunnel lining has an insignificant influence on the normal forces induced in the lining. This is in good agreement with the results introduced by Do *et al.* (2014d). However, as far as bending moment is concerned, Fig. 7 points out a noticeable difference in the results obtained with a straight pattern and with a staggered pattern of the joints.

As expected, the bending moments induced in a staggered lining are higher than the ones induced in a straight lining. This could be attributed to the stiffer tunnel lining in case of using a staggered pattern. The maximum differences of about 50% are observed at the crown and bottom of the tunnel (Fig. 7(a)) caused by the effect of different distribution of the joints in the 2 case of the joint patterns. Indeed, the influence of a joint on the reduction of the bending moment will be greater when the joint is located near a point where the bending moments are maximum. In the current study, the lateral earth pressure coefficient of the soil is 0.5 (see Table 1) which cause the maximum bending moments are predicted at the crown and invert of the tunnel. When the straight lining is used, joints at these locations cause the maximum decrease of the bending moment. However, the presence of concrete part at these locations in the case of using a staggered lining leads to a smaller reduction of the bending moment. Consequently, the maximum differences between the bending moments induced in the tunnel lining in 2 joint patterns are observed at the crown and invert as mentioned above.

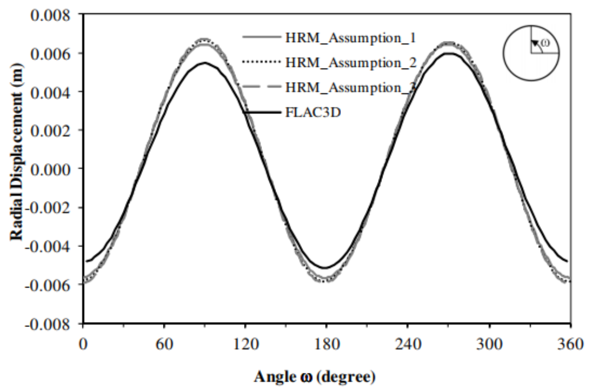
In order to highlight the effect of the connections between successive rings along the tunnel direction, an additional case in which the true connections between lining rings was considered has been performed. The rigidity characteristics of the ring joint connection have been represented by a set of rotational, axial and radial springs. The interaction mechanism of each spring is the same as the ones described by the same authors (Do *et al.* 2013a, 2014d). Owing to the presence of the true connection between successive rings, the lining rings in the additional case are more flexible than the ones simulated in previous case in which the ring connections are assumed to be rigid. As a consequence, the bending moments induced in the lining are reduced while the normal forces are quite similar (Fig. 7(a)). The maximum difference in the bending moments is about 5%. In other words, the stiffer the connection between two successive rings, the higher the structural forces induced in the tunnel lining. The same conclusions can be found from studies performed by Do *et al.* (2013a), Arnau and Molins (2012), Blom (2002), Klappers *et al.* (2006).

On the basis of the above results, it is reasonable to conclude that a 3D numerical model, which allows the staggered pattern of the lining to be taken into consideration, is necessary to accurately simulate the behaviour of a segmental tunnel lining. In addition, the assumption of rigid connection between successive rings, which has been applied in the present HRM method, could be adopted from the design point of view due to the fact that this case corresponds to the worst situation of internal forced induced in the tunnel lining.

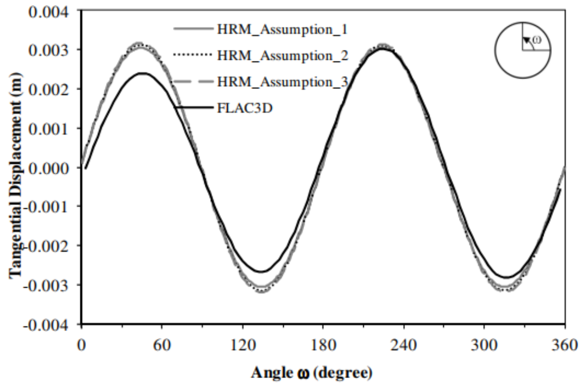
5. Comparison between the HRM and FLAC^{3D} numerical methods

As described in section 2, three assumptions on the segmental joints simulation have been developed in the HRM method to model the staggered pattern between successive lining rings (Do *et al.* 2014a). On the basis of comparison with the FLAC^{3D} numerical results, using the same joint pattern with 6 segmental joints on a lining ring, the main purpose of this section is to determine which assumption is most appropriate to simulate the staggered characteristics of a segmental tunnel lining.

For comparison purpose, instead of using the non-linear behaviour as described by Do *et al.* (2014a,b), the linear elastic soil springs in the HRM model have been adopted in this section. This assumption permits to better compare

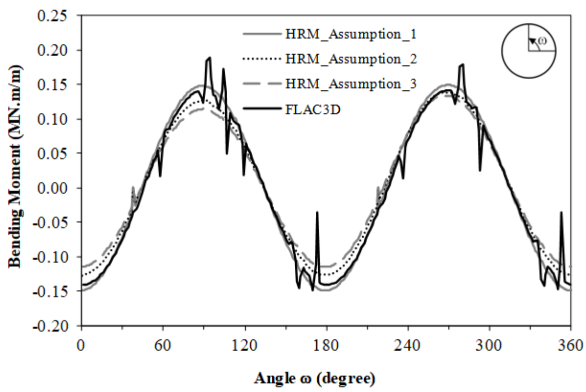


(a) Radial displacements

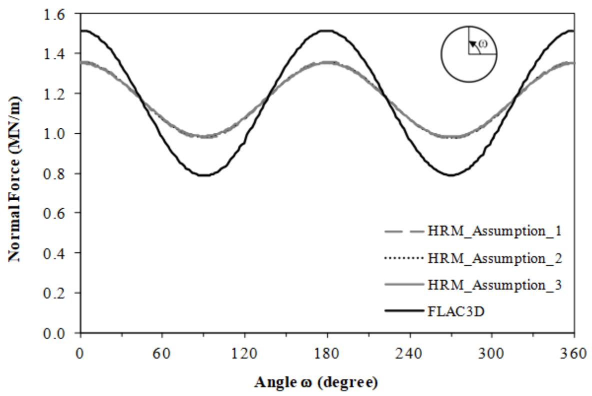


(b) Tangential displacements

Fig. 8 Displacement in the tunnel lining, comparison between the HRM method and FLAC^{3D} model



(a) Bending moment



(b) Normal forces

Fig. 8 Structural forces in the tunnel lining, comparison between the HRM method and FLAC^{3D} model the two models (3D numerical one and HRM). This means that the normal spring stiffness, k_n, and tangential spring stiffness, k_s, at nodes along the tunnel lining in the HRM model are constant. Their values have been determined on the basis of the comparison of results obtained with the HRM and the FLAC^{3D} model (case of a continuous lining). Using the determined spring stiffnesses, comparison between the HRM and FLAC^{3D} model has been conducted for segmental linings.

Figs. 8 and 9 illustrate the lining displacements and structural forces, respectively, using a staggered joint pattern with rigid ring connections, at ring 582. Fig. 8 shows an insignificant influence of the three assumptions in the HRM method for the lining displacements. Their tangential displacement results are quite similar to the one obtained with the FLAC^{3D} model (Fig. 8(b)). Nevertheless, noticeable differences in radial displacements obtained by the two methods can be observed (Fig. 8(a)). This could be attributed to the fact that the loading condition acting on the tunnel lining is not the same in the two methods. In the case of the HRM method, the external loads act directly and explicitly on the beam elements. The external loads in the FLAC^{3D} model are instead applied at the model's boundary that act on the tunnel support through the continuous soil and an arch effect can be created in the ground around the tunnel (Fig. 4).

It can be seen from Fig. 9 that the structural lining force results of the HRM method using the three assumptions on the 3D effect of the segmental tunnel lining (see Fig. 3) are similar. The normal forces are quite similar for all the three assumptions in the HRM method (Fig. 9(b)). A considerable difference in the shape of the normal forces along the tunnel periphery can be observed. Like for the lining displacements, the difference in the normal forces could be explained by the impact of external loads that act on the tunnel lining, which are not similar in the two methods. Additionally, this could also be attributed to the effect of the interaction between the beam elements in the HRM model. Indeed, when the tunnel lining moves toward the soil, reaction forces from the surrounding soil mass acting on the tunnel lining through springs placed at nodes along the tunnel section in the HRM (at angles ω of 0^0 and 180^0 in this study) will appear. The compressive normal forces induced in the tunnel lining at these sections will therefore be transferred to the section at which normal forces are currently smaller (at angles ω of 90^0 and 270^0 in this study). Consequently, normal forces at these sections which are originally small will increase as observed in the HRM results.

Without considering the suddenly change of the bending moment value at the segmental joint location, Fig. 9(a) shows that the mean line of the bending moment obtained with the FLAC^{3D} numerical analysis is closer to the corresponding value obtained by the HRM model in case of using the assumption 1 than with the two other assumptions. Indeed, the maximum differences between the bending moment obtained with FLAC^{3D} model and that of assumptions 1, 2 and 3 introduced in the HRM are 6%, 9.8% and 18.1%, respectively, which are observed at locations corresponding to angles ω of 0^0 or 180^0.

The following comments can be made on the basis of the previous analysis:

-The structural force and lining displacement results obtained using the HRM method are basically in good agreement with the numerical FLAC^{3D} results;

The influence of the joints between successive rings in segmental linings can be taken into consideration through numerical joints using one of above the three proposed assumptions in the HRM method. In this case study, assumption 1 allows the numerical results obtained using the HRM method to be in better agreement with the FLAC^{3D} results than the two others

6. Conclusions

A simplified 3D numerical model, using the FLAC^{3D} finite difference software, has been developed. The numerical results obtained with this model indicated that a 3D numerical model, which allows the staggered pattern of the lining to be taken into consideration, is necessary to accurately simulate the behaviour of a segmental tunnel lining. In addition, the assumption of rigid connection between successive rings, which has been applied in the HRM method, could be adopted from the design point of view.

In order to estimate the efficiency of the HRM method, the numerical results of the three assumptions on the segmental joints have been compared with numerical results obtained with the simplified 3D numerical model. The results have pointed out that the assumption 1 gives the structural lining forces and lining displacements which are in better agreement with those of the 3D numerical model than the two others. In addition, the results of a 3D numerical model pointed out that a rigid connection between successive rings is an acceptable assumption.

The numerical results presented in the paper show that the HRM method can be used to investigate the behaviour of a segmental tunnel lining instead of a 3D numerical modelling.

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