THEORETICAL AND NUMERICAL ANALYSIS OF THE THREE-DIMENSIONAL RESPONSE OF SEGMENTAL TUNNEL LININGS SUBJECTED TO LOCALIZED LOADS.

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ABSTRACT

Segmental tunnel linings present a significant 3D response when they are subjected to localized loads or to other scenarios that produce different deformations of adjacent rings. The present paper analyzes the interaction mechanisms mobilized in such conditions, determining the most influence parameters and their repercussion on the structural response of the lining. A complete set of numerical analyses is carried out on a complex 3D numerical model that accurately reproduces a real tunnel section on multiple scenarios. Numerical results show the structural benefits of the lining three-dimensional response when subjected to localized loads, allowing the determination of the influence presented by the main involved parameters. The surrounding ground stiffness determines the interaction degree achievable between adjacent rings, whilst lining longitudinal compression determines the maximum load for which a complete interaction is produced.

Keywords: Segmental tunnel linings, localized loads, rings interaction, frictional joints, local arch mechanism.

1. INTRODUCTION

The utilization of the modern tunnel boring machines (TBMs) is mainly associated to segmental tunnel linings, which consist of precast concrete rings sequentially placed as the tunnel drilling advances (Fig. 1). Each ring comprises a certain number of segments, defining a multiple-jointed structure that presents a complex structural response (Muir Wood, 1975; Blom, 2002; Molins and Arnau, 2011). According to such particular configuration, the real three-dimensional behavior of a segmental tunnel lining should be located somewhere between the response of a group of isolated rings and the response of a rigid pipe. The clarification of the

interaction mechanisms existing between adjacent rings, as well as the determination of the main phenomena and variables involved on it, would definitely contribute to the improvement and optimization of the design of segmental tunnel linings.

Figure 1. Tunnel boring machine and segmental tunnel lining.

The main interaction mechanism is activated when radial relative displacements occur between adjacent rings (Fig. 2), producing the transfer of tangential forces through the circumferential joints (Fig. 1). Segmental tunnel linings are commonly subjected to nearly hydrostatic loads that smoothly vary along the tunnel track. Therefore, all rings present similar loading patterns, expecting the consequent similar deformation of all of them, and do not producing significant relative radial displacements between adjacent rings. This fact traditionally enables the common 2D design procedure, where an isolated ring model is employed to determine the internal forces in the lining. On the other hand, recent researches pointed out the three-dimensional response that segmental tunnel linings can present even under design loads. The staggered configuration of joints can produce small relative displacements between adjacent rings, activating the force transfer mechanisms, and producing an increase of the stiffness and internal forces of the lining (coupling effects) (Blom, 2002; Klappers *et al.*, 2006). In correspondence to the limited relative displacements originated in usual design conditions, Arnau and Molins (2012) concluded that a significant three-dimensional response should be only expected when segmented tunnel linings are embedded in soft ground conditions or subjected to high unbalanced loads.

Apart from the usual conditions used to determine the design loads, tunnels can be subjected to different situations in which more significant radial relative displacements between adjacent rings can occur and, therefore, a more relevant three-dimensional response of the lining is expected. Certain ground scenarios can cause localized loads over a certain tunnel section or

even a unique ring. These loads can present different origins like small faults in rocks, ground swelling phenomena, or ground columns produced during the tunnel excavation due to the weakness of the surrounding ground. Localized loads imply different loading of adjacent rings, obtaining the consequent different deformations, and originating radial relative displacements between them. In fact, all tunnel situations that produce different structural responses of adjacent rings will activate the interaction mechanisms. As a consequence, a significant three-dimensional response of segmental linings is expected in all kinds of structural discontinuities like tunnel openings, connections to shafts or between parallel tunnels, sudden changes in surrounding ground stiffness, etc.

Up to date, research attempts available in the bibliography related to the structural response of segmental linings subject to these situations is certainly limited. Klappers *et al.* (2006) performed an analysis of the particular situation of a tunnel section with an opening (to build a cross passage between two tubes) by employing a 3D shell elements model. Simplified approaches were used to reproduce the response of the joints, using lateral springs which consider the frictional response of the rings' coupling in the circumferential direction, whilst nonlinear rotational springs were used to reproduce the response of the longitudinal ones. The structural behavior of the tunnel section was analyzed for a wide range of longitudinal forces, from 5 to 40 MN, in order to consider different hypotheses about the long term remaining of the longitudinal forces initially introduced by the TBM during the construction process. Contrarily to the observed for usual design loads (Arnau and Molins, 2012), the numerical study noticed that the longitudinal force level presents a significant influence on the deformation and the internal forces of the lining. Consequently, it was concluded that an appropriate consideration of the three-dimensional response of the lining is necessary when analyzing situations that create different structural responses of adjacent rings.

Therefore, it has been pointed out the necessity of accurately known and comprehend the three-dimensional effects governing the structural response of segmental tunnel linings when analyzing their behavior under localized loads or other situations that create significant relative displacements between adjacent rings. Present paper analyzes and describes the structural mechanisms and phenomena involved in the transfer of forces between adjacent rings, clearly determining the influence of the most relevant parameters in the structural response of the lining. For such purpose, an advanced 3D numerical model is developed in order to accurately reproduce the structural response of the joints, especially the variable stress state and the correspondent actual friction in the circumferential joints. The structural response of a real tunnel section of eleven rings is analyzed under several values of a localized load for different scenarios of ground stiffness and longitudinal compression stress levels. The detailed analysis of the numerical results provided significant conclusions about the three-dimensional response of segmental tunnel linings subjected localized loads. The structural benefits produced by

interaction mechanisms are pointed out, and the influence presented by the longitudinal stress state of the lining and the ground surrounding conditions are clearly stated.

2. INTERACTION MECHANISMS UNDER LOCALIZED LOADS

The rings of segmental tunnel linings are multiple-hinged structures and, as a consequence, their structural stability requires the surrounding stiffness provided by the ground. The localized loading of a ring (F_L) produce its deformation until the surrounding ground provides the necessary reaction force (F_{GR}) to equilibrate the applied load (Fig. 2). The surrounding ground stiffness determines the necessary ground deformation to achieve the required reaction force, thus conditioning the radial displacements experienced by the ring (Fig. 2).

Figure 2. Isolated ring stability mechanism under localized loads.

The three-dimensional response of the linings is provided by the structural interaction of adjacent rings and, therefore, it is directly conditioned by the configuration of the circumferential joints. Out of really soft soil conditions, where dowel and socket systems are sometimes used (Blom, 2002), the majority of tunnel projects present a planar configuration of those joints. Then, the contact between rings is exclusively provided by the packing sheets (packers) initially placed to assure the adequate transfer of the longitudinal force applied by the TBM during the construction process (Fig. 1 and 2).

Relative radial displacements occurred between the loaded ring and his adjacent ones (ΔU_R), producing the shear deformation of the packers (Fig. 3), and originating the transfer of

tangential forces $F_{R,B}$ between rings. Then, higher force transfers are expected for soft ground conditions due to the highest deformation experienced by the loaded ring.

Figure 3. Tangential response presented by the packing material (packers).

The usual plane configuration of joints produce that the mechanical response of the packer-concrete interface is determined by a frictional mechanism. Therefore, the transferred force $F_{R,B}$ is limited by the maximum tangential stress that packers can resist before slipping (τ_{sl}), which depends on the existent normal compression stress (σ_p). According to this phenomenon, several researches have indicated the necessity of properly considering the longitudinal force present at a tunnel lining in order to adequately reproduce its three dimensional response (Blom *et al.*, 1999; Mo and Chen, 2008).

Figure 4. Segmental lining longitudinal resistant mechanism under localized loads.

The transfer of tangential forces from the loaded ring (F_R) produces the deformation of the adjacent ones, originating the longitudinal deformation profile shown in figure 4. As a result, the stress distribution in the circumferential joints is locally modified (Fig. 4). The compression stress at certain packer (σ_p) varies along its height, modifying the maximum tangential stress (τ_{sl}) for different points of a same packer.

Additionally, the relative movement between adjacent rings shown in figure 4 produces a jack arch mechanism due to the dislocation of the segments (Fig. 5). As a consequence, the compressive forces in the load influence zone increase with the lining deformation (δ in Fig. 4). Therefore, this mechanism directly increase the maximum tangential stress of packers and the consequent capacity of transferring loads between adjacent rings.

Figure 5. Diagram of the jack arch mechanism produced by the dislocation of the segments.

3. CASE STUDY AND PARAMATERS OF ANALYSIS

The determination of the three-dimensional response of segmental tunnel linings under localized loads is tackled through the numerical analysis of a real tunnel section. Several intensities of a localized load are applied on a diversity of scenarios defined by varying the most influence parameters in the structural response; the surrounding ground stiffness and the longitudinal compression. The results will be also compared to those obtained by the most common design approaches, an isolating ring and a rigid pipe, in order to clearly expose the influence of the three-dimensional structural response in front of localized loads.

3.1. Segmental lining

The segmental lining selected for the case study corresponds to an eleven rings section of the Line 9 tunnel of Barcelona's subway. As it is shown in figure 6, each ring is composed by seven conventional precast concrete segments (A, B and C) plus one key segment (K), defining a universal ring with an external diameter of 11.6m, 1.80m wide, and 0.57° of conicity.

Each segment presents a regular thickness of 350mm, which is reduced to 204mm at the ends to conform the concrete-to-concrete configuration of the longitudinal joints (view Fig. 1 and 6). Circumferential joints (between adjacent rings, Fig. 1) present a planar surface in which 30 plastic packing sheets (packers) are regularly placed (fig. 6). Each packer presents a height of 204mm (configuring the same joint height than in longitudinal joints), 2mm thickness, and encompasses an angle of 8° (Fig.6).

Figure 6. Ring configuration of the analyzed Line 9 section.

The adequate tracking of the tunnel implies the rotation of the rings in order to use its conicity, defining different positions of the K segment. Table 1 summarizes the configuration of the analyzed section, where the reference line for determining the angular positions is the positive x axe (Fig. 6).

Table 1. K segment positions of the modeled section of Line 9 Tunnel.

Modeled number	Ring	1	2	3	4	5	6	7	8	9	10	11
K	angular	138	114	234	354	18	306	66	210	90	282	210
Z	initial	0	1802	3604	5406	7208	9010	10812	12614	14416	16218	18020
Z	final	1800	3602	5404	7206	9008	10810	12612	14414	16216	18018	19820

3.2. Localized loading

The objective of the present research is to comprehend the structural interaction of adjacent rings when the structural lining is subjected to localized loads. In order to allow the reading of the numerical results in the clearest manner for achieving such objective, the usual ground pressure is not considered, and a localized load is exclusively applied at the central ring of the modeled section (Fig. 7). According to such configuration, the structural response obtained in the other rings is exclusively caused by the interaction mechanisms, thus facilitating their analysis and comprehension.

Figure 7. Localized loading pattern applied in the numerical study. 3D and plant view.

The localized load consists of a vertical pressure applied at the crown of the central ring (vertically projected to ring 6), ranging from 0 to 2 N/mm², which covers a 5m wide band and the entire ring width (Fig. 7). This load pattern implies a loading angle of 51°, which is close to the value of the worst loaded angular extension for a circular tunnel (60°) defined by Marí and Molins (2007).

3.3. Longitudinal force and ground stiffness scenarios

As it is exposed in the conceptual analysis of section 2, the structural response of segmental tunnel linings should be conditioned by the surrounding ground stiffness and the present longitudinal force.

Table 2. Different scenarios applied to the localized load model.

<i>Analyzed scenarios</i>		
<i>Ground Stiffness, E_s (N/mm²)</i>		<i>Longitudinal pre-compression, $\sigma_{c,l}$(MPa)</i>
Soft (SF)	100	1
Medium (ME)	1000	2.5
Hard (HD)	10000	3.5
		5
Total amount of cases		12

With the aim of covering a wide range of situations, three different ground stiffness scenarios are analyzed. Table 2 presents the values of the ground elastic modulus adopted to characterize Soft (SF), Medium (ME) and Hard (HD) ground.

A wide range of values is necessary to analyze the influence of the longitudinal force present at the lining. TBMs exert different longitudinal forces depending on multiple parameters like its typology, the tunnel diameter, or the ground conditions. Additionally, recent research pointed out that the remaining longitudinal force experiences a reduction with time caused by the longitudinal creep of the lining (Arnau *et al.*, 2012). Consequently, four different levels of longitudinal pre-compression stress are analyzed for the case study, from 5 to 1 MPa (Table 2). This maximum stress is obtained by applying a force of 62 MN, representing a hard rock drilling, to the geometrical characteristics of the case study. Longitudinal force is considered equally distributed around the tunnel section, thus producing a uniform compression. The case in which no longitudinal pre-compression remains in the lining is covered by the isolated rings results since no significant interaction will be generated.

Therefore, a total amount of 12 different scenarios subjected to an increasing localized pressure are analyzed.

3.4. Base of comparison

Additionally, two different sets of analyses are performed in order to evaluate the influence of considering the three-dimensional effects in the structural response of the lining. On one hand, the results obtained exclusively modeling the loaded ring (appropriately considering the longitudinal joints behavior) establishes the base of comparison in respect to the isolated ring approaches commonly used in design practice. On the other hand, the analysis of the segmental tunnel lining as a rigid pipe (without consideration of joints) provides the results that define an upper bond for the effects caused by the structural interaction mechanisms.

4. NUMERICAL MODELING

A complex three-dimensional nonlinear numerical model is created in order to properly simulate the structural response of the eleven rings section selected as the case of study. Present section describes the adopted hypothesis and techniques used to appropriately create the model. Numerical analyses are carried out by using the Finite element software Diana 9.4.

4.1. Concrete Segments

Concrete segments are modeled by means of 4-node quadrilateral curved shell elements, codified as Q20SH in Diana 9.4 (TNO, 2009). In order to facilitate the comprehension of the complex rings interaction mechanisms, which includes sliding and gapping of the joints, linear elastic properties are initially assumed for concrete, taking a modulus of elasticity of $E_c=38,700\text{N/mm}^2$ and a Poisson ratio of $\nu=0.2$. A more realistic reproduction of the reinforced concrete response is tackled in section 5.4, considering the nonlinear response of concrete caused by cracking in tension, crushing in compression, and the yielding phenomenon on steel reinforcement bars. The real positions of the K segment and the particular inclination of its longitudinal joints (9.52°) are realistically simulated in the finite elements model.

4.2. Joints

Longitudinal joints (between segments of the same ring) are modeled by means of shell interface elements, covering the total width of the ring (Fig. 8). They present a rigid response in compression, whilst gapping appears under tension to adequately simulate the local opening of the joint due to rotation (Arnau and Molins, 2011). Shear response is considered as stiff in order to reproduce the mechanical locking caused by the cylinder usually installed at mid height to center the segments during its placing.

Figure 8. Definition of the joints in the shell elements model.

The connection between adjacent rings is exclusively performed through the packers. Therefore, circumferential joints are also reproduced by means of shell interface elements placed at the exact positions of packers (Fig. 8). The normal and shear stiffness of the interface are determined according to the 2mm thickness of the packers and their elastic properties, a modulus of elasticity of $E_p=202.1\text{N/mm}^2$ (Arnau *et al*, 2012) and the correspondent shear

modulus of $G_p=77.7\text{N/mm}^2$. The frictional response of the packer-concrete surface is simulated by means of a Mohr-Coulomb constitutive model, adopting a friction coefficient of $\mu_p=0.2076$ obtained by Arnau and Molins (2012) from the tests performed by Cavalaro (2009) on the packer used in the Barcelona Line 9 tunnel.

During the erection process of the segments, provisional steel bolts are used in order to fix the new segment to the placed ones. The tightening of the bolts produce a small compression stress in the joint, contributing to slightly delay the opening of the joint under rotation. In order to consider this effect, a gap formation value of 0.278N/mm^2 is assumed, meaning the value of tension that has to be achieved to produce the opening of the joint.

Same shell interface elements are used for modeling both longitudinal and circumferential joints, which is codified as L16IF in software Diana v9.4. They are configured to properly reproduce the nonlinear response of the joints when opening by presenting two integration points along their width, and eleven along their height. In all cases, the influence of the waterproof gaskets is not considered.

4.3. Ground-Structure interaction.

The ground structure interaction is considered by means of three different sets of spring elements placed in radial, tangential and longitudinal directions (Blomet *al*, 1999; Plizzari and Tiberti, 2006; Arnau and Molins, 2011). Unilateral response is adopted in radial springs in order to avoid tensile forces between the ground and the structure. The stiffness of the radial springs (K_r) is determined by equation 1, which corresponds to the analytical solution of a circular tunnel in elastic ground, whilst the tangential (K_t) and longitudinal (K_l) spring stiffness (Eq. 2 and 3) are assumed as 1/3 of the radial one (Molins and Arnau, 2011) (R corresponds to the tunnel radius, whilst E_s and ν are the elasticity modulus and the Poisson coefficient of the ground respectively).

$$K_r = \frac{E}{R \cdot (1 + \nu)} \quad (\text{Eq. 1})$$

$$K_t = \frac{K_r}{3} \quad (\text{Eq. 2})$$

$$K_l = \frac{K_r}{3} \quad (\text{Eq. 3})$$

4.4. Analysis procedure.

The correct simulation of the tunnel real response requires the division of the loading procedure in two steps. The longitudinal force is initially applied at one side of the section, longitudinally fixing the opposite one, and disabling the longitudinal spring elements in order to adequately generate the lining pre-compression without guiding loads to the ground. The second step consists in the progressive appliance of the localized load once the longitudinal ground-structure interaction has been enabled.

The resultant model presents a total amount of 19812 structural elements, 62040 spring elements, and 20680 nodes (spring elements to ground do not add nodes). It is numerically solved by using a regular Newton-Raphson iteration procedure, assuming a relative energy tolerance ratio of 0.01% as a convergence criterion.

5. RESULTS

5.1. Structural response of the lining

The numerical results show that when a localized load is applied on a lining in hard ground conditions, significant bending forces are only produced at the loaded ring (Fig. 9). This quasi-individual response is fully consistent with the conclusions obtained in the “in situ” loading test presented in Molins and Arnau (2011), where no significant contribution of the adjacent rings was measured for a rock tunnel subjected to a localized load. On the other hand, the same load applied to the same structure embedded in soft ground, produces significant circumferential bending forces to adjacent rings (Fig. 9) clearly showing its structural contribution to resist the acting load. Therefore, the reduction of the surrounding ground stiffness implies a higher interaction between adjacent rings, thus increasing the three-dimensional response of the segmental tunnel lining.

In all ground stiffness, the evolution of the vertical ovalization (crown minus base vertical displacement, O_v) of the loaded ring shows the influence of the longitudinal force on the lining stiffness (Fig. 10). Higher longitudinal compressions imply a reduction on the deformations obtained as the load pressure increases. This response is caused by the increase of the tangential force transfer of packers originated by a higher longitudinal compression, producing that the lining behaves as a rigid pipe for a wider range of loads. When a localized pressure of 1N/mm^2 is applied, the reduction of the longitudinal pre-compression from 5 to 1Mpa implies an increase of the central ring deformation of 210% for soft ground (SF) and 44% for hard ground (HD). As it was expected according to the theoretical explanation given in section 2, the three dimensional response of the lining presents a higher relevance with the decrease of the surrounding ground stiffness.

Hard ground (HD)

Soft ground (SF)

Figure 9. Circumferential bending forces for a localized pressure of 1N/mm^2 and longitudinal pre-compression of 5 MPa.

Figure 10. Evolution of the loaded ring vertical ovalization for hard (HD) and soft ground (SF) conditions, depending on the longitudinal compression stress.

An effective and comprehensible way to appraise the structural interaction between rings consists in analyzing the relative vertical ovalization (RO_v , Eq. 4) experienced by the directly adjacent rings (rings 5 and 7) respect to the locally loaded one (ring 6). As can be observed in figure 11, the relative adjacent ring ovalization remains almost constant for small load values and independent of the lining pre-compression, achieving a value of 80% in soft ground conditions (SF) in front of the 40% obtained for hard ground (HD).

$$RO_v = \frac{O_{v_5} + O_{v_7}}{2 \cdot O_{v_6}} (\%) \quad (\text{Eq. 4})$$

At certain load, the relative ovalization of the adjacent rings suddenly decreases, denoting the point where a significant number of packers start slipping (vertical dot lines in Fig. 11). Once the slipping starts, the structural collaboration tends to be stabilized in a similar value around 20% for all the analyzed cases. The value of the slipping load do not show dependency on the surrounding ground conditions, and remains only influenced by the existing longitudinal compressive stress in the lining. The results obtained show an almost perfect linearity between the longitudinal compression value and the necessary load to produce the significant slipping of packers (Fig. 12), presenting a relation coefficient of 0.255, which is close to the assumed packer-concrete friction coefficient ($\mu_p=0.2076$).

Figure 11. Relative vertical ovalization of the rings adjacent to the loaded one for different longitudinal pre-stress.

Figure 12. Relation between the localized pressure that produces the significant slipping of the packers and the longitudinal compression stress.

Figure 13 shows the evolution of the central ring packers slipping for a longitudinal pre-compression of 2.5 MPa and medium ground conditions (ME). The points indicate the circumferential joint interface elements that present a complete slipping (each packer is simulated by means of four interface elements). The slipping of packers starts immediately out of the loaded zone (Fig. 13a), expanding mainly to the sides of the ring as the load increase (Fig. 13b). When the slipping of the tunnel crown packers is produced, almost the whole upper part of the ring is sliding (Fig. 13c). This point coincides with the load that produces changes

in the adjacent ring ovalization response, which was previously ascribed to the significant slippage of packers (vertical dot lines in figure 11).

Figure 13. Central ring circumferential joint elements that present a complete slippage as load increases. Scenario: medium ground (ME) and longitudinal pre-stress of 2.5 MPa.

The significant slipping of packers produces a faster increase of the loaded ring deformation. As a consequence, the jack arch mechanism described in section 2 is enhanced, producing significant increments of the longitudinal compression stresses under the load appliance zone (Fig. 14). For the particular case analyzed in figures 13 and 14 (continue line), the fast increase of the crown compression provides higher tangential resistances to crown packers, stopping their slipping process for higher localized loads whilst the sliding extension continues to the lower part of the ring (Fig. 13d and 13e). Advanced load stages produce the restart of the crown packers slipping, presenting sliding at almost whole ring (Fig. 13f).

Figure 14. Local compression increase produced at the tunnel crown by the jack arch mechanism. Scenario: medium ground (ME) and longitudinal pre-stress of 2.5MPa.

Figure 15 shows the amount of elements per joint that present slipping for longitudinal pre-compressions of 1 and 2.5 MPa, previously and before the significant slipping observed in figure 11. The analysis of the whole tunnel reveals that significant slipping of packers is also produced out of the circumferential joints of the central ring (Fig. 15). In fact, for soft ground conditions, the central joints of the modeled section (between rings 5-6 and 6-7) present a lower amount of packer elements slipping than others located farthest from the load (3-4 and 4-5 in Fig. 15). For medium ground conditions (ME) the amount of slipping elements are similar in the four central joints, whilst central ring joints present the maximum number for hard ground conditions (HD). The increase of the localized loads produces the presence of a significant slipping for more and further joints, showing that significant contribution of the adjacent rings remains when the significant slipping occurs. As it was stated along the present paper, the softening of the ground stiffness implies a higher diffusion of the applied load (view figure 9), encompassing more rings and circumferential joints (Fig. 15).

Longitudinal pre-compression, $\sigma_{c,l}=1\text{MPa}$

Longitudinal pre-compression, $\sigma_{c,l}=2.5\text{MPa}$

Figure 15. Amount of joint elements presenting a complete slipping for different scenarios. The total number of joint elements in each ring is 120, four per packer.

On the other hand, the local compression zone caused by the jack arch mechanism does not show dependency with the surrounding ground stiffness. As can be observed in figure 16, the maximum compression at the tunnel crown is achieved under the loaded zone, progressively decreasing along the two adjacent rings at each side, and defining an influence zone of five rings independent of the ground stiffness (rings 4 to 8). According to the highest deformation experienced by the loaded ring on soft ground conditions, the compression increase before and after the significant slipping of packers (localized loads of 0.5 and 1.5N/mm² respectively in figure 11) is higher than in hard ground conditions.

As it was previously explained, the jack arch mechanism is produced by the dislocation of the segments, modifying the stress distribution along the height of the packers as depicted in figure 17 for the packer placed at the crown of the central ring. The increase of the applied load produces higher local stresses at one side of the packer whilst gapping phenomenon can appear at the opposite side for significant dislocations (view localized pressures of 1 and 2 N/mm² in Fig. 17).

Figure 16. Longitudinal axial force at tunnel crown. Longitudinal pre-compression of 2.5MPa (-875kN/ml).

Figure 17. Stress distributions presented at midpoint of a central ring crown packer. Scenario: medium ground (ME) and longitudinal pre-stress of 2.5 MPa.

5.2. Jack arch mechanism

The jack arch mechanism produces a local increase of the longitudinal compression in a zone comprised under the localized load and the two adjacent rings at each side (Fig. 16). Therefore, and assuming that the loaded ring remains straight (neglecting bending deformations), the longitudinal force increase should be caused by the dislocation of the two adjacent rings to the loaded one (Fig. 18).

The increase of the longitudinal force is originated by the variation in length (ΔL) (Eq. 5, 6, 7) caused by the dislocation of the segments when a radial relative displacement (δ) occurs. The relative displacement experienced by the involved rings (δ_1) and (δ_2) is defined by a coefficient (c), which defines the proportion of the total displacement (δ) experienced by the ring adjacent to the loaded one (δ_2) (Eq. 8, 9, 10).

Figure 18. Segments dislocation and idealization of the lining local stiffness.

$$\Delta L = \Delta L_1 + \Delta L_2 \text{ (Eq. 5)} \quad \Delta L_1 = L_1 - L_c \text{ (Eq. 6)} \quad \Delta L_2 = L_2 - L_c \text{ (Eq. 7)}$$

$$\delta = \delta_1 + \delta_2 \text{ (Eq. 8)} \quad \delta_1 = (1 - c) \cdot \delta \text{ (Eq. 9)} \quad \delta_2 = c \cdot \delta \text{ (Eq. 10)}$$

The longitudinal lengths of the segments L_1 and L_2 are trigonometrically obtained according to figure 18 (Eq. 11, 12, 13, 14, 15). Notice that L_2 is conditioned by different contact points at each side of the segment, originating the angle θ defined by the height of the circumferential joints packer (h_p) (Eq. 15).

$$L_1 = L_c \cdot \cos(\alpha_1) \text{ (Eq. 11)} \quad \alpha_1 = \arcsin\left(\frac{\delta_1}{L_c}\right) \text{ (Eq. 12)}$$

$$L_2 = \frac{L_c}{\cos(\theta)} \cdot \cos(\theta - \beta) \text{ (Eq. 13)} \quad \beta = \arcsin\left(\frac{\delta}{L_c}\right) \text{ (Eq. 14)} \quad \theta = \arctan\left(\frac{h_p}{L_c}\right) \text{ (Eq. 15)}$$

The local increase of the longitudinal force (ΔF), caused by a certain increase of length (ΔL), depends on the longitudinal stiffness of the system (k_t) (Eq. 16). According to the Hooke's law, the linear elastic response of the structural materials can be simulated by means of linear springs (Fig. 18). Then, the determination of the longitudinal stiffness of the local system (k_t) can be obtained by considering the serial association of the springs reproducing the particular stiffness of the concrete segments (k_c) and the packers (k_p) (Eq. 17, 18, 19). A_c and A_p correspond to the cross area of concrete segments and packers respectively, E_c and E_p are modulus of elasticity of concrete and packing materials, whilst L_c and e_p determine the length of the elements in longitudinal direction (Fig. 18). Equation 20 defines longitudinal stiffness of the local system according to the number of concrete segments (n_c) and packers (n_p) included in the zone of influence affected by the jack arch mechanism.

$$\Delta F = \Delta L \cdot k_t \text{ (Eq. 16)}$$

$$\frac{1}{k_t} = n_c \cdot \frac{1}{k_c} + n_p \cdot \frac{1}{k_p} \quad (\text{Eq. 17})$$

$$k_c = \frac{E_c \cdot A_c}{L_c} \quad (\text{Eq. 18})$$

$$k_p = \frac{E_p \cdot A_p}{e_p} \quad (\text{Eq. 19})$$

$$k_t = \frac{1}{\frac{n_c \cdot L_c}{E_c \cdot A_c} + \frac{n_p \cdot e_p}{E_p \cdot A_p}} \quad (\text{Eq. 20})$$

Figure 19. Vertical displacement at tunnel crown. Localized pressure of 0.5N/mm² and longitudinal pre-compression of 2.5MPa (-875kN/ml).

Notice that this formulation is based on the assumption that the vertical displacement experienced by the loaded ring is exclusively caused by the dislocation of the two segments contiguous segments at each side (view Fig. 18). As can be observed in figure 19, where the vertical displacements obtained in one scenario of the sensitivity analysis are shown, it is not possible to apply this assumption for really soft ground conditions (SF). In such conditions, the displacements already presented at the ends of the section and their progressive increase disables the possibility to relate the vertical displacement of the loaded ring with the local compression increase through the proposed formulation.

In order to assure the suitability of the proposed model out of soft soil conditions, the analytical expressions are used to predict the evolution of the maximum longitudinal force at the tunnel crown, and compare them to the obtained numerical results. Four different cases are analyzed by combining the pre-compressions of 2.5 and 5 MPa for the medium (ME) and hard (HD) ground scenarios. According to the previously described results, an influence zone of 5 segments and the respective 6 packers is assumed ($n_c=5$, $n_p=6$), as depicted in figure 18. Table 3 shows the adopted values for the necessary parameters to apply the analytical formulation.

Parameter c defines the proportion of the relative vertical deformation experienced by the adjacent ring (δ_2). The general deformation of a ring depends on the ground stiffness and, therefore, it is necessary to determine the value of c for the different ground scenarios analyzed. The analysis of the numerical results provides an average value of $c=0.8$ and $c=0.9$ for the

medium (ME) and hard (HD) ground scenarios respectively. The determination of the parameter c also respects the hypothesis that the vertical deformation of the loaded ring is affects only the five central rings (Fig. 18).

Table 3. Adopted values for calculating the local increase of the longitudinal compression.

<i>Parameters</i>	<i>Values</i>
Concrete deformation modulus, E_c (N/mm ²)	38,700
Packer deformation modulus, E_p (N/mm ²)	201,2
Concrete ring width, L_c (mm)	1800
Packer thickness, e_p (mm)	2
Concrete area, A_c (mm ² /ml)	35,000
Packer area, A_p (mm ² /ml)	13,600
Concrete segments in the influence zone, n_c	5
Packing elements in the influence zone, n_p	6
Parameter c for medium ground (ME)	0.8
Parameter c for hard ground (HD)	0.9

The evolution of the vertical relative displacement at the tunnel crown (δ), stated as the input variable in the analytical model for each analyzed case, is obtained from the numerical models results. As can be observer in figure 20, the evolution of the maximum longitudinal force at the crown of the loaded ring obtained with the proposed analytical model presents a very good agreement respect to the numerical results, thus validating both the described resistant mechanism and the proposed analytical formulation.

Figure 20. Evolution of the maximum longitudinal axial force at the loaded ring. Analytical vs experimental results.

5.3. Influence of the three-dimensional effects

The structural analysis of segmental tunnel linings is commonly carried out by means of isolated ring models; do not considering the real three-dimensional response of the lining. In all cases, adjacent rings interaction produces a significant increase on the lining stiffness in front of the isolated ring analysis (Fig. 21). As long as the significant sliding of the packers has not been achieved, the vertical ovalization of the loaded ring is reduced close to 90% in soft ground and over 50% in hard ground conditions. The decrease of the longitudinal force significantly diminishes the percentiles of deformation reduction in front of the isolated ring model, but a minimum value depending on the surrounding ground stiffness is maintained.

Figure 21. Reduction of loaded ring vertical ovalization respect to the isolated ring results.

The contribution of the adjacent rings also implies a significant reduction of the circumferential bending forces obtained at the crown of the central ring in front of the isolated ring analyses (Fig. 22). Circumferential bending forces present reductions between 48% and 62% before the packer slipping. Contrarily to the observation in lining deformation (Fig. 21), the reduction of the bending forces does not show proportionality with the surrounding ground stiffness.

Figure 22. Reduction of loaded ring circumferential bending forces respect to the isolated ring results.

The reduction of the bending forces originated by the structural interaction between adjacent rings also produces a reduction on the tensile principal stress at the tunnel crown (Fig.23). As a consequence, the amount of localized load necessary to achieve the maximum tensile strength of concrete (4.1N/mm^2 , dot lines in figure 23) and produce the cracking of the segments significantly increases respect to the isolated ring approaches.

Figure 23. Evolution of the tensile principal stress at the crown of the central ring.

The longitudinal force level will also play a decisive role on the cracking load. For medium ground conditions (ME), the increase of the longitudinal pre-compression from 1 to 2.5MPa implies a load increase of 52.2% to produce the cracking of the tunnel crown. On the other hand, in the soft ground case (SF) the tensile principal stress increases really fast, achieving the concrete tensile strength close to the load that produces the slipping of packers for a longitudinal pre-compression of 1MPa . Therefore, for the soft ground conditions, the longitudinal force level only presents significant influence on the lining resistance for values under 1MPa (Fig. 23).

The rigid pipe model implies the unrealistic assumption that joints present the same stiffness as segments and the capacity to transfer tensile forces through them. For soft ground conditions (SF), it originates a modification on the resistant mechanism of the lining, producing that the maximum tensile principal stresses at the tunnel crown are obtained in the adjacent rings (5 and 7) instead of the loaded ring (6). As a consequence, the results presented in figure 23 for soft ground are not directly comparable.

These unrealistic assumptions also condition the principal stress calculated in the concrete segments and, therefore, it is important to also consider the longitudinal pre-compression. For medium ground conditions (ME), the principal stress of the lining behave very similar to the rigid pipe response until a localized pressure around 0.65 N/mm^2 , which corresponds to the load that produces a significant slipping of the packers for such pre-stress value (view Fig. 11). As can be also observed in figure 23, the results of the principal stress of a rigid pipe can significantly differ if the longitudinal pre-compression of the lining is not considered (NP).

In general, the results show that the consideration of the longitudinal force and its magnitude implies an increase of the necessary localized load to produce the cracking of the tunnel crown (Fig. 24). For hard rock conditions, the structural mechanism that originates the maximum tensile stress in the tunnel crown differ in respect to softer ground conditions, producing that the isolated ring model provides a higher resistance to cracking than the consideration of the real three dimensional effects. Localized loads produce internal bending forces in circumferential direction (originating the main deformation of the ring) but also in longitudinal direction (between circumferential joints). Usual conditions imply that bending forces in circumferential direction become more significant than in longitudinal direction (view medium ground results -ME- in Fig.24), emerging as the dominating phenomenon in segments cracking. For the analyzed hard rock conditions, bending forces in both directions take similar values, but the compressive axial force is significantly higher in circumferential direction than in longitudinal (hard ground -HD- in Fig. 25). As a consequence, the tensile stress in longitudinal direction becomes higher (view Fig. 26), changing the usual mechanism of cracking of the ring.

Figure 24. Influence of the longitudinal pre-compression on the localized pressure for crown cracking.

Figure 25. Axial and bending internal forces at the loaded ring crown in circumferential and longitudinal direction for hard (HD) and medium (ME) ground conditions. Longitudinal pre-compression of 2.5 MPa.

Figure 26. Tensile stresses produced at the loaded ring crown due to circumferential and longitudinal internal forces. Longitudinal pre-compression of 2.5 MPa.

5.4. Influence of concrete cracking

Differently to other situations that can produce a significant interaction of adjacent rings like tunnel openings or connections, localized loads mainly present an exceptional origin. As a consequence, they are not commonly considered on design process and, therefore, can easily produce the cracking of the structure. The numerical analyses performed on previous sections show that the maximum tensile stress of concrete can be easily achieved, inclusively for small values of the load pressure depending on the existent longitudinal compression (Fig. 23). These analyses were carried out assuming a linear elastic response of concrete and, therefore, it is necessary to determine the influence of considering concrete cracking in the structural behavior of segmental tunnel linings subjected to localized loads.

Table 4. Scenarios analyzed with concrete nonlinear material properties.

Case	Ground Stiffness, E_s (N/mm ²)	Longitudinal Pre-compression, $\sigma_{c,l}$
ME-1MPa NLM	1000	1
ME-2.5MPa NLM	1000	2.5
ME-5MPa NLM	1000	5
SF-2.5MPa NLM	100	2.5

In order to determine the significance of considering the real brittle response of concrete instead of employing a linear elastic approach, four different representative cases of the previously described scenarios are analyzed (Table 4). A circumferential reinforcement of $\phi 25$ separated 200mm is symmetrically placed at both sides of each segment, presenting a concrete cover of 50mm. Specific reinforcement finite elements are added to the 11 rings shell model, assigning them an elastic-plastic response with an elastic modulus of $E_s=200$ GPa and a yield strength of $f_y=500$ N/mm². Concrete behavior is assumed to be elastic-plastic in compression and

completely brittle in tension, presenting an elastic modulus of $E_c=38.7$ GPa, a compressive strength of 50 N/mm^2 and a tensile strength of 4.1 N/mm^2 .

The numerical procedure of loading is the same previously described in section 4.4, achieving in all the analyzed cases the maximum planned localized pressure.

Numerical results show that the nonlinear material consideration does not imply a significant influence on the deformation of the loaded ring, nor in the adjacent ring ovalization, when the lining is embedded on medium ground conditions (ME). This fact shows how the significant stiffness of the surrounding ground easily compensates the decrease of the ring stiffness caused by concrete cracking. As a result, differences of 10-12% respect to the linear elastic material consideration are obtained for the maximum circumferential bending forces produced at the loaded ring in such ground conditions.

Figure 27. Linear vs Nonlinear material response for soft ground conditions (SF)

The analysis of the lining embedded on soft ground (SF) reveals a more significant influence of concrete cracking on the vertical ovalization of the loaded ring (Fig. 27), slightly increasing since a localized pressure close to 0.75 N/mm^2 , and becoming higher since 1.4 N/mm^2 . At this level of loading, the evolution of the maximum circumferential bending moment of the loaded ring shows a drastic reduction respect to the linear consideration (Fig. 28). This point corresponds with the combination of internal forces of 3480 kN/m of axial force and a circumferential bending moment of 753 mN/m , producing the exhaustion of the reinforced concrete section as can be observed in the interaction diagram presented in figure 29.

Therefore, and according to the numerical results, the use of nonlinear material models is only relevant when analyzing segmental tunnel linings subjected to localized loads in soft ground conditions. Significant differences are only produced when the sectional resistance of the segments is reached at some point, producing a new plastic hinge that significantly increases the flexibility of the loaded ring.

Figure 28. Maximum circumferential bending moment for linear and nonlinear material response on soft ground conditions (SF).

Figure 29. Interaction diagram of the section and evolution of the central ring maximum circumferential bending moment with the localized load increase.

6. CONCLUSIONS

Segmental tunnel linings present a significant three-dimensional response when subjected to localized loads or to any other situation that produces differences in the structural response of adjacent rings (tunnel openings, shaft connections, sudden ground changes, etc). The relative radial displacements of adjacent rings occurred in such situations activate the interaction mechanisms, producing the transfer of forces between rings. A detailed theoretical study is carried out, describing the main involved phenomena, and revealing a significant complexity of the structural response of the lining caused by the combination of circumferential and longitudinal mechanisms.

A sensitivity analysis based on the appliance of a localized load in a real tunnel section is performed to analyze the structural interaction of adjacent rings and the three-dimensional

response of the lining. An advanced 3D numerical model that can properly consider all joints and materials responses is successfully applied to analyze a complete set of scenarios.

The results obtained shown that the structural contribution between adjacent rings produces a stiffer response of the lining and an increase of its resistance under localized loads. A higher degree of interaction implies an increase of the three-dimensional response, thus increasing both the reduction of the lining deformation and the necessary load to produce the cracking of the segments.

For a certain lining configuration (thickness, joints positions and height, packer materials, etc), the level of interaction depends on the surrounding ground stiffness, increasing with the softening of the ground conditions. On the other hand, the longitudinal compression existent at the lining determines the load that produces the significant slipping of packers, without influence of the surrounding ground conditions. The increase of the lining longitudinal compression implies the assessment of the maximum rings interaction for higher loads, thus increasing the structural benefits of the three dimensional response of the lining for a wider range of loads.

Whilst the significant slipping of packers has not been reached, the deformation of segmental tunnel linings tends to behave similar to a rigid pipe. In such conditions, the analyzed case shows a reduction of the lining deformation ranging between 53% and 88% in respect to the isolated ring approach for hard and soft ground conditions respectively. The circumferential bending moment presented in the lining under the load applying zone also presents a significant reduction between 47 and 63% in respect to the isolated ring results.

A localized load (or similar local deformations) originates a jack arch mechanism due to the dislocation of the segments of the lining, producing a local increase of the longitudinal compression in the load appliance zone. The analysis and description of this local mechanism allowed the proposal of a consistent analytical formulation in order to predict the maximum increase of the longitudinal force, which was satisfactorily validated against the numerical results and, thus, fully explaining the resisting mechanism.

In general it can be concluded that segmental tunnel linings present significant three-dimensional effects under localized loads or situations where significant radial displacements between adjacent rings are produced. As a consequence, the accurate prediction of segmental linings response requires an appropriate three dimensional consideration, taking into account the current longitudinal force level.

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REFERENCES

- Arnau, O., 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, 778-788.
- Arnau, O., Molins, C., Blom, C.B.M., Walraven, J.C., 2012. Longitudinal-time dependent response of segmental tunnel linings. *Tunnelling and Underground Space Technology*, 28, 98-108.
- Arnau, O., Molins, C., 2012. Three dimensional structural response of segmental tunnel linings. *Engineering Structures*, 44, 210-221.
- Blom, C.B.M., van der Horst, E.J., Jovanovic, P.S., 1999. Three-dimensional Structural Analyses of the Shield-Driven “Green Heart” Tunnel of the High-Speed Line South. *Tunnelling and Underground Space Technology*, Vol 1, N° 2, 217-224.
- Blom, C.B.M., 2002. Design philosophy of concrete linings for tunnels in soft soils. Ph.D. Thesis, Technische Universiteit Delft.
- Cavalero, S.H.P., 2009. Aspectos tecnológicos de túneles construidos con tuneladora y dovelas prefabricadas de hormigón. Ph.D. Thesis. Universitat Politècnica de Catalunya. (in spanish).
- Klappers, C., Grübl, F., Ostermeier, B., 2006. Structural analyses of segmental lining – coupled beam and spring analyses versus 3D-FEM calculations with shell elements. *Proceedings of the ITA-AITES 2006 World Tunnel Congress, Safety in the Underground Space*, 6 pp.
- Mari, A.R., Molins, C., 2007. Design of the strengthening of tunnel linings under localized pressures. *Proceedings of the 33rd ITA-AITES World Tunnel Congress - Underground Space - The 4th Dimension of Metropolises*, pp. 1481-1486.
- Mo, H.H., Chen, J.S., 2008. Study on inner force and dislocation of segments caused by shield machine attitude. *Tunnelling and Underground Space Technology*, 23, 281-291.
- Molins, C., Arnau, O., 2011. Experimental and analytical study of the structural response of segmental tunnel linings based on an *In situ* loading test. Part 1: Test Configuration and Execution. *Tunnelling and Underground Space Technology*, 26, 764-777.

Muir Wood, A.M., 1975. The circular tunnel in elastic ground. *Géotechnique*, 25, 115-127.

Plizzari, G.A., Tiberti, G., 2006. Steel Fibers as Reinforcement for Precast Tunnel Segments. Proceedings of the ITA-AITES 2006 World Tunnel Congress and 32 ITA General Assembly. 6pp.

TNO, 2009. Diana user's manual. Release 9.4. <http://www.tnodiana.com>

APPENDIX 1. NOTATION

A_c	Concrete cross area
A_p	Packer cross area
c	Coefficient defining the ratio δ_2/δ
e_p	Packer thickness
E_c	Concrete deformation modulus
E_p	Packer deformation modulus
E_s	Steel deformation modulus
f_y	Steel yield strength
ΔF	Local increase of the longitudinal force
F_L	Localized load
F_T	Tangential force
G_p	Packershear modulus
K_t	Longitudinal stiffness of the local system
K_c	Longitudinal stiffness of a segment
K_p	Longitudinal stiffness of a packer
ΔL	Total length increase
$\Delta L_{1,2}$	Length increase of segments
$L_{1,2}$	Longitudinal length of segments
L_c	Concrete ring width
n_c	Amount of segments in the influence zone
n_p	Amount of packers in the influence zone
O_v	Vertical ovalization of a ring
RO_v	Relative vertical ovalization of the adjacent rings respect to the loaded one
δ	Lining relative vertical displacement
$\delta_{1,2}$	Relative vertical displacement of segments
σ_p	Packers normal stress
μ_p	Packer-concrete friction coefficient
ν	Poisson ratio
τ_p	Packer tangential stress
τ_{sl}	Maximum tangential stress of packers