Tunnelling and Underground Space Technology 49 (2015) 384–399

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Theoretical and numerical analysis of the three-dimensional response of segmental tunnel linings subjected to localized loads

Oriol Arnau [a,b,*], Climent Molins [b]

[a] Department of Structures and Materials, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Circuito Escolar S/N, E2, Ciudad Universitaria, 04510 México D.F., Mexico
[b] Department of Construction Engineering, Universitat Politècnica de Catalunya (UPC), Jordi Girona 1-3, C1, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 26 June 2013
Received in revised form 7 May 2015
Accepted 31 May 2015

Keywords:
Segmental tunnel linings
Localized loads
Rings interaction
Frictional joints
Local arch mechanism

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.

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.

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

* Corresponding author at: Department of Construction Engineering, Universitat Politècnica de Catalunya (UPC), Jordi Girona 1-3, C1, 08034 Barcelona, Spain.
E-mail addresses: OArnauD@iingen.unam.mx (O. Arnau), climent.molins@upc.edu (C. Molins).

http://dx.doi.org/10.1016/j.tust.2015.05.012
0886-7798/

Notation

A_c	concrete cross area	K_p	longitudinal stiffness of a packer
A_p	packer cross area	ΔL	total length increase
c	coefficient defining the ratio δ_2/δ	$\Delta L_{1,2}$	length increase of segments
e_p	packer thickness	$L_{1,2}$	longitudinal length of segments
E_c	concrete deformation modulus	L_c	concrete ring width
E_g	ground deformation modulus	n_c	amount of segments in the influence zone
E_p	packer deformation modulus	n_p	amount of packers in the influence zone
E_s	steel deformation modulus	Ov	vertical ovalization of a ring
f_y	steel yield strength	ROv	relative vertical ovalization of the adjacent rings respect to the loaded one
ΔF	local increase of the longitudinal force	δ	lining relative vertical displacement
F_L	localized load	$\delta_{1,2}$	relative vertical displacement of segments
F_T	tangential force	σ_p	packers normal stress
G_p	packer shear modulus	μ_p	packer–concrete friction coefficient
K_{rad}	radial ground stiffness	ν	poisson ratio
K_{tan}	tangential ground stiffness	τ_p	packer tangential stress
K_{lon}	longitudinal ground stiffness	τ_{sl}	maximum tangential stress of packers
K_t	longitudinal stiffness of the local system		
K_c	longitudinal stiffness of a segment		

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 and sudden changes in surrounding ground stiffness.

Up to date, research attempts available in the bibliography related to the structural response of segmental linings subject to these situations are 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

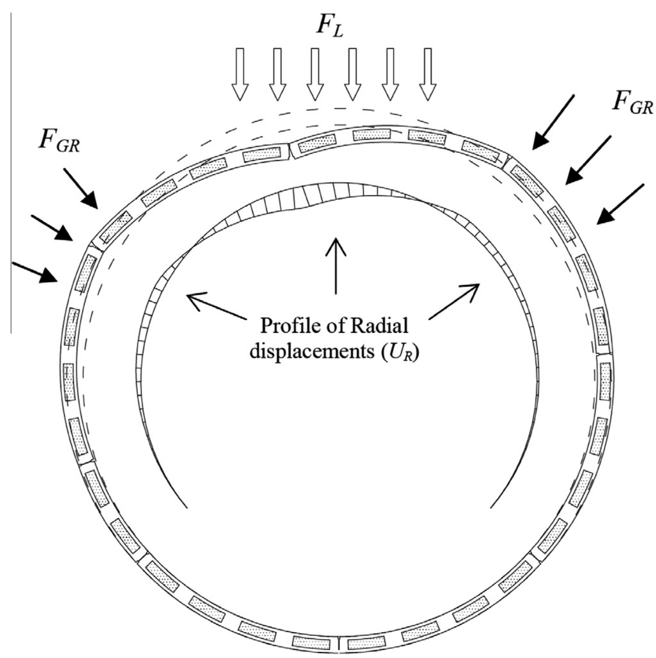

Fig. 2. Isolated ring stability mechanism under localized loads.

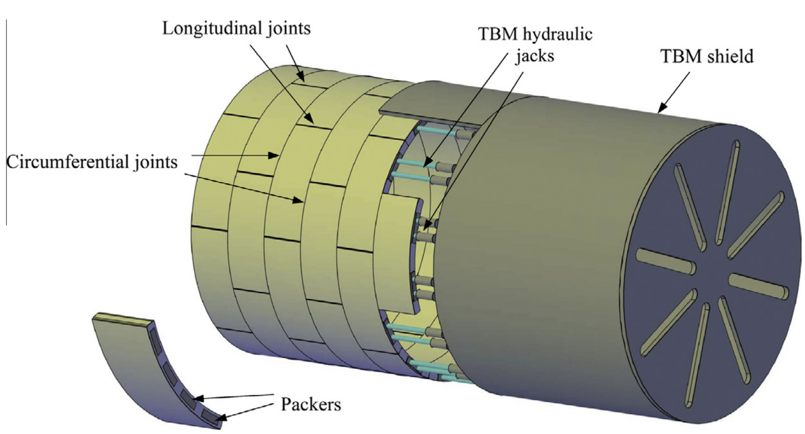

Fig. 1. Tunnel boring machine and segmental tunnel lining.