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Analytical solution for longitudinal bending stiffness of shield tunnels

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ABSTRACT

The longitudinal bending stiffness of tunnels is one of the most important parameters for the structural design of the tunnel longitudinal deformations during seismic loading. The aim of the paper is to derive an analytical solution for the longitudinal bending stiffness of a segmental liner, typically used on tunnels built with a shield. For the derivation, it is assumed that the tunnel liner includes bolts, segments and rubber gaskets. All the elements are considered as linear elastic. The bolts are assumed to work only in tension and the rubber gaskets are assumed to work only in compression. The deformation of any tunnel cross section complies with the assumption that normals to the neutral axis remain normal and thus the neutral axis does not change along the tunnel during deflection. Based on these assumptions, a longitudinal equivalent model for shield tunnels is developed and the governing equations are obtained. A closed-form analytical solution for the longitudinal bending stiffness is developed and verified by providing comparisons between its results and those from the Finite Element program ABAQUS. A parametric analysis, using the new analytical solution, is included to investigate the influence of key parameters such as the thickness of the rubber gaskets, the ratio of the liner thickness to the internal tunnel diameter, and the transverse bending stiffness of the tunnel cross section on the longitudinal bending stiffness of the tunnel.

1. Introduction

Shield-driven tunneling has been widely used for the construction of underground space for e.g. transportation, utility networks, etc. The mechanical behavior of shield tunnels has attracted the interest of researchers and engineers over the past decades, given that the lining is not a continuous ring structure. It consists of segments connected through joints, bolts and rubber gaskets. Also, tunnel segments are often articulated or coupled at longitudinal and circumferential joints. Therefore, not only the characteristics of the concrete of the segments influence the behavior of the liner, but also the mechanical and geometrical characteristics of the joints (Klappers et al., 2006; Yu et al., 2013a; Yu et al., 2013b; Ye et al., 2014). As a result, the presence of the joints should be taken into consideration for the design of the tunnel lining, as they may affect the response of the support in terms of stresses and deformations. This can be done using numerical analyses, but this may be difficult and time consuming if joint details and connection between segments (e.g. bolts) need to be explicitly modeled.

Tunnel behavior is often approached as two two-dimensional uncoupled problems, though it is a three-dimensional problem (Liao et al., 2008; Yu et al., 2018a), namely: (1) deformation and bending in the transverse direction; and (2) deformation and bending in the longitudinal direction. It is well-established that tunneling is a deformation-based problem and so, bending stiffness, both in the transverse and longitudinal directions, is the critical parameter for structural design and analysis (e.g. Einstein and Schwartz, 1979; Yu et al., 2018c; Yuan et al., 2018). Bending stiffness in the transverse direction has been widely studied by a number of researchers (e.g. Wood, 1975; Liu and Hou, 1991; Lee and Ge, 2001), especially by Lee et al. (2001) who proposed an analytical solution for an estimate of the transverse stiffness based on the equivalence of a jointed shield-driven tunnel lining and a continuous ring structure (i.e. the liner is assumed as a rigid pipe without joints). Comparatively, only limited studies on the longitudinal stiffness of the tunnel can be found in literature, as a result perhaps of

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Nomenclature

a, b	major and minor axis of the deformed tunnel cross section
y_φ, φ	location of the neutral axis
ds	arbitrary differential element along the liner
r	undeformed outer radius of the tunnel
y	distance from the differential element to the horizontal center line of the cross section
α	angle between the differential element and the vertical direction
D	undeformed outer diameter of the tunnel
ΔD_1	maximum horizontal displacement of the non-homogeneous ring
ΔD_2	maximum horizontal displacement of the homogeneous ring
$(EI)^*$	transverse bending stiffness of the non-homogeneous ring
EI	transverse bending stiffness of the homogeneous ring
η	effective ratio of transverse bending stiffness
M	bending moment
t	thickness of the segment
δ_1^t	tensile deformation of the bolts
δ_1^c	compressive deformation of the rubber gaskets
E_b	Young's modulus of the bolts
A_b	area of cross section of the bolts
A_s	area of cross section of the segments
E_1	Young's modulus of the rubber gaskets
l_1	length of Component I
E_2	Young's modulus of the segment
ε_2^t	tensile strain of the segment
ε_2^c	compressive strain of the segment
δ_2^j	joint opening
l_2	length of Component II
l	total length of the element considered for the analysis
I_2	moment of inertia of the tunnel cross section
θ_1	bending rotation of the cross section in Component I
θ_2	bending rotation of the cross section in Component II
θ_3	bending rotation of the cross section in Component III
θ	sum of each one of the rotations sustained by each component
ξ	effective ratio of the longitudinal bending stiffness of the tunnel
f	deflection of the FEM model
P	applied concentrated load in the FEM model
L	length of the FEM model

the complex structural characteristics of the lining of shield tunnels. Shiba et al. (1988) was the first to propose an analytical solution for the longitudinal bending stiffness, assuming that the tunnel lining, composed of segments and joints, can be approximated as a homogeneous continuous beam with constant cross section. Later on, Zhang et al. (2009) proposed a generalized longitudinal equivalent continuous model to include the effect of the bolts in the circumferential joints. Based on that, Li et al. (2014) expanded the model to include the elasto-plastic behavior of the bolts.

The literature shows that analytical solutions for the bending stiffness of shield tunnel liners, in the longitudinal direction, often assume that the liner is continuous along the axis of the tunnel (i.e. the liner is assumed as a rigid pipe without joints). There are two issues associated with this assumption: One is that the contribution of the transverse bending stiffness is neglected. The liner of shield tunnels, since it is composed of an assembly of segments and joints (i.e. both circumferential and longitudinal), is a three-dimensional structure and, thus, the longitudinal and the transverse stiffnesses of the liner are related to each other. Two, structural details such as rubber gaskets in the circumferential joints are not considered when computing the longitudinal stiffness. Rubber gaskets are one of the key components of the circumferential joints and should be included because of their contribution to the longitudinal deformation of the liner.

The aim of this paper is to address these two issues. That is, include in the formulation of the longitudinal stiffness the transverse stiffness of the liner and the structural details of the liner such as segments, bolts and rubber gaskets. Several assumptions are made to solve the problem: (1) the tunnel is assumed as a longitudinal equivalent continuous model that includes bolts, segments and rubber gaskets; (2) all the elements are assumed as linear elastic, with the bolts working only in tension and the rubber gaskets working only in compression; and (3) the deformation of any tunnel cross section is such that normals to the neutral axis

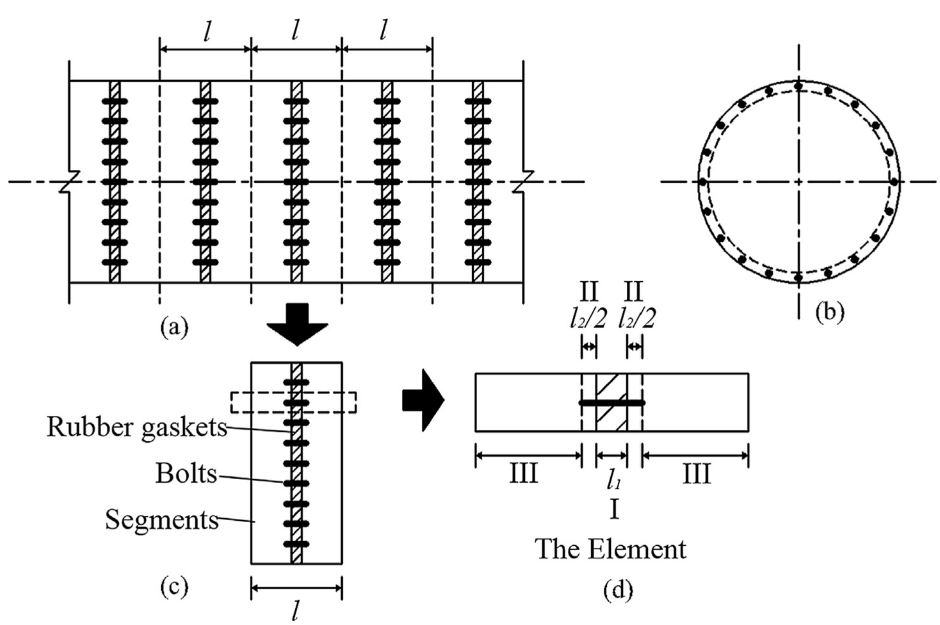

Fig. 1. Longitudinal model for the liner of shield tunnels: (a) assembly of rings or elements; (b) cross section of the tunnel; (c) element composition: segments, bolts and rubber gaskets; and (d) detail view of the same element composition in Fig. 1c.