Construction and Building Materials 175 (2018) 746–767

Contents lists available at ScienceDirect

Construction and Building Materials

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

Analytically-based simplified formulas for circular tunnels with two liners in viscoelastic rock under anisotropic initial stresses

Fei Song [a,b], Huaning Wang [a,c,*], Mingjing Jiang [c,d,e]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China
[b] Department of Geotechnical Engineering and Geo-sciences, Universitat Politècnica de Catalunya, Barcelona 08034, Spain
[c] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[d] Department of Civil Engineering, Tianjin University, Tianjin 300072, China
[e] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

HIGHLIGHTS

- A general analytical solution is proposed for circular tunnels with two liners in viscoelastic rock.
- The anisotropic initial stresses, any viscoelastic models and installation times of two liners can be considered.
- Analytically-based simplified formulas for final liner pressures and tunnel convergence are provided.
- A tunneling design method for the installation times of second lines is presented.

ARTICLE INFO

Article history:
Received 18 January 2018
Received in revised form 3 April 2018
Accepted 9 April 2018

Keywords:
Circular tunnel
Liner
Viscoelasticity
Analytical solution
Simplified formula

ABSTRACT

The time-dependency in tunneling is mainly due to the rheological properties of the rock and tunnel construction processes. Rock rheology results in tunnel convergence and pressures acting on the liners increase with time, both of which are critical parameters to be determined for tunnel and liner designs. In this study, a general analytical solution was derived and the simplified formulas were suggested based on the analytical results, which allow for the predictions of liner pressures and tunnel convergence. The anisotropic initial stresses and rock viscoelasticity, as well as the primary and secondary liners and their installation times were all accounted for.

The derivation procedure for generalized viscoelastic rock models was first provided by considering a circular tunnel under the anisotropic initial stress field supported by two elastic liners which were put in place at different times in plane strain conditions. The time-dependent analytical displacement and stress fields were proposed for the entire time stages, and these were consistent with the results from the numerical simulations and the measured data.

Then, based on a large amount of data obtained from analytical solutions, the simplified formulas were suggested by data fitting for the final liner pressures and tunnel convergence, when the rock could be simulated with the generalized Kelvin viscoelastic model. A high fitting precision was found to be evident through a comparison between the results from analytical and simplified formulas. The formulas in succinct form are the function of most of the relevant parameters of the rock and liners; for example, the shear moduli and viscosity of the rock, thicknesses and installation times of the second liner. However, they are only available to the three groups of first liner parameters, which are most commonly adopted in engineering. An application example was then provided to illustrate the application of simplified formulas for the determination of the installation times of the second liner.

1. Introduction

Most types of rock exhibit the rheological characteristics [1], which are known to induce gradual deformations over time, and occur even after the completion of underground excavations. The time-dependency in tunneling is mainly due to the rheological

* Corresponding author at: School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China.
E-mail address: wanghn@tongji.edu.cn (H.N. Wang).

https://doi.org/10.1016/j.conbuildmat.2018.04.079
0950-0618/

properties of the host rock, as well as the construction processes of tunnels. Supports, which are typically in the form of shotcrete liners or steel sets herein described as the primary support (first liner), are installed immediately after the excavations are completed to seal the rock and withstand the loads that may arise during the excavations [2]. The secondary support (second liner) are often put in place much later than the primary support to ensure the long-term stability of the tunnels [2,3]. The rock rheology results in an increase over time of the tunnel convergence and pressure which act on the liners, and are considered to be the critical parameters for the determinations of tunnel and liner designs. The parameters of the rock viscosity, installation time, and stiffness of the two liners, strongly affect the fields of displacement and stress in the rock and liners. Therefore, a proper simulation of the entire process of excavation and support installation is crucial to obtain a reliable tool for the determination of the optimal values of the tunneling parameters, and to achieve optimal designs [4,5].

A convergence-confinement method [3,6,7] provides an efficient way for determining liner pressures by considering the rock-liner interactions. The pressure can be achieved by the intersection between the convergence and confinement curves, where the convergence curve quantifies the tunnel convergence as a function of the internal pressure. Meanwhile, the confinement curve quantifies the pressure taken by the supports when the tunnel wall converges. Although this method has been used in tunnel designs which consider the elasto-plastic [3,8,9], viscoelastic [10], and viscoelasto-plastic [11] of the host rock, it is only valid for circular tunnels with a single liner which are subjected to isotropic initial stress.

Numerical methods have been widely used in the analysis of lined tunnels, with consideration given to more complex geological conditions [12–15]. Although numerical methods can provide some useful results, they require long run-times, especially when complete parametric analyses need to be performed. As an alternative, analytical solutions can be used to quickly obtain a first estimation of the design parameters, and provide guidance in the primary stages of the design processes. These solutions make it possible to run parametric investigation for a wide range of parameter values in order to better understand the mechanical behavior. The insights into the nature of the problems which can be gained from analytical solutions are important aspects which should not be overlooked [16].

In regards to the rock-liner interactions, many analytical solutions have been developed for lined circular tunnels constructed in elastic or viscoelastic surrounding rock. By using complex variable methods, and assuming that the rock is elastic, the analytical solutions for the stress and displacement around a lined circular tunnel were achieved by Li and Wang [17,18]. By introducing a relaxation factor to account for the initial stress relief prior to the installations of the liners, an elastic solution was proposed for circular tunnels with a single liner [19,20]. Unlike the linear elastic materials with algebraic constitutive equations, linear viscoelastic materials have their constitutive relations expressed by a set of operator equations. Since it is very difficult to obtain analytical solutions for complex viscoelastic problems, most of the solutions presented in the current references were derived for circular tunnels with single liners which were subjected to isotropic initial stresses (axisymmetric problems) [21–24]. Sulem et al. [21] presented analytical solutions for axisymmetric problems in order to determine the radial displacements and pressures applied on tunnel liners by describing the surrounding rock as a Kelvin-Voigt model. Fahimifar et al. [23] provided an analytical solution using the correspondence principle to predict the time-dependent tunnel convergence, which accounted for the effects of the tunnel advancement, along with a Burger model of the rock. By assuming the Burger's viscoelastic model of the rock around an axisymmetric tunnel with one elastic liner, solutions for stresses and displacements were derived by Nomikos et al. [24], and a parametric study was also performed to investigate the effects of the liner parameters. Lo and Yuen [25] provided solutions for circular tunnels subjected to an anisotropic initial stress state by accounting for the viscoelasticity of the rock, as well as the liner installation time. However, these solutions were for tunnels with a single liner.

Naggar, Hinchberger and Lo presented a closed-form solution for tunnels with composite liners in an infinite elastic medium [26]. In the aforementioned study, the partial gap prior to the liner installation, as well as the two interface conditions between the first and second liner, were considered. Mason and Abelman [27] investigated the two-liner system provided to a circular tunnel which was subjected to a uniform shear at infinity, and the elastic analytical solutions were proposed. In these references, the liners were assumed to be instantaneously installed at the end of the excavation. In reality, they may be installed at any time after the excavation in the tunnel is complete, which is the case considered in this study. Recently, analytical solutions were provided by Wang et al. [4,5] for circular tunnels with two/n-liner systems, where the rock rheology, excavation process, and liner installation times were all accounted for. However, the solutions are applicable only to axisymmetric tunnels where the isotropic initial stresses were considered.

The in-situ stress measurements and observations have shown that the initial stresses are generally anisotropic. Therefore, in order to achieve the analytical solutions applicable for more general conditions in tunnel designs, the following should be considered: (1) an anisotropic initial stress state; (2) rheology properties of the host rock; (3) primary and secondary liners and (4) times of liner installation, all of which are accounted for in this study. For deeply buried circular tunnels supported by two liners, the analytical solutions for the stress and displacement fields in the host rock and liners will be first derived for the all the time stages, where the unified viscoelastic models will be adopted to simulate the rheology of different rocks. Then, based on the large amount of data obtained by the analytical solutions for the rock which is assumed as a generalized Kelvin viscoelastic model, the succinct simplified formulas for the final liner pressures and tunnel convergence will be proposed for the purpose of easy use in engineering. An application example will be provided to illustrate the application of the simplified formulas presented in this study.

2. Statement of the problem

This study considers the deeply buried circular tunnels in the rheological rock where two liners have been sequentially installed. Throughout the analyses, the following assumptions are made:

(1) The surrounding rock is homogeneous and isotropic, and its rheology could be described as linear viscoelasticity;
(2) The tunnel is deeply buried, and therefore no linear variations of the stresses with depth are considered. The initial stress field around the tunnel is idealized as p_0 for the vertical pressure, and λp_0 for the horizontal pressure, where λ is a ratio of the horizontal over vertical stresses;
(3) The liners are assumed as linearly elastic. The primary (first) and secondary (second) liners are instantaneously installed at $t = t_1$ and t_2, respectively. No-slip conditions are considered between rock and the first liner, and the first and second liners;
(4) The excavation is slow enough that it may be assumed that it does not induce any dynamic stress.

The analysis of the distribution of the stresses and displacements near the longitudinal tunnel face is a three-dimensional