International Journal of Rock Mechanics & Mining Sciences 68 (2014) 85–106

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

An analytical approach for the sequential excavation of axisymmetric lined tunnels in viscoelastic rock

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ARTICLE INFO

Article history:
Received 20 February 2013
Received in revised form
21 November 2013
Accepted 3 February 2014
Available online 25 March 2014

Keywords:
Sequential excavation
Tunnel construction
Rheological
Liner
Analytical solution

ABSTRACT

The main factors for the observed time dependency in tunnel construction are due to the sequence of excavation, the number of liners and their times of installation and the rheological properties of the host rock. A generalized derivation procedure for any viscoelastic model is presented accounting for the sequential excavation of a circular tunnel supported by any number of liners of different thicknesses and stiffnesses installed at different times in a viscoelastic surrounding rock under a hydrostatic stress field under plane strain axisymmetric conditions. Sequential excavation was accounted for assuming the radius of the tunnel growing from an initial value to a final one according to a time-dependent function to be prescribed by the designer. The effect of tunnel advancement was also considered. For the generalized Kelvin viscoelastic model, explicit analytical closed form solutions were presented, which can be reduced to the solutions for the Maxwell and Kelvin models.

An extensive parametric analysis was then performed to investigate the effect of the excavation process adopted, the rheological properties of the rock, stiffness, thickness and installation times of the liners on tunnel convergence, pressure on the liners and on the stress field in the rock for a support system made of three liners. Several dimensionless charts for ease of use of practitioners were provided.

1. Introduction

Numerical methods such as finite element, finite difference and to a lesser extent boundary element are routinely used in tunnel design. However, full three-dimensional (3D) analyses for an extended longitudinal section of a tunnel still require long runtimes, so that the preliminary design and most of the design choices are made on the basis of simpler analytical models [1]. In fact, analytical solutions are employed as a first estimation of the design parameters also providing guidance in the conceptual stage of the design process. Parametric sensitivity analyses for a wide range of values of the input parameters of the problem are run based on them. In addition, they provide a benchmark against which the overall correctness of subsequent numerical analyses is assessed.

The main factors for the observed time dependency in tunnel construction are due to the rheological properties of the host rock [2], the sequence and speed of excavation [3,4] and the time of installation of the liners [5]. The analytical solution derived in this paper accounts for all the three aforementioned aspects.

Concerning the first factor, most types of rocks exhibit time-dependent behavior [1], which typically continues well after the end of the excavation process. In case of sequential excavations, the observed time-dependent tunnel convergence also depends on the interaction between the prescribed steps of excavations and the natural rock rheology. After excavation, support is provided to the underground opening to reduce tunnel convergence with concrete or shotcrete liners widely employed for tunnels in rock masses. The time of installation of the liners heavily affects the observed displacements of the surrounding rock and the pressure arising between liner and rock mass which are both critical parameters for tunnel design [5]. A full analysis of the construction sequence of tunnels including the

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http://dx.doi.org/10.1016/j.ijrmms.2014.02.002
1365-1609

entire process of excavation and installation of the supports is paramount to obtain an engineering model to be used as a reliable design tool to determine the optimal design solutions.

In this paper, the rock rheology is accounted for by linear viscoelasticity. The so-called (according to the traditional terminology of rock mechanics [6,7]) Kelvin, Maxwell and generalized Kelvin models will be considered. Unlike the case of linear elastic materials with constitutive equations in the form of algebraic equations, linear viscoelastic materials have their constitutive relations expressed by a set of operator equations. In general, it is very difficult to obtain analytical solutions for most of the viscoelastic problems, especially in case of time-dependent boundaries, although some closed-form or theoretical solutions have been developed for excavations in rheological rock [8–10]. However, in all these works the excavation is assumed to take place instantaneously, i.e. the process of excavation in the tunnel cross-section is ignored and only the longitudinal advancement of the tunnel face is considered, typically by introducing a fictitious lining pressure so that the problem can be mathematically cast as a fixed boundary problem. Sequential excavation is a technique becoming increasingly popular for the excavation of tunnels with large cross-section in several countries [3,11]. For instance, tunnels of 200 km, along the new Tomei and Meishin expressways in Japan, have been built via the so-called center drift advanced method. In this method, first a central pilot tunnel much smaller than the final cross-section is excavated, typically by a tunnel boring machine (TBM), then the tunnel is subsequently enlarged either by drilling and blasting or TBM to its final cross-section before the first liner is installed [11,12]. This sequential excavation technique has been adopted by the Japanese authorities “as the standard excavation method of mountain tunnels” [13]. In several other cases of sequential excavation, the enlargement of the cross-section to its final size occurs before the installation of the first liner [3]. The analytical solution presented in this paper accounts for any time dependent excavation process employed to excavate the tunnel cross-section. Many problems of linear viscoelasticity can be solved using the principle of correspondence [14–16]. However, the cross-section of a tunnel is excavated in stages, which implies a time-dependent geometrical domain, so that the principle of correspondence cannot be employed.

Concerning the geomaterial–liner interaction, many analytical solutions have been developed for circular tunnels in elastic or visco-elastic surrounding rock [17–20]. Assuming an isotropic stress state and a viscoelastic Burgers' model for the rock, Nomikos et al. [21] derived analytical solutions in closed form and performed a parametric study on the influence of the liner parameters on tunnel convergence and the mechanical response of the host rock. Different supports such as sprayed liners, two liners system and anchor-grouting support, were analyzed by Mason [23–25]. Liners were assumed to be instantaneously applied at the end of the excavation. In the tunnel practice, however, liners may be installed at any time after excavation, which is the case considered in this paper.

Supports made of two liners are very popular. However, in several recent tunnels, concrete was sprayed onto the excavation walls in steps at various times [23,26] so that it becomes convenient to analyze the support system as a system made of n liners. Moreover, composite liners containing several rings of different materials can be analyzed conveniently as a system of several liners [24].

In this paper, an analytical formulation for the stress and displacement fields in the host rock and in the liners has been derived accounting for sequential excavation for lined circular tunnels excavated in viscoelastic rock (generalized Kelvin model with the Maxwell and Kelvin models as particular cases) and supported by any number of elastic liners installed at various times. The work presented here is applicable to a general support system made of n liners; therefore it is a substantial generalization of the analysis of a two-liner support system presented in [27]. Moreover, the effect of various excavation rates, along both the radial and the longitudinal directions of the tunnel, on the response of the support system has been investigated for the first time. The tunnel face effect was considered by applying a fictitious internal pressure as in [20].

Although the obtained analytical solutions are rigorously applicable only to the axisymmetric case, i.e., a single deeply buried tunnel, Schuerch and Anagnostou [28] demonstrated that solutions achieved for axisymmetric conditions are still valid for a wide range of different ground conditions and for several cases of noncircular tunnels despite a small error being introduced.

Then a parametric study has been performed for the case of a three-liner support in order to investigate the influence of the viscoelastic rock parameters, the excavation process, shear modulus, thickness and installation time of each liner on radial convergence and support pressure. Several charts of results have been plotted for the ease of use of practitioners.

2. Assumptions and definition of the problem

The excavation of a circular tunnel in rheological rock lined with a number n of liners set in place at various times is considered in this paper. To derive the analytical solution, the following assumptions were made:

(1) The tunnel is of circular section. The surrounding rock is homogeneous, isotropic and with its rheology suitably described by linear viscoelasticity. The tunnel is deeply buried and subject to a hydrostatic state of stress.
(2) The tunnel excavation is sequential, i.e. the tunnel radius grows from an initial value to a final one. Then liners are installed in sequence.
(3) The speed of excavation is small enough so that no dynamic stresses are ever induced.

Regarding the simulated sequential excavation, it was assumed that the tunnel radius varies over time from an initial value R_{ini}, at time $t=0$, to a final radius R_{fin}, at time $t=t_0$. Then support is provided to the opening by installing the first liner instantaneously. The construction process can be divided into the following $(n+1)$ stages: (1) excavation stage, spanning from time $t=0$ until the time of installation of the first liner, at $t=t_1$, with $t_1>t_0$. From $t=0$ to $t=t_0$, the cross-section of the tunnel is excavated sequentially. During the time interval between t_0 and t_1, pressure is released from the rock before any support is put in place. (2) First liner stage, spanning from time t_1 to the time of installation of the second liner, $t=t_2$. When the first liner is put in place, at $t=t_1$, $p_1(t)$ is the contact pressure between rock and the first liner which will change in the successive stages due to the installation of the successive liners. (i) i-th Liner stage, spanning from time t_i to the time of installation of the $i+1$-th liner, $t=t_{i+1}$. When the i-th liner is put in place, at $t=t_i$, $p_i(t)$ is the contact pressure between the $(i-1)$-th liner and the i-th liner. (ii) n-th Liner stage, spanning from time $t=t_n$ onwards (until $t=\infty$). When the n-th liner is installed, $p_n(t)$ is the pressure between the $(n-1)$-th and the n-th liner.