Tunnelling and Underground Space Technology 71 (2018) 62–80

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Analysis of time-dependent deformation in tunnels using the Convergence-Confinement Method

Chrysothemis Paraskevopoulou[a,*], Mark Diederichs[b]

[a] School of Earth and Environment, University of Leeds, Leeds, UK
[b] Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada

ARTICLE INFO

Keywords:
Long-term behaviour
Time-dependency
Creep
Visco-elastic parameters

ABSTRACT

During the excavation of a tunnel the accumulated wall displacement and the loading of tunnel support is the result of both the tunnel advance (round length and cycle time) and the time-dependent behaviour of the surrounding rock mass. The current approach to analyze the tunnel wall displacement increase is based on the Convergence-Confinement Method (CCM) performed with either analytical (closed form solutions) or the usage of the Longitudinal Displacement Profiles. This approach neglects the influence of time-dependency resulting in delayed deformation that may manifest even minutes or hours after excavation. Failure to consider the added displacements in the preliminary design can result in false selecting the time of installation and the type of support system causing safety issues to the working personnel, leading to cost overruns and project delivery delays. This study focuses on investigating and analyzing the total displacements around a circular tunnel in a visco-elastic medium by performing an isotropic axisymmetric finite difference modelling, proposing a new yet simplified approach that practitioners can use taking into account the effect of time.

1. Introduction

Understanding the nature and origin of deformations due to an underground opening requires, as Panet (1993) noted, both knowledge of the rock-support interaction and interpretation of field data. Monitoring and measurement of tunnel wall displacements has shown that deformation initiates during excavation and may continue long after the tunnel construction is completed. This tunnel wall movement, also known as convergence, is the result of both the tunnel face advancement and the time-dependent behaviour of the rock mass. Many researchers (Fenner, 1938; Parcher, 1964; Lombardi, 1975; Brown et al. 1983; Corbetta et al. 1991; Duncan-Fam, 1993; Panet, 1993, 1995; Peila and Oreste, 1995; Carranza-Torres and Fairhurst, 2000; Alejano et al. 2009; Vrakas and Anagnostou, 2014; Cai et al. 2015; Cui et al. 2015 etc.) have studied the interaction between the rock mass and the applied support. They have proposed various methodologies that are commonly used as a preliminary tool for quickly assessing the system behaviour (between the surrounding rock mass and support) during both the design and construction process of underground projects (Gschwandtner and Galler, 2012). In addition, most of these solutions are based on the well-known and widely used Convergence-Confinement Method (CCM). CCM is a two-dimensional simplified approach that can be used to simulate three-dimensional problems as the rock-support interaction in tunnels. More specifically, CCM is widely utilized to estimate the required load capacity of the proposed support system. The traditional approach of this methodology involves the Ground Reaction Curve and the Longitudinal Displacement Profile that when used in combination with the Support Characteristic Curve (SCC) they provide information on the required support load in regards to the tunnel face location as a percentage of the anticipated maximum tunnel wall displacement. Gschwandtner and Galler (2012) suggested a new approach for using the CCM while considering the time-dependent material of the support by investigating different support scenarios of rockbolts and shotcrete, investigating how the behaviour of the support system changes over time. However, even the more commonly applied simplified formulations of CCM do not explicitly capture the time-dependent component of rock mass deformation. Time-dependent closure, for instance due to creep, can have a significant impact on support loading. Failure to account for these additional loads and deformations can result in unexpected failures, causing safety issues for the working personnel, leading to cost overruns and project delivery delays (Paraskevopoulou and Benardos, 2013). Questions of the applicability of such methods when dealing with time-dependent rheological rock-masses are addressed in this paper by investigating the total observed displacement on tunnel walls in an isotropic visco-elastic medium, taking into consideration both the tunnel advancement and cumulated

* Corresponding author.
E-mail address: c.paraskevopoulou@leeds.ac.uk (C. Paraskevopoulou).

http://dx.doi.org/10.1016/j.tust.2017.07.001
Received 23 November 2016; Received in revised form 21 June 2017; Accepted 4 July 2017
0886-7798/

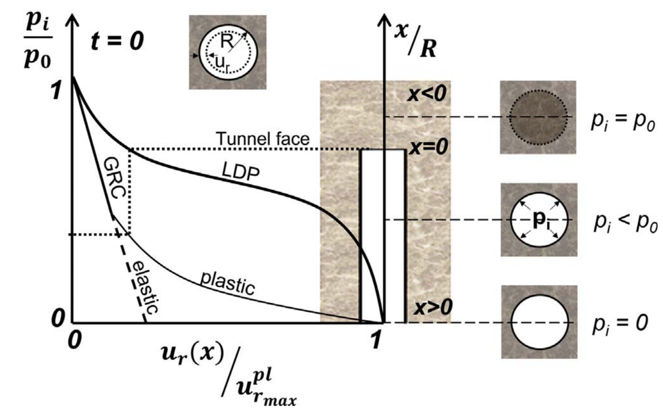

Fig. 1. The Ground Reaction Curve response of an elasto-plastic material and its relation to the LDP. Y-axis on the left refers to the internal pressure (p_i) normalized to the in-situ pressure (p_0), Y-axis on the right refers to the distance from the face (x) normalized to the tunnel radius (R) and X-axis refers to the radial displacement at a location x normalized to the maximum radial displacement.

deformation due to the rheological behaviour of the material over time.

1.1. Ground Reaction Curve (GRC) and Longitudinal Displacement Profile (LDP) calculations

An important component of the CCM method is the Ground Reaction Curve (GRC). This is a characteristic line that records the decrease of an apparent (fictitious) internal (radial) support pressure, from the in situ pressure to zero when considering the unsupported case of a circular tunnel after excavation. This pressure reflects the tunnel excavation process as the tunnel is being excavated (out-of-section) past the section of interest and continues to be excavated beyond the reference position (usually the location of the tunnel face) as shown on the right part of Fig. 1. The internal pressure (p_i) acts radially on the tunnel profile (from the inside) and represents the support resistance needed to hinder any further displacement at that specific location (Vlachopoulos and Diederichs, 2009). In reality, this pressure represents an idealized sum of the contribution of the nearby unexcavated tunnel core (surrounding rock mass) and any applied support installed and is zero for a fully excavated unsupported tunnel. The GRC depends on the rock mass behaviour. It is assumed to be linear for an elastic material but it varies if the material is elasto-plastic or visco-elastic etc. Many researchers have studied the GRC responses of different materials. For example, Brown et al. 1983; Alejano et al. 2009; Wang et al. 2010; González-Cao et al. 2013 have proposed analytical solutions for strain-softening rock masses based on different GRCs. Vrakas (2017) proposed a finite strain semi-analytical solution for the ground response problem of a circular tunnel in elasto-plastic medium with non-linear strength envelopes. Panet (1993) gives examples of GRCs of the most used visco-elastic models that are discussed in Section 2.2.

For elastic or moderately yielding rock masses approximately one third of the total displacement is observed at the tunnel face (Hoek et al., 2008) shown as x = 0 on the right hand axis of Fig. 1. The deformation initiates in front of the face ($x < 0$), usually one to two tunnel diameters ahead of the face, and reaches its maximum magnitude at three to four tunnel diameters away from the face inside the tunnel ($x > 0$).

A Longitudinal Displacement Profile (LDP) of the tunnel closure is a

Table 1
Analytical solutions for LDP calculation depending on the medium.

Reference	Analytical Solution	Medium Behaviour
Pane and Guenot (1982)	$\frac{u_r}{u_{max}} = 0.28 + 0.72[1 - (\frac{0.84}{0.84 + x/R})^2$	Elasto-Plastic
Corbeta et al. (1991)	$\frac{u_r}{u_{max}} = 0.29 + 0.71[1 - \left(-1.5(x/R)^{0.7}\right)]$	Elastic
Panet (1993, 1995)	$\frac{u_r}{u_{max}} = 0.25 + 0.75[1 - \left(\frac{0.75}{0.25 + x/R}\right)^2]$	Elastic
Chern et al. (1998)	$\frac{u_r}{u_{max}} = [1 + exp\left(\frac{-x/R}{1.1}\right)^{-1.7}]$	Elasto-plastic
Unlu and Gercek (2003)	$\frac{u_r}{u_{max}} = \frac{u_o}{u_{max}} + A_a(1 - e^{B_a(x/R)}),\quad x/R \le 0$ $\frac{u_r}{u_{max}} = \frac{u_o}{u_{max}} + A_b[1 - ((B_b + (x/R))^2],\quad x/R \ge 0$ $\frac{u_o}{u_{max}} = 0.22v + 0.19,\quad x/R = 0$ $A_a = -0.22v + 0.19 \quad B_a = 0.73v + 0.81$ $A_b = -0.22v + 0.81 \quad B_b = 0.39v + 0.65$	Elastic
Vlachopoulos and Diederichs (2009)	$\frac{u_r}{u_{max}} = \frac{u_o}{u_{max}} e^{x/R},\quad x/R \le 0$ $\frac{u_r}{u_{max}} = 1 - (1 - \frac{u_o}{u_{max}})e^{(-3x/R)/(2r_p/R)},\quad x/R \ge 0$ $\frac{u_o}{u_{max}} = \frac{1}{3}e^{-0.15(r_p/R)},\quad x/R = 0$ r_p − plastic radius	Elasto-plastic