Tunnelling and Underground Space Technology 77 (2018) 59–67

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Reliability of tunnel lining design using the Hyperstatic Reaction Method

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A R T I C L E I N F O

Keywords:
Tunnel
Tunnel lining
Soil/structure interaction
Reliability analysis
Direct coupling
FORM
Monte Carlo simulation
Limit state design
Hyperstatic Reaction Method

A B S T R A C T

The reliability analysis of tunnel linings is a challenging task, due to the complex nature of soil-structure interactions, and due to the large uncertainty in soil properties and soil-structure interaction parameters. Usually, numerical models are employed to properly describe structural geometry and soil-structure interactions, rendering reliability solutions computationally expensive. In the past, tunnel reliability was addressed by local point estimate methods, which are very economical in the number of points where the numerical solutions are computed, but which can be quite inaccurate. More recently, surrogate modelling techniques have been employed to alleviate the computational burden, producing global response approximations. In this paper, an alternative procedure is proposed, which consists in the direct coupling between mechanical and reliability solution algorithms. Such direct coupling is viable because the very efficient Hyperstatic Reaction Method is employed to model the soil-structure interactions. Typical concrete tunnel lining is addressed. Solutions are computed for several failure modes of the tunnel lining, also considering that failures can occur at any point along the tunnel perimeter. Solutions for individual failure modes are computed by FORM, and system reliability is computed by different Monte Carlo simulation techniques.

1. Introduction

Evaluation of ground pressure is one of the major issues to be addressed in the design of tunnels. The problem is not easy to address due to uncertainties in soil parameters and in the interaction between tunnel lining and surrounding soil mass (Takano, 2000; Han et al., 2017). The pressure acting on the tunnel lining can be calculated using different methods, which can be categorized in four groups: empirical and semi-empirical methods, ring and plate models, and numerical models (Kim and Eisenstein, 1998). These methods have been reviewed in detail by a number of authors (Deddeck and Erdmann, 1985; Kim and Eisenstein, 1998; Takano, 2000).

Ground pressure surrounding tunnels arises from vertical and horizontal components. The horizontal pressure is usually derived from the vertical pressure, multiplied by a lateral ground pressure coefficient. It is hence very important to correctly evaluate vertical pressures.

Ground pressure models considering the existence of elastic reaction springs around the tunnel lining, but neglecting vertical pressures at the lower part of the tunnel, were developed by Deddeck and Erdmann (1985); Takano (2000) and Oreste (2007). Do et al. (2014b) considered the active upward pressure at the lower half of the tunnel, by comparing Einstein and Schwartz's (1979) analytical method with numerical results obtained by finite differences, using the FLAC3D software. The presence of active upward pressures was also considered by Mashimo and Ishimura (2003), using beam-spring models.

Following Blom (2002), the vertical ground loads at the lower part of the tunnel should take into account the weight of the tunnel. Since inside the tunnel there is no soil, it is frequently assumed that the dead weight of the tunnel lining itself has an insignificant effect and can be ignored. The upward ground pressures are therefore reduced at the lower half of the tunnel lining.

Obviously, there are significant uncertainties in evaluating active pressures acting on the tunnel lining. These uncertainties arise from random soil parameters, as well as from uncertain soil-structure interaction parameters. By modelling uncertain soil parameters as random variables, the reliability of tunnel lining design in the ultimate limit state is analysed in this paper. Tunnel lining reliability is evaluated w.r.t. overburden thickness, using the first order reliability method, as well as different Monte Carlo simulation methods.

A review of the literature reveals a handful of papers dealing with different aspects of tunnel reliability. Some early papers (Rosenblueth, 1975; Hong, 1998; Zhao and Ono, 2000) advocated use of point estimate methods to evaluate the probability of wall convergence of circular tunnels and face stability of shallow tunnels. More recently, Napa-

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https://doi.org/10.1016/j.tust.2018.03.028
Received 27 November 2017; Received in revised form 22 March 2018; Accepted 24 March 2018

García et al. (2017a) showed that such point estimate methods are potentially inaccurate; increasing the accuracy requires higher-order moment methods, which are more expensive to compute. Hence, in general, point estimate methods should not be used for geotechnical reliability analysis (Napa-García et al., 2017a).

The reliability of tunnels excavated in fractured rock masses was addressed in a number of more recent papers: Low and Einstein (2013) and Liu and Low (2017) address roof wedge formations and rock-bolt reinforcements; Zhang and Goh (2012) addressed ultimate and serviceability limit states of rock caves; Napa-García et al. (2017b) addressed the problem of block falls as a distributed system over tunnel length.

Due to complex nature of tunnel lining interactions with the surrounding media, numerical analysis is employed nowadays, making reliability analysis computationally expensive. To alleviate the computational burden, surrogate modelling has been employed extensively in tunnel reliability studies. Response surfaces were employed by Mollon et al. (2009); Zhang and Goh (2015); Lü et al. (2017a) and Hamrouni et al. (2017); Support Vector Machines were employed by Zhao et al. (2014), Radial Basis Functions by Wang et al. (2016), Multivariate Adaptive Regression Splines were employed in Zhang and Goh (2013) and Goh et al. (2017); logarithmic regression models by Zhang and Goh (2016); and Moving Least Squares were employed by Lü et al. (2017b).

In contrast to the above references, this paper proposes the reliability analysis of tunnel linings, considering soil-structure interactions, by so-called direct coupling (Sudret and Der Kiureghian (2000); Leonel et al., 2011; Napa-García et al., 2014) between finite element and reliability analysis software. Because the Hyperstatic Reaction Method is employed, solutions are sufficiently fast to compute, even for crude Monte Carlo simulation with a moderate number of samples. Multiple limit states are considered, w.r.t. bending moment, axial and shear strength of the concrete lining, whose maximum values can occur at any point around the tunnel perimeter. Reliability indexes for individual failure probabilities are evaluated by FORM, and series system reliability is evaluated by different Monte Carlo simulation techniques.

As pointed out in the above literature review of applications of reliability analysis to geotechnical engineering problems, the majority of authors take the surrogate modelling approach, where the response of expensive numerical models is replaced by simpler, analytical surrogates. In this paper we address an alternative scheme, which is the so-called direct coupling approach. This nomenclature “direct coupling” is not evident in the literature because in other areas (structural analysis, for instance), direct coupling approach is the rule, and surrogate modelling is adopted eventually. Moreover, to the best of the authors knowledge, this is the first time that reliability analysis of tunnels is made using the Hyperstatic Reaction Method.

The remainder of this paper is organized as follows. The Hyperstatic Reaction Method is presented in Section 2. Problem formulation is addressed in Section 3, which also briefly described the reliability analysis techniques employed in the paper. Numerical results are presented and discussed in Section 4. Concluding remarks are presented in Section 5.

2. The hyperstatic reaction method

The Hyperstatic Reaction Method (HRM) is a numerical method particularly suitable for the design and analysis of tunnel lining (Fig. 1). The method requires definition of the active loads that act directly on the support structure. Passive reactive loads are developed in those sections where the tunnel lining moves toward the surrounding ground.

In the HRM method, the tunnel lining is represented by one-dimensional beam elements (Fig. 2), which can estimate bending moments, axial and shear forces (Oreste, 2007). The ground interacts with the tunnel lining in two ways: through the applied active loads (q_v and q_h) and through the normal and tangential springs connected to the nodes of the structure (Fig. 1).

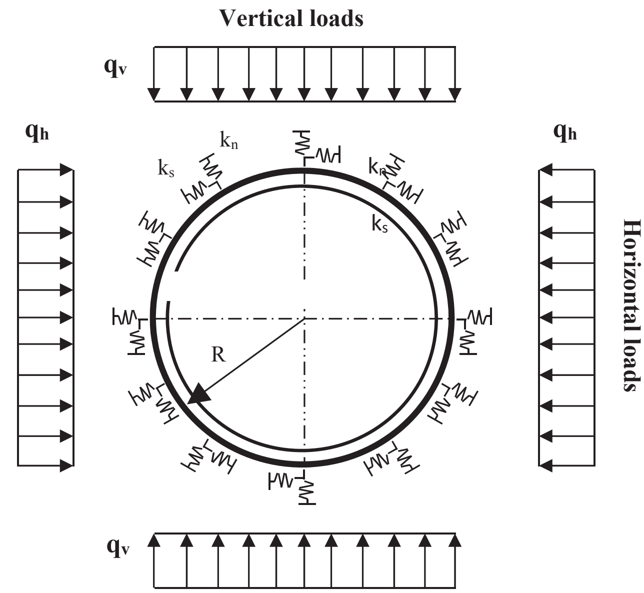

Fig. 1. Scheme of tunnel lining, with active vertical and horizontal loads, following the hyperstatic reaction method. Key: q_v: vertical load; q_h: horizontal load; k_n: normal stiffness of the interaction springs; k_s: tangential stiffness of the interaction springs; R: tunnel radius; E_sJ_s and E_sA_s: bending and normal stiffness of the lining (Oreste, 2007; Do et al., 2014a).

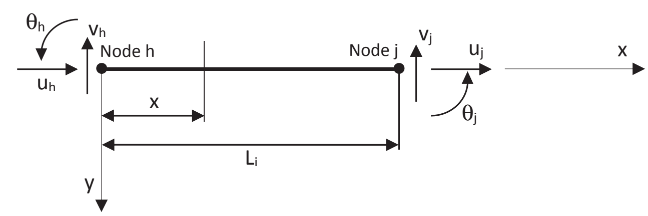

Fig. 2. Scheme of beam-type finite element with reference to local Cartesian coordinates. Key: h: initial node; j: final node; u: axial displacement; v: transverse displacement; θ: rotation; x and y: local Cartesian coordinates (Oreste, 2007).

The global stiffness matrix **K** is obtained by assembling the local stiffness matrices of each single element, which already account for the stiffness of normal and tangential springs. The vector of unknown displacements $\boldsymbol{u}$ is evaluated as:

$$\mathbf{K}\boldsymbol{u} = \mathbf{F} \tag{1}$$

where **F** is the force vector. Once nodal displacements are known, strains and stresses can be computed at every node of the structure (Huebner et al., 2001). Stresses are integrated over the cross-section resulting in internal forces and moments.

2.1. Ground-support interaction

The interaction between ground and the tunnel lining occurs in two ways: through the normal springs and tangential springs connected to the nodes of the structure and through the active loads.

Depending on the stiffness of normal and tangential springs, passive loads acting on the tunnel lining can change. Oreste (2007) introduced a non-linear (hyperbolic) relationship between reaction pressure p and support deformation δ:

$$p = p_{\lim}\left(1 - \frac{p_{\lim}}{p_{\lim} + \eta_0\delta}\right) \tag{2}$$

where $p_{\lim}$ is the maximum reaction pressure that the ground can offer