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Behaviour of segmental tunnel linings under seismic loads studied with the hyperstatic reaction method

Ngoc-Anh Do [a,d], Daniel Dias [b,*], Pierpaolo Oreste [c], Irini Djeran-Maigre [d]

[a] Hanoi University of Mining and Geology, Faculty of Civil Engineering, Department of Underground and Mining Construction, Hanoi, Vietnam
[b] Grenoble Alpes University, 3SR Laboratory, 38041 Grenoble Cedex 9, France
[c] Politecnico of Torino, Department of Environmental, Land and Infrastructural Engineering, Italy
[d] University of Lyon, INSA of Lyon, Laboratory LGCIE, Villeurbanne, France

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ABSTRACT

This paper proposes a numerical procedure, named hyperstatic reaction method, that can be used for the analysis of segmental tunnel linings under seismic loads. The effects of seismic loads are taken into account by means of in-plane shear stress. The parameters that are necessary to calculate the tunnel lining under seismic loads are presented. A specific implementation has been developed using a finite element framework. The results deduced from the hyperstatic reaction method have been compared and validated with those obtained by means of a finite difference numerical model using $FLAC^{3D}$. A parametric study, which allows the effects of seismic magnitude, tunnel dimension and segmental joints on the seismic-induced bending moment and normal forces to be shown, has been performed.

1. Introduction

Understanding the behaviour of underground structures during seismic events is one of the most interesting challenges in geotechnical engineering. Despite the multitude of studies that have been carried out over the years, the dynamic response of underground structures is still far from being fully understood. Consequently, current engineering practice lacks conclusive information that may be used in the design of tunnel lining structures.

Generally, the impact of seismic loads on tunnels can be taken into consideration through full dynamic analysis or quasi static analysis. Full dynamic analysis, which is also called time history analysis, represents the most complex level of seismic analysis, and, as a result, it is also the most precise method. This type of analysis is generally conducted using a numerical tool. In Do et al. [1], a comparison between a full dynamic time-history analysis and pseudo-static methods has been made using a linear soil behaviour. The results indicated that the pseudo-static analysis gives results that are in good agreement with those predicted by the full dynamic analysis, when a low seismic excitation is considered (maximum acceleration of 0.0035 g). However, pseudo-static analysis is inadequate, under the impact of a high dynamic excitation (maximum acceleration of 0.35 g), in determining the normal forces and bending moment induced in a tunnel lining. It has been suggested that an equivalent static solution could yield smaller structural lining forces than those of a full dynamic solution. However, full dynamic analysis is not economic, due to the long calculation time that is necessary [1]. This is why the application of full dynamic analysis is still limited. The recently common trend is to use pseudo-static analysis techniques with analytical methods (e.g., [2–5]) or numerical analyses (e.g., [6,7]).

The implementation of tunnel response analysis using the quasi static approach can be grouped into two approaches: (1) the deformation based method and (2) the force based method. The deformation based method, which is described in detail in Hashash et al. [8], is based on the calculation of the shear strain due to earthquakes at a tunnel depth and then applying this strain to the tunnel structure. The force based method instead usually assumes that the earthquake loads are caused by the inertial forces from the surrounding ground. The additional inertial force is equal to the product of the seismic coefficient, related to the peak ground acceleration, and the weight of the element in the model. While the deformation based method is developed in both analytical solutions (e.g., [2–5]) and numerical analyses (e.g., [6,8,9]), the application of the force based method to tunnels is usually carried out using commercial software (e.g., [10,11]).

* Corresponding author. Tel.: +33 456520994.
E-mail address: daniel.dias@ujf-grenoble.fr (D. Dias).

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In order to use the force based method in an analytical model, it is necessary to estimate the dynamic loads that act on the tunnel structure. One procedure that is commonly used to determine the increase in lateral earth pressure under seismic circumstance is the Mononobe–Okabe method (Hashash et al. [8]). However, the Mononobe–Okabe method was originally developed for aboveground earth retaining walls, assuming that the retaining wall yields sufficiently to develop minimum active and maximum passive earth pressure. Obviously, the behaviour of a tunnel and that of a retaining wall structure under dynamic conditions are not similar in many cases.

The component that has the most significant influence on the behaviour of a tunnel lining under seismic loads, except for the case of a tunnel sheared by a fault, is the ovaling or racking deformation generated by seismic shear or S-wave propagation (Hashash et al. [6], Peinzen [12]). Wang [5] suggested two separate load schemes for rectangular tunnels: a pseudo-static concentrated force for deep tunnels, and a pseudo-static triangular pressure for shallow tunnels. However, this kind of cross-section shows different behaviour from that of the circular tunnel studied in this paper, under seismic loads.

As far as circular tunnels are concerned, El Naggar et al. [13] developed a closed-form solution for moments and thrusts in a jointed composite tunnel lining, on the basis of external load scheme that was proposed by Peinzen and Wu [3], which is also used in this study. This solution has been adapted to evaluate the effect of in-plane shear stresses induced by ovaling deformation.

This paper has the aim of proposing the use of a numerical procedure to the hyperstatic reaction method (HRM) in order to analyse of segmental tunnel linings exposed to seismic loads. This method has been developed on the basis of the HRM that was proposed by Oreste [14], and then developed by Do et al. [15,16]. Seismic loads are determined on the basis of in-plane shear stresses which were introduced in the works of Peinzen and Wu [3] and El Naggar et al. [13]. The parameters that are necessary to calculate the tunnel lining under seismic loads are presented. A specific implementation has been developed using a finite element (FEM) framework.

The HRM results have been compared and validated with the numerical results obtained using the FLAC^{3D} model. A parametric study has been performed which allows the effect of seismic magnitude, tunnel dimension and segmental joints on the seismic-induced bending moment and normal forces in a tunnel lining to be evaluated.

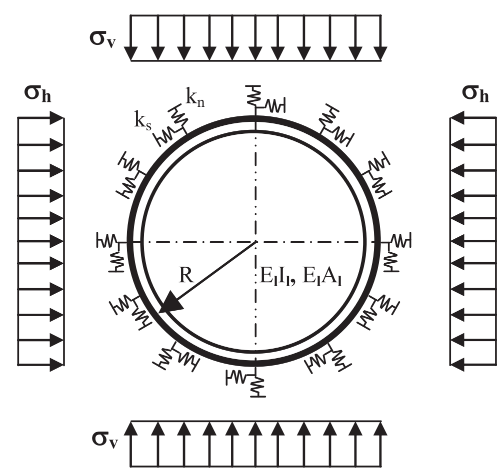

Fig. 1. Calculation scheme of support structures with the hyperstatic method. Active loads are applied to the tunnel support through vertical loads, σ_v, and horizontal loads, σ_h. Key: σ_v: vertical load; σ_h: horizontal load; k_n: normal stiffness of the interaction springs; k_s: tangential stiffness of the interaction springs; R: tunnel radius; E_lI_l and E_lA_l: bending and normal stiffness of the support (Do et al. [15,16]).

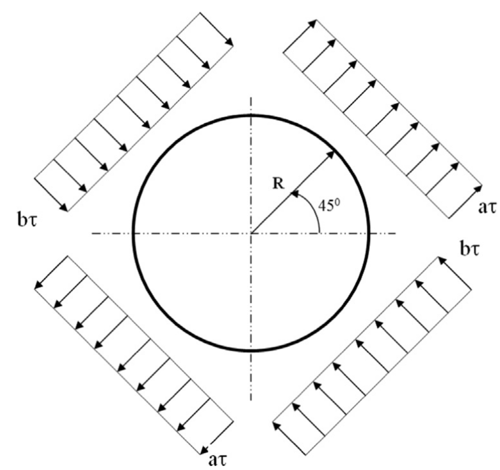

Fig. 2. Proposed equivalent external forces under a seismic event in the HRM.

2. The mathematical formulation of the HRM

2.1. The HRM under static conditions

On the basis of the work by Oreste [14], Do et al. [15,16] have developed a numerical HRM approach for the analysis of segmental tunnel linings under static loads. Fig. 1 shows the problem geometry under static conditions.

In order to avoid an unnecessary increase in the length of the paper, details of the HRM applied to a segmental tunnel lining subjected to static loads are not presented in this study. Those readers who are interested can refer to the work by Oreste [14] and Do et al. [15,16].

2.2. The HRM under seismic conditions

In the HRM, it is necessary to estimate the active loads that act on the tunnel lining. Ovaling deformation can develop in a circular tunnel during a seismic event due to the in-plane shear stresses caused by vertically propagating horizontal shear waves (Peinzen and Wu [3] and El Naggar et al. [13]).

For the pseudo-static analysis of circular tunnels, the in-plane shear stress is calculated as follows (Peinzen and Wu [3] and El Naggar et al. [13]):

$$t = \gamma_{c.} G \tag{1}$$

where γ_c is the shear strain that is deduced from a ground-response analysis, and G is the shear modulus of the soil.

Assuming that the in-plane shear stress is constant at the depth of the tunnel, the free-field shear stress is usually applied as a far-field stress in analytical solutions (e.g., Peinzen and Wu [3] and El Naggar et al. [13]).

It should be noted that, in the HRM, beam elements interact with the neighbouring ones through nodes. Compressive external loads applied in one direction will also yield tensile loads in a perpendicular direction. Therefore, the external loads caused by shear stress under seismic events, which act on the tunnel lining in the HRM, can be different from those applied in the analytical solution proposed by El Naggar et al. [13]. The two parameters, a and b, presented in Fig. 2 have been adopted to represent the change in external loads under seismic condition in the HRM.

On the basis of the seismic load scheme that acts on the tunnel lining in the HRM method presented in Fig. 2, it can be seen that this load scheme is more or less identical to that of the load components under the static condition presented in Fig. 1, but the horizontal loads are in opposite directions and all the external loads are rotated counter-clockwise by $\pi/4$. This would therefore seem to suggest that