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Response characteristics of rectangular tunnels in soft soil subjected to transversal ground shaking

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ABSTRACT

A numerical parametric study was conducted on diverse soil-rectangular tunnel systems, aiming to shed light on critical response characteristics of rectangular tunnels subjected to transversal ground shaking. Salient parameters that affect the dynamic response, such as: (i) the soil-tunnel relative stiffness and interface properties, (ii) the shape, dimensions and burial depth of the tunnel section, (iii) the soil deposit characteristics, and (iv) the input motion characteristics, were accounted for in this study. This paper summarizes the key findings of this investigation, focusing on the complex deformation modes of the tunnels during shaking, the dynamic earth pressures and the soil dynamic shear stresses developed around the tunnel, and the dynamic lining forces. The numerical results indicated a combined racking-rocking deformation pattern for the tunnels during shaking, while inward deformations of the slabs and the side-walls were also observed for flexible tunnels, when soil inelasticity was encountered. To quantify the racking deformation of rectangular tunnels, a series of numerical racking ratio - flexibility ratio (*R-F*) relations were developed and compared with existing analytical and empirical ones. The rocking response of rectangular tunnels was quantified by means of dimensionless relations (θ/γ_{ff}-F), similar to the *R-F* relations. The soil-tunnel relative stiffness, the interface characteristics and the soil yielding affected significantly the above relations, as well as the dynamic earth pressures, the soil dynamic shear stresses and the dynamic forces developed on the lining during shaking. The presented results lead to a better understanding of the seismic response of rectangular tunnels in soft soil, while the proposed relations contribute towards the improvement of the *R-F* analysis method.

1. Introduction

Tunnels constitute crucial components of the transportation and utility networks in an urban area. Although these types of structures behaved better than above ground structures during recent strong earthquakes, post-earthquake observations have demonstrated that they may undergo extensive deformations or even collapse under strong ground shaking, especially when seismic design provisions are not encountered (e.g. Sharma and Judd, 1991; Wang, 1993; Iida et al., 1996; Power et al., 1998).

The seismic response of tunnels is quite distinct compared to that of above ground structures, as the kinematic loading induced by the surrounding ground prevails over inertial loads stemming from the oscillation of the structure itself (Wang, 1993; Hashash et al., 2001).

The response of tunnels and embedded structures (e.g. culverts, underground stations, underground reservoir structures, etc.) against ground shaking and earthquake induced ground failures has been a subject of intense research by a series of experimental (Chou et al., 2010; Shibayama et al., 2010; Chian and Madabhushi, 2012; Cilingir and Madabhushi, 2011a, 2011b, 2011c; Lanzano et al., 2012; Chen et al., 2013; Tsinidis et al., 2015; Abuhajar et al., 2015a, 2015b; Ulgen et al., 2015; Hushmand et al., 2016; Tsinidis et al., 2016a, 2016b), numerical (Hashash et al., 2005; Huo et al., 2005; Anastasopoulos et al., 2007, 2008; Amorosi and Boldini, 2009; Kontoe et al., 2011, 2014; Bilotta et al., 2014; Baziar et al., 2014; Lanzano et al., 2015) and analytical (Bobet et al., 2008; Park et al., 2009; Bobet, 2010) studies, during the recent years. However, several issues related to the dynamic response of rectangular tunnels, including (i) the complex deformation modes of tunnels mobilized during ground shaking, (ii) the amplitude and distribution of the seismic earth pressures on the tunnel side-walls and slabs, and (iii) the soil dynamic shear stresses mobilized around the perimeter of the tunnel during shaking, are still under investigation. Hence, conventional design specifications are based primarily on simplified

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methods (e.g. Wang, 1993; Penzien, 2000; Hashash et al., 2001; ISO, 2005; FHWA, 2009), the implementation of which, may lead to substantial differences in the seismic design for underground structures (Pitilakis and Tsinidis, 2014).

This study aims to shed light on the above open issues, by means of an extended numerical parametric study, which was conducted on a series of idealized soil-rectangular tunnel configurations. The analyses are focused in the transversal direction, as this commonly related to the maximum stress state of the lining. Crucial parameters that affect the dynamic response of the soil-tunnel system, such as: (i) the soil-tunnel relative stiffness, (ii) the soil-tunnel interface properties, (iii) the shape, dimensions and burial depth of the tunnel, (iv) the soil properties and response and (v) the input motion characteristics, are accounted for in this study. The presented results, in terms of (i) racking deformations and rotation of the tunnel sections (due to rocking), (ii) dynamic earth pressures and soil dynamic shear stresses developed around the tunnel, and (iii) dynamic internal forces, lead to a better understanding of the dynamic response of rectangular tunnels in soft soil.

2. Outline of the parametric analysis

The problem, examined herein, is schematically illustrated in Fig. 1a. A concrete rectangular tunnel (width: $a \times$ height: b) is embedded in a homogeneous and uniform soil deposit, resting on elastic bedrock. The distance between the invert slab of the tunnel and the bedrock is larger than the largest dimension of the tunnel. Hence, the potential effect of the bedrock on the tunnel response is minimized.

The size of the tunnel, the mechanical properties of which are summarized in Table 1, ranged, so as to model diverse typologies (e.g. culverts, subway tunnels, underground arteries, etc.), as displayed in Fig. 1b. In particular, the tunnel width, a, ranged between 2.0 m and 18.0 m, while the tunnel height, b, ranged between 2.0 m and 10.0 m. Hence, the corresponding aspect ratios, $\lambda = a/b$, varied between 0.5 and 3.0. It is noted that the aspect ratios discussed throughout the paper are computed based on the distances of the centroids of the structural elements.

An internal column was considered at the middle of the span (i.e. central column) for tunnels with aspect ratio, λ, greater than 2 (e.g. tunnels with large spans), as this concept is more rational from a static design viewpoint. To investigate the effect of this column on the dynamic response of the tunnel, additional analyses were conducted for the 12×6 (m) tunnel ($\lambda = 2$), excluding the internal column (single box analyses), and their predictions were compared to those of the double box analyses (i.e. analyses with the internal column).

The burial depth of the tunnels, h, varied between 3 m and 12 m, to investigate the response of both shallow and deep tunnels.

Table 1
Lining mechanical properties.

	Elastic modulus, E (GPa)	Poisson ratio, ν	Density, ρ (t/m^3)
Concrete C30/37	32	0.2	2.5

Hence, the overburden depth ratio (defined as h/a) varied between 0.17 and 6.0.

The majority of analyses were carried out assuming a visco-elastic homogeneous soil deposit, with soil properties, corresponding to soil classes B and C, according to the Eurocode 8 (CEN, 2004). Table 2 summarizes the mechanical properties of the investigated soil deposits. The selection of a homogeneous, isotropic and visco-elastic soil was made, in order to generalize the conclusions regarding the tunnels' response (e.g. deformations modes). Additionally, this assumption facilitated the direct comparison of the numerical predictions with key results and references that are commonly adopted in the seismic analysis of tunnels (Wang, 1993; Penzien, 2000; Anderson et al., 2008).

A sensitivity analysis was conducted, to investigate the effects of crucial soil parameters, such as the soil's Poisson ratio, ν, and soil's damping, D, on the response of the tunnels, as discussed in the following sections. Additionally, a series of nonlinear analyses were performed for 6×6 (m) square tunnels, assuming diverse strength properties for the surrounding ground (Table 2), aiming to investigate the effect of soil yielding on response characteristics of the tunnel.

For the sake of simplicity, the lining thickness, t, was assumed to be constant for all structural elements (i.e. slabs, side-walls and columns), while it was deliberately chosen and changed for each soil-tunnel configuration, to achieve flexibility ratios, F, varying between 0.2 (i.e. rigid tunnel) and 10 (i.e. quite flexible tunnel). A series of static frame analyses were performed, following Wang (1993), to facilitate the selection of the lining thickness for the various flexibility ratios. For the computation of the flexibility ratios, the following relation was used:

$$F = (G_s \times a)/(S \times b) \quad (1)$$

where G_s is the soil shear modulus and S is the required force to cause a unit racking deflection of the structure. It is worth noticing that some of the adopted lining thicknesses are unrealistically large or small for practical applications. However, the selection was made in order to create an abacus of cases that can describe a wide range of lining flexibilities, including extreme scenarios.

3. Numerical analysis

The analyses were carried out under plane strain conditions, using the finite element code ABAQUS (ABAQUS, 2012). The soil

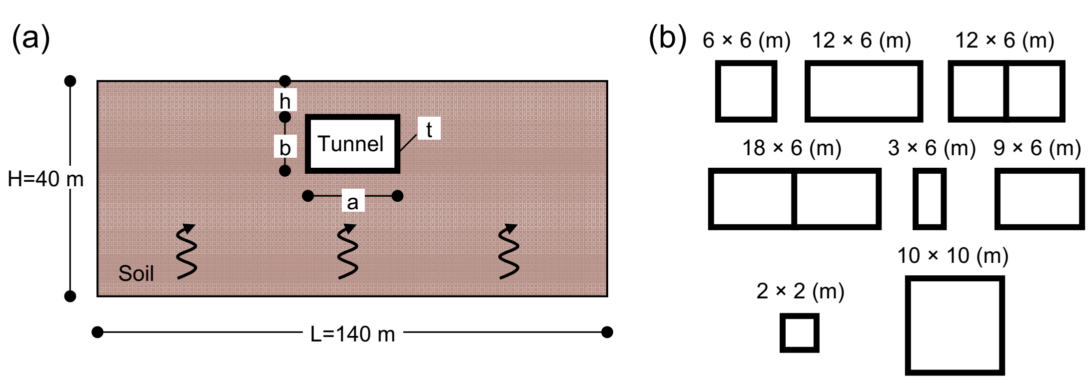

Fig. 1. (a) Schematic illustration of the problem and (b) dimensions of the investigated tunnels.