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Seismic behaviour of circular tunnels accounting for above ground structures interaction effects

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ABSTRACT

Tunnels are commonly designed under seismic loading assuming "free field conditions". However, in urban areas these structures pass beneath buildings, often high-rise ones, or are located close to them. During seismic excitation, above ground structures may cause complex interaction effects with the tunnel, altering its seismic response compared to the "free field conditions" case. The paper summarizes an attempt to identify and understand these interaction effects, focusing on the tunnel response. The problem is investigated in the transversal direction, by means of full dynamic time history analyses. Two structural configurations are studied and compared to the free field conditions case, consisting of one or two above ground structures, located over a circular tunnel. Above ground structures are modeled in a simplified way as equivalent single-degree of freedom oscillators, with proper mechanical properties. Several parameters that are significantly affecting the phenomenon are accounted for in this parametric study, namely the soil to tunnel relative flexibility, the tunnel dimensions, the tunnel burial depth and the soil properties and nonlinearities during shaking. Tunnels response characteristics are compared and discussed, in terms of acceleration, deformations and lining dynamic internal forces. Internal forces are also evaluated with analytical closed form solutions, commonly used in preliminary stages of design, and compared with the numerical predictions. The results indicate that the presence of the above ground structures may have a significant effect on the seismic response of the tunnel, especially when the latter is stiff and located in shallow depths.

1. Introduction

Tunnels constitute crucial components of the transportation and utility networks in urban areas. The associated impact in case of earthquake induced damage denotes the importance of proper seismic design especially in seismic prone regions.

It is generally believed that underground structures are less vulnerable to seismic shaking compared to above ground structures. However, several cases of severe damage or even collapse have been reported in the literature, mainly for shallow embedded structures in soft soils ([10,17,19,28,31,33,40,42,43] among others).

During an earthquake, tunnels are subjected to shaking due to wave propagation and permanent ground displacements due to ground failure (lateral spreading, landslides and fault rupture). In both the cases, the kinematic loading imposed by the adjacent soils prevails, while the inertial loads are generally of secondary importance. Therefore, the seismic behavior of underground structures and tunnels is quite distinct compared to the above ground structures [13,17].

Several methods are available in the literature for the evaluation of the seismic response of underground structures and tunnels [4,11,12,16,29,35,36,41]. The results of these methods may significantly deviate, even under the same design assumptions, due to both inherent epistemic uncertainties and knowledge shortfall regarding some crucial issues that considerably affect the seismic response [30]. In order to better understand the seismic behavior of these types of structures several experimental research studies have been recently carried out (e.g., [8,22,38,39] among others).

Available design methods for shaking, usually assume free field conditions, precluding the existence of above ground structures in the adjacent area of the tunnel (e.g., above the tunnel). However, in urban areas, tunnels often pass beneath or close by high-rise buildings. During shaking, the vibration of these above ground structures may create complex interaction phenomena with the tunnel, passing often few meters below their foundation, which are expected to affect the seismic wave propagation field. In this sense, they may modify the dynamic response of the tunnel, while at the same time the existence of the tunnel close to the surface

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and the foundations of the buildings, may alter the response of the buildings themselves.

Dynamic interaction effects in urban areas (e.g., “city effects”) have been mainly examined between above ground structures. A comprehensive review is made by Menglin et al. [27]. Regarding the dynamic interaction phenomena between above ground and embedded structures, most researchers focus on the effect of an underground structure, often a circular tunnel or a cavity, on the response of the above ground structures. The underground structure is commonly assumed to be embedded in an elastic half-space, while the effects are usually expressed in terms of surface ground motion amplification [9,20,23–25,34,43].

On the other hand, the inverse problem, i.e., the effects of above ground structures on the response characteristics of embedded structures (e.g., shallow tunnels) have not been thoroughly studied. The present paper presents an attempt to identify, understand and quantify these potential effects. For this purpose, a numerical parametric study is conducted, assuming different structures, soil and tunnel configurations. The problem is investigated in the transversal direction, as this direction is related to the lining maximum developing stress states and affects directly the cross-sectional structural design of the tunnel. Parameters that significantly affect the phenomenon and considered herein are the soil to tunnel relative flexibility, the tunnel dimensions, the tunnel burial depth and the soil properties accounting also for their non-linear behavior during strong shaking. The response of the examined cases is discussed in terms of acceleration, deformations and lining internal forces. Lining forces are also evaluated with existing closed form analytical solutions (e.g., [41]), commonly used in preliminary stages of design of circular tunnels in the absence of any above ground structure, and the results are compared to the numerical data.

2. Numerical simulation

A series of dynamic time history analyses is performed on representative structural systems comprising of a circular tunnel and models of above ground buildings. The analysis is performed in the transversal direction, with the surface structures been simulated as equivalent single degree of freedom (SDOF) oscillators with rigid foundations. Inertial properties of the equivalent SDOFs correspond to usual buildings (e.g., 6–8 storey buildings). The case studies are summarized in Fig. 1. One of the buildings (e.g., Structure A) is located above the tunnel, assuming that the tunnel is constructed with an underground excavation method (e.g., using a tunnel boring machine). In cases of two surface structures, the second one (e.g., Structure B) is located just aside the first one. Table 1 tabulates the mechanical properties of the tunnel and structures along with the assumed fixed-based fundamental periods of the above ground structures (T_{fix}).

Two different sand soil deposits are considered herein. One of them corresponds to a rather loose soil deposit representing a soil type *C* according to Eurocode 8 [7] with fundamental frequency equal to 1 Hz, while the second one corresponds to a stiffer deposit (i.e., soil type B according to Eurocode 8), with fundamental frequency equal to 2.5 Hz. The shear wave velocity gradient profiles are presented in Fig. 2. Mechanical properties of the assumed soil deposits are tabulated in Table 2.

To study the effects of the tunnel size and burial depth, the diameter of the circular tunnel (d) is ranging between 5 and 10 m, while the tunnel burial depth (h) is also ranging between 5 and 10 m. Both dimensions and depths are common in practice.

Moreover, the soil to tunnel relative flexibility is examined through the so called flexibility ratio [41], which is estimated using the following analytical formulation:

$$F = \frac{E_S(1-\nu_l^2)r^3}{6E_l I_l(1+\nu_S)} \tag{1}$$

where, E_s is the soil elastic modulus, ν_s is the soil Poisson ratio, E_l is the lining elastic modulus, ν_l is the lining Poisson ratio, I_l is the lining moment of inertia (per unit width) and r is the circular tunnel radius. The flexibility ratio of the investigated cases is ranging from almost zero (quite rigid tunnel) to 10 (quite flexible tunnel). Few very flexible tunnels ($F>30$) are also evaluated, so as to study the effect of this crucial parameter to extreme ends. To achieve the desirable flexibility ratio, the tunnel lining thickness (t_l) is adequately selected for each case.

The analyses are performed, under plane strain conditions in total stresses, using the finite element code ADINA [3]. Despite the generic nature of the specific code, ADINA can efficiently reproduce the complex phenomena implicated in a dynamic time history analysis, including wave propagation through soil media and dynamic soil–structure interaction effects [2,18,26].

More specifically, the soil is meshed with plane strain elements, while the tunnel and the above ground structures (SDOFs) are modeled using beam elements (Fig. 3). The adopted element size is selected in a way that ensures the following criteria:

(a) Efficient reproduction of all the waveforms of the whole frequency range under study (e.g., following the principle that the element size must be 8–10 times smaller than the minimum wavelength of interest),
(b) converge criteria of the analysis (for elasto-plastic analysis) and
(c) efficient simulation of the soil close to the tunnel.

Therefore, a finer discretization near the tunnel is selected, allowing a low element aspect ratio (for the soil elements) and a low face corner angle (for the beam elements simulating the circular tunnels).

The base boundary of the model is simulated as rigid bedrock, where the seismic input motion is applied in terms of displacement time history. For the vertical boundaries kinematic constrains are introduced, forcing the opposite vertical sides to move simultaneously, simulating the shear waves propagating upwards, e.g., tie constrains [1].

To simplify the analyses, a solid connection between the soil and structures is assumed. Although, interface characteristics are quite crucial for the dynamic response of embedded structures [15,21,30,32,37], this assumption is quite common in engineering practice, as it corresponds to an upper limit for the developed shear stresses around the tunnel.

The tunnel and the above ground SDOF structures are assumed to behave within the linear elastic range. For the soil behavior two assumptions are made. In the first series of analyses a linear visco-elastic material is used, while for the final analyses an elasto-plastic Mohr Coulomb material is implemented, in order to account for the permanent soil response due to yielding. In the latter case, the soil shear strength is assumed to increase with depth (Table 2), following the increase of the soil stiffness (Fig. 2). Viscous damping (5% for all the examined cases and elements, for sake of simplicity) is employed in the frequency depended Rayleigh type. For the elasto-plastic analyses additional energy dissipation is introduced by the hysteretic soil response.

Investigated systems are subjected to a simplified Ricker wavelet of nominal frequency equal to 1 Hz and amplitude equal to 0.1 g, introduced at the model base (Fig. 4a). Input motion nominal frequency is selected equal to the fundamental frequency of one of the soil deposits (soil type C) in order to study the effects of soil resonance. In addition, input motion amplitude is selected in order to produce at the tunnel depth and the soil surface,