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Technical Note

Seismic response of shallow circular tunnels in two-layered ground

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ABSTRACT

The effect of ground stratification on the seismic response of circular tunnels is investigated, as most practice-oriented studies consider homogeneous ground. A finite element plain-strain model of a circular tunnel cross-section embedded in a two-layered ground is used to highlight the influence of stratification on the tunnel's seismic response. The layers interface was placed at the crown, centre and invert level.

It is proved that ground stratification has an important role in the lining seismic forces. When the tunnel is fully embedded in one of the layers, the seismic lining forces may vary significantly in comparison with the single-layer case. If the tunnel intercepts both layers, maximum lining forces aggravation occurs when the lower layer is very stiff.

1. Introduction

The number of tunnels has grown significantly over the last decades. Part of these tunnels is built in seismic regions.

Three types of deformations characterise the response of tunnels to ground shaking [1]: (1) axial compression and extension; (2) longitudinal bending; and (3) ovaling/racking.

The component that has the most significant influence on the tunnel lining under seismic loading, except for the case of the tunnel being directly sheared by a fault, is the ovaling or racking deformations [2]. Studies suggest that, while ovaling may be caused by waves propagating horizontally or obliquely, vertically propagating shear waves are the predominant form of earthquake loading that causes these types of deformations [3]. Simplified analytical solutions to investigate the seismic response of tunnels are very attractive tools for preliminary design, as they provide a quick and easy calculation of the seismic design loads in the tunnel lining in terms of axial force and bending moment.

The use of equivalent linear properties in analytical solutions as an approximate way of simulating soil's nonlinearity can be successfully used for the preliminary seismic design of circular tunnels (e.g. [3–6]).

Much effort has been made to develop simple closed-form analytical solutions for the prediction of thrust and moment in the circular tunnel lining due to seismic-induced ovaling deformation (e.g. [2,3, 7–10]). These solutions assume the medium as homogeneous linear elastic half-space and the ovaling deformation is derived under quasi-static two-dimensional plane-strain conditions.

This paper tackles two important shortcomings of the closed-form solutions:

1. Analytical solutions consider quasi-static lining ground interaction, neglecting inertial interaction, and simple shear loading applied at the free-field, corresponding to shear strain constant with depth. In this paper dynamic analyses are performed simulating the vertical propagation of shear waves in a homogeneous visco-elastic layer lied on rigid bedrock, which leads to an increasing with depth shear strain profile.
2. When the surrounding medium is a natural deposit, it is often horizontally layered, but the analytical solutions do not take into account the possible stiffness contrast between two consecutive layers. In this case, the seismic response of circular tunnels becomes more complex and the use of numerical simulations to predict the behaviour of tunnels arises as the most efficient alternative.

This paper investigates the seismic response of circular tunnels constructed by boring excavation in a two layered ground at relatively shallow depth. The paper main goal is to

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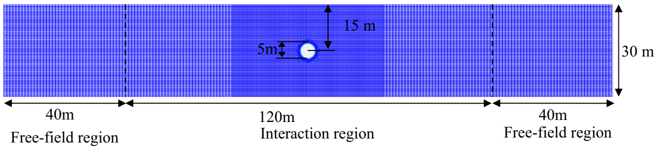

Fig. 1. Finite element mesh.

identify under which two-layered conditions the seismic lining forces are aggravated/attenuated.

2. Numerical model

2.1. FE model

The finite element mesh (Fig. 1) simulates a soil mass 30 m thick in plane-strain conditions with 31226 isoparametric 4-node rectangular elements, overlying a rigid bedrock, using the finite element programme SAP2000 [11].

As relatively shallow tunnels are more vulnerable than deep tunnels under seismic loading, the tunnel's centre was placed 15 m deep.

The diameter of the circular opening was defined equal to 5.0 m. The lining is modelled as continuous and impervious circular ring with linear elastic behaviour using 72 2-node beam elements. No relative movement (no-slip) was allowed on the tunnel lining-soil interface, because interface elements were not available in the code used. Full-slip case, that assumes no tangential resistance transmitted from soil to the lining, is not examined in this paper.

The model considers only the vertical propagating shear waves in visco-elastic layers lying on rigid bedrock. The degrees-of-freedom of the bottom boundary are completely restrained, because the displacements computed are relative to the base.

The mesh is composed of a central region to simulate the ground–tunnel interaction, and two lateral regions, simulating the free-field ground response. In the free-field regions, all nodes at the same depth have the same horizontal displacement (tied nodes assumption) and the vertical displacement is restrained. This option intended to adjust their motion to the free-field ground motion induced by the vertical propagation of shear waves.

The interaction region is where soil and tunnel interact, thus the degrees-of-freedom of the nodes are free in both vertical and horizontal directions.

The maximum size of the elements in the direction of wave propagation was calculated to be less than one-tenth of the lowest wavelength of interest in the simulation [12]. The latter may be evaluated by the ratio between the minimum wave velocity, $V_{min}=46\ \mathrm{ms}^{-1}$, and the highest frequency of the input wave, $f_{max}=10$ Hz. In this work, the element size adopted is 0.50 m.

2.2. Materials properties

Both ground and lined tunnel were simulated using single-phase linear elastic model. Their material properties are given in Table 1. The ground properties adopted are representative of soft to stiff soil and cover the most interesting part of the ground/tunnel relative flexibility (flexibility ratio, *F*, ranging from 0.6 to 60). The mechanical parameters of the lined tunnel are taken as the typical properties of a reinforced concrete lining.

2.3. Numerical simulation using closed-form assumptions

Table 1
Materials properties.

	Ground	Tunnel lining
Young's modulus (MPa)	10; 50; 100; 250; 500; 1000	24,800
Poisson's ratio	0.3	0.2
Volumetric unit mass (ton/m^3)	2.0	2.5

Table 2
Soil parameters, lining's thicknesses, and corresponding flexibility ratios.

		Flexibility ratio, *F*					
Soil Young's modulus (MPa)		10	50	100	250	500	1000
Lining's thickness	$t=0.25$ m	0.60	2.98	5.96	14.89	29.78	59.55
	$t=0.50$ m	–	0.074	–	–	3.72	–

The Wang's closed-form solution [3] is widely used to predict the transverse seismic response of the tunnel and is used as reference in this work. This solution takes into account explicitly the soil–structure interaction based on the following assumptions:

- the ground is an infinite, linear elastic, homogeneous and isotropic medium;
- the tunnel is circular with uniform thickness and without any discontinuities; the lining thickness is small in comparison to the tunnel diameter. The lining has linear elastic behaviour.
- Plane strain conditions are postulated for soil and lining.
- The effect of construction sequence is not considered.
- In the direction normal to the lining, soil and lining are fully connected; in the tangential direction, only full connection between soil and the lining case (no-slip) is considered.

The seismic action is introduced by external static forces that induce ground distortion related to a vertically propagating shear wave. The detailed solution is summarised in Appendix A.

In the numerical simulation, simple shear loading was imposed through the application of forces at the upper nodes of the model. The lining deformations and forces are analysed and discussed in Section 3.

The ground's Young's modulus was varied parametrically in order to capture a wide range of flexibility ratios. Table 2 shows the flexibility ratios covered in this work.

2.4. Numerical simulation using direct integration dynamic analysis

A direct integration dynamic analysis using the finite element method was conducted to compute seismic forces and deformations induced to circular tunnels. A short unit impulse was adopted as input motion (peak acceleration $=1\ \mathrm{ms}^{-2}$ at 0.2 s, and null acceleration for all other instants) to evenly excite all the frequencies relevant for the analysis.

Rayleigh damping coefficients were adjusted to 5% viscous damping coefficient at the system's fundamental frequency. In all the analyses, a time step of $\Delta t=0.01$ s and an implicit HHT numerical integration scheme with $\alpha=0$, $\beta=0.25$ and $\gamma=0.5$ was used.

3. Results and discussion

3.1. Single-layer deposit

3.1.1. Static simple shear analysis

The main parameters that govern the predicted loads by the analytical solutions are the compressibility, *C*, and the flexibility, *F*, ratios and the maximum free-field shear-strain γ_{ff} (see Appendix A).