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Effects of the asynchronism of ground motion on the longitudinal behaviour of a circular tunnel

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ABSTRACT

The seismic performance of underground tunnels is affected by some significant factors mostly depending on the seismic loading conditions, the tunnel structure in interaction with the surrounding soil and the three dimensional geometry of the tunnel and the soil stratigraphy. The paper addresses the problem of underground tunnels when subjected to asynchronous seismic shaking along the axis in comparison with the synchronous case that is usually considered in the tunnels design. The study also includes the effect of the curved shape of the tunnel axis, the sudden change of dynamic impedance along its axis, the direction of the propagating wave and the effect of the initial state of stress induced by the excavation process. A finite element model able to catch the main deformation patterns of a tunnel subjected to non-uniform seismic load, coupling the axial and longitudinal deformations has been defined in Plaxis 3D. The numerical model has been first validated with a simplified benchmark case where the soil behaves elastically, and afterwards on the real case of the Metro Line 6 of Naples, assuming a more sophisticated constitutive model for the soil. The results of the 3D full dynamic analyses show the effect of the ground motion asynchronism on the distributions of internal forces in the tunnel lining.

1. Introduction

Approaching the surface, seismic waves induce several effects in the ground such as ground failure (i.e. liquefaction, fault displacements, slope instability) and ground shaking. In absence of ground failure, most of the seismic damages on tunnels in soft ground occur for ground shaking caused by the propagation of shear waves (Hashash et al., 2001). This loading condition determines on long underground structures (ie. tunnels, pipelines, subways,) axial deformation, longitudinal bending and ovaling/racking (Owen and Scholl, 1981), The longitudinal deformation component in particular, is caused by the spatially varying ground motion, including wave scattering, wave passage, site amplification effects. These effects are not always considered in the seismic design of underground structures especially for long tunnels although they produce such modification of the ground motion with respect to the case in which the spatial variability is not considered. As consequence, because the behavior of the underground structure is governed by the surrounding soil deformation during seismic shaking, the different seismic shaking conditions affect the seismic response of the tunnel structure in different ways. During the propagation of the earthquake signal in fact, the arrival time of the seismic wave along the structure is different producing an overlapping effect of the waves in the direction of the length of the structure.

In the specific case of *long structures* (eg. tunnel, immersed tunnels, pipelines), that is when their length is much longer than the wavelength, the effect of travelling seismic waves is not negligible as some laboratory experiments, conducted through multi-point shaking table tests on long tunnels able to reproduce this non-uniform seismic loading, have shown recently. Chen et al. (2007) and Yu et al. (2018) for instance, have conducted some tests on different long tunnels to investigate the effect of the waves passage, achieving the same result that the non-uniform seismic excitation produces larger tunnel deformation compared with the uniform loading case.

This field of research has had a remarkable development in last years because, with the observation of the tunnel damages occurred after recent seismic events (such as San Fernando earthquake in California in 1971, Kobe earthquake in Japan in1995, Duzce earthquake in Turkey in 1999, Chi-Chi earthquake in Taiwan in 1999, Bam earthquake in Iran in 2003, Wenchuan earthquake in China in 2008), the seismic design and risk management of existing and new tunnels is assuming an increasingly social and economic impact on modern countries where underground tunnels represent a large slice of civil

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infrastructures.

Many methods are available in the technical literature the seismic design of tunnels in longitudinal direction: (1) Free field deformation approach (St. John and Zahrah, 1987); (2) Seismic deformation method (Kawashima, 1999); (3) Beam-springs model (4) Mass-beam-springs model (Kiyomiya, 1995; Yu et al., 2016); (5) Multi masses-beam-springs model (Li et al., 2017). The first two methods ignore the tunnel mass and thus the effect of the soil-structure inertial interaction. They use an uncoupled approach where the ground motion is solved in free-field condition and modified to take into account soil-structure interaction trough a beam-spring model. The third method instead, models the dynamic interaction between an elastic beam with mass, representing the tunnel lining, and visco-elastic spring elements representing the soil (hence the name beam-springs model). The last two models, mass-beam-springs models, consider also the inertia of the soil in the solution of the dynamic equilibrium: the soil layer is modelled as a single lumped mass (Yu et al., 2016) or a vertical array of lumped masses (Li et al., 2017).

Three-dimensional numerical models are less common since they are highly time consuming and need very large computer memory. Applications can be found in literature such as: 3D analyses by boundary element method (Stamos and Beskos, 1995; Stamos and Beskos, 1996); 3D pseudo-static (Park et al., 2009) and dynamic analyses (Yu et al., 2013; Li and Song, 2015) by finite element method.

However, 3D full dynamic numerical analyses are able to simulate the entire process of seismic soil-structure interaction under the waves passage, including also some effects such as for example tunnel lining details, different soil constitutive models, different shaking conditions, returning a more realistic seismic response of the tunnel.

This paper describes a three-dimensional numerical model able to catch the main deformation patterns of a tunnel subjected to non-uniform seismic loadings, coupling the axial and longitudinal deformations. The numerical model has been tested in a simplified benchmark case where the soil behaves elastically, and tested afterwards on a real case assuming a more sophisticated constitutive model for the soil, that is the hardening soil (Schanz et al., 1999) with small strain overlay constitutive model (Benz et al., 2009).

The effect of the asynchronous ground motion has been investigated for the case of the Metro Line 6 of Napoli, which dynamic response under uniform seismic loads has been already studied in plane strain conditions (Fabozzi et al., 2017a). This enabled a comparison between the uniform and non-uniform shaking in terms of dynamic increment on internal tunnel lining forces and time histories of acceleration in the ground.

This case of study has been taken into account for the geometry of the tunnel stretch and ground conditions. In fact, the tunnel stretch follows a curved route and runs across a soil/rock interface that emphasizes the effect of the asynchronism ground motion.

2. Three-dimensional numerical model

In this section a 3D computational model of the seismic response of a tunnel subjected to asynchronous wave passage is described: a free-field analysis is described first, that reproduces the asynchronism of the seismic motion; then the soil-tunnel interaction is taken into account.

2.1. Free field analysis

The spatial variability of the ground motion is dealt assuming a plane wave front propagating longitudinally and upwards from the rigid bedrock up to the ground surface. Ground shaking occurs in the orthogonal direction respect to the longitudinal one.

Under these simplified hypotheses, a three-dimensional FE model has been developed in Plaxis 3D (Brinkgreve et al., 2013) to investigate the free-field soil response (Fig. 1a). It has a depth, H, equal to 60 m, a width, B, equal to 200 m and a length, Y, equal 400 m. The longitudinal dimension of the model has been set in order to guarantee the progress of the asynchronous input wave while the width is such that the effect of the boundaries is minimized in the middle of the model.

The model consists of one soil layer (Fig. 1a) with a shear wave velocity, V_s, equal to 250 m/s overlying the seismic bedrock (V_s = 800 m/s). Table 1 shows the main soil parameters.

The free field seismic loading condition has been simulated by applying to the base of the model time histories of acceleration in the plane perpendicular to *y*-axis. In order to reproduce the longitudinal propagation of the seismic waves, they have been applied with a time-lag, *TL*, along the propagating direction. The assigned time-lag is proportional to the ratio between the nodes distance and the bedrock velocity. In this model, the base boundary has been divided in sixteen surfaces and the same time history of acceleration has been assigned to

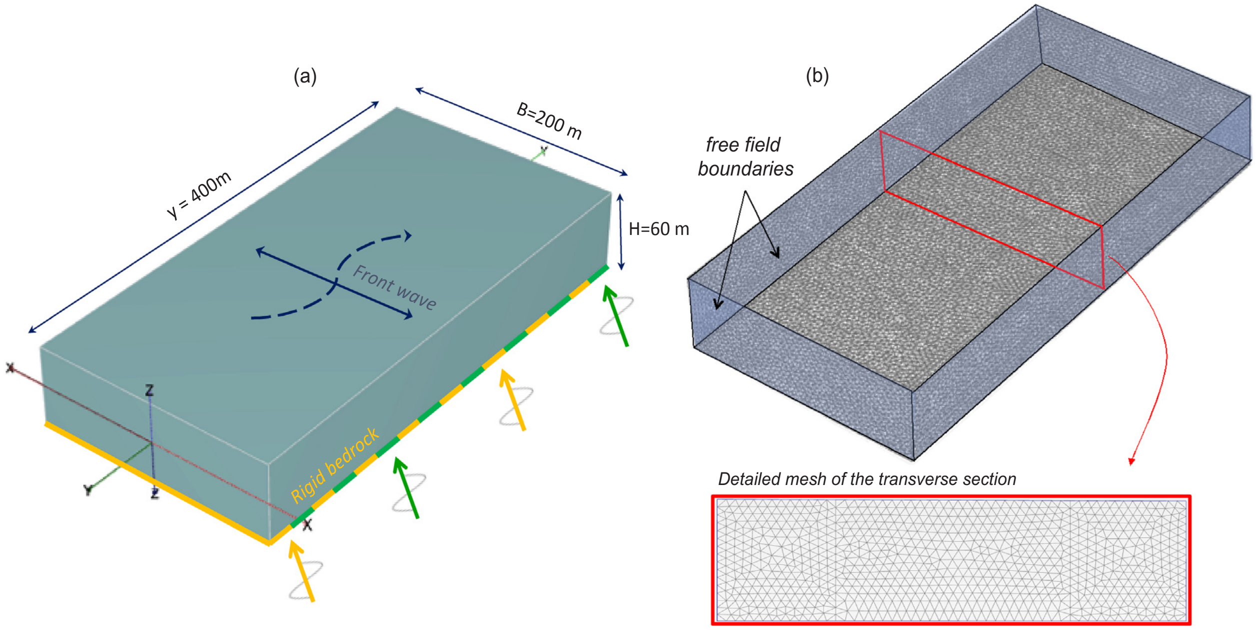

Fig. 1. (a) Geometric scheme of the model adopted in Plaxis 3D to simulate the asynchronism of the seismic motion in longitudinal direction y and (b) numerical mesh of the model.