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Behavior of shallow tunnel in soft soil under seismic conditions

Milind Patil[a], Deepankar Choudhury[b,*], P.G. Ranjith[c], Jian Zhao[c]

[a] IITB-Monash Research Academy, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
[b] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India
[c] Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia

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ABSTRACT

In tunneling practices, it is vital to have an accurate estimate of the depth of embedment of the tunnel; lining thickness and shape of the tunnel, which enables resisting of stresses; and deformation generated by the surrounding soil under seismic loading conditions. The present study highlights the behavior of shallow tunnel in soft soil under seismic conditions by using the finite element (FE) analysis. The developed numerical model is compared with available analytical solutions. Thereafter, a series of parametric studies are carried out by varying the tunnel embedment ratio, soil-tunnel interface conditions, lining thickness, shape of the tunnel, and input ground motion. It has been observed that distortion in the tunnel lining is dependent on the depth of embedment and the flexibility ratio of the tunnel. Ovaling (in a circular tunnel) and racking (in a rectangular tunnel) are found to decrease significantly when embedment ratio is greater than 2. Nearly 6–18% of greater distortion and 20% of greater bending moment are obtained in the full-slip interface condition when compared to the no-slip interface condition. The maximum induced bending moment in the tunnel lining is directly proportional to its flexural rigidity. An unconventional square tunnel with rounded corners, yields 55% lesser bending moment than the square tunnel under the same seismic loading condition. This study also highlights the importance of the input ground motion characteristics that govern the development of the maximum dynamic earth pressure around the lining of the tunnel, and the heaving of the ground surface just above the crown. The outcomes of the present study will be useful in design through understanding the effects of various influencing parameters that control the stability of the tunnel in soft soil under seismic loading conditions.

1. Introduction

The construction of tunnels is gaining popularity for transportation and other utilities due to the restrictions in the expansion of surface infrastructure. Many cities in the world are already having or planning to construct tunnels as part of metro projects. In the past, engineers believed that seismic design for underground structures is not necessary, because they suffer lesser damage than surface structures. However, the damages that were observed in recent earthquake events (Loma Prieta earthquake, 1989; Kobe earthquake, 1995; Duzce earthquake, 1999; Chi-Chi earthquake, 1999; Niigata earthquake, 2004; Wenchuan earthquake, 2008; Tohoku earthquake, 2011) have proved that underground structures are vulnerable to earthquakes. There are few studies that explain the seismic behavior of tunnels that are constructed in rock or non-cohesive dense soil (Dowding and Rozen, 1978). Tunnels that are constructed in soft soil at shallow depth suffer more damages than deeper tunnels in intact rock (Sharma and Judd, 1991; Power et al., 1998); nonetheless, a very few studies that explain the seismic response of a tunnel in soft soil are available. Owen and Scholl (1981) described the seismic response of tunnels in terms of different modes of tunnel deformations such as axial deformation, curvature deformation, ovaling, and racking deformation. Wang (1993) and Penzien (2000) proposed closed-form analytical solutions to calculate the thrust and bending moment in the tunnel lining and the effect of racking and ovaling. Hashash et al. (2001, 2005) and Patil et al. (2015) extensively reviewed the methods that are used in practice to determine the seismic forces in the design of tunnels that have different tunnel-soil interaction properties. Cilingir and Madabhushi (2011a, 2011b, and 2011c) conducted a set of centrifuge model tests and investigated the effects of input ground motion and depth on seismic behavior of tunnels in dry sand. In recent years, the knowledge deficit in the understanding of the seismic behavior of tunnels motivated researchers to carry out enormous amounts of research by experimental (Lanzano et al., 2012; Tsinidis et al., 2015, 2016), numerical (Kontoe et al., 2011, 2014; Amorosi and Boldini, 2009; Debiasi et al., 2013; Patil et al., 2017; Tsinidis, 2017) and analytical (Huo et al., 2005; Bobet et al., 2008;

* Corresponding author at: Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.
E-mail addresses: dc@civil.iitb.ac.in, dchoudhury@iitb.ac.in (D. Choudhury).

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Bobet, 2010) studies, in which the response of underground structures to seismic shaking and earthquake-induced ground failures was studied. However, certain complex issues that are related to soft soil tunneling need to be explored in detail: (a) prediction of tunnel distortions caused by ground shaking, (b) distribution of axial force and bending moment in tunnel lining due to seismic loading, (c) effect of excess pore water pressure on the tunnel, (d) evaluation of the seismic performance of various shapes of tunneling in soft soil, and (e) effect of soil-tunnel interface conditions.

In the present study, a detailed finite element (FE) analysis has been carried out to investigate the complex behavior of shallow tunnels in soft soil under seismic conditions. A parametric study has been carried out to understand the effect of (a) depth of embedment, (b) lining thickness, (c) shape of the tunnel, and (d) input ground motion on the behavior of the tunnel-soil system. The outcome of the present analyses will help in the proper prediction of stresses and deformations within the surrounding soil and the additional forces in the tunnel lining, which are caused by those deformations.

2. Details of finite element analyses

In the present study, a commercial FE computer program, PLAXIS 2D AE.02, is used to perform plain-strain numerical analysis that can simulate the non-linear dissipative behavior of soil that is subjected to cyclic loading. The appropriate geometry of the numerical model and the boundary conditions are adopted to represent the far-field medium. In the present analysis, a horizontally layered soil system (similar to Hu et al., 2003) is assumed for all set of analyses. The top soil layers, at 30–40 m, are very soft silty clays that are underlain by silty clay with silty sand. The geotechnical soil properties of the soft soil are summarized in Table 1. Fig. 1 (a) and 1 (b) show the schematic diagram of a two-dimensional numerical model and deformed mesh, respectively. The Mohr-Coulomb model is used to simulate the behavior of the soil elements, while a linear elastic model was adopted for the tunnel lining. The methodology to model linear elastic behavior of tunnel lining is adopted based on the information obtained from other published literature (Tsinidis, 2017; Gomes et al., 2015; Kontoe et al., 2011, 2014; Do et al., 2013; Amorosi and Boldini, 2009; Wang, 1993). The Young's modulus (E_l) and Poisson's ratio (ν_l) of the concrete lining were assumed to be 30 GPa and 0.2, respectively. The unit weight of the concrete is taken to be 25 kN/m^3. Under fully dynamic loading conditions, the behavior of the soil is primarily governed by its dynamic properties (see Table 2). Therefore, the shear wave velocity (V_s) is treated as the primary input parameter along with the strength parameter (undrained shear strength, s_u) of the soil. The stiffness parameters are calculated from dynamic properties as follows:

$$G_0 = \rho_s V_s^2 \tag{1}$$

$$E_s = 2G_0(1 + \nu_s) \tag{2}$$

where ν_s is the Poisson's ratio of the soil material, G_0 is the initial shear modulus of the soil, ρ_s is the density of the soil material, and E_s is the modulus of elasticity of the soil.

Table 1
Soft soil properties adopted in numerical analysis (modified after Hu et al., 2003).

Soil layer	Unit weight γ (kN/m^3)	Undrained shear strength S_u (kPa)	Horizontal permeability k_x (m/s)	Vertical permeability k_y (m/s)
1	18.4	29.9	5.50×10^{-7}	2.50×10^{-9}
2	17.5	27.4	3.50×10^{-6}	1.70×10^{-8}
3	16.9	19.8	5.13×10^{-8}	1.91×10^{-9}
4	18	26.3	3.40×10^{-6}	3.51×10^{-8}
5	18.1	30	2.13×10^{-5}	2.67×10^{-6}

Under earthquake loading, the soil is subjected to cyclic loading and unloading, which generates a hysteresis loop with the dissipation of energy and consequent damping. The Mohr-Coulomb model cannot simulate hysteretic damping in the numerical analysis. To compensate for the modeling limitation of simulating hysteretic damping, the total amount of damping is introduced through the frequency-dependent Rayleigh formulation in terms of viscous damping, which is defined as follows:

$$2\omega\xi = \alpha + \beta\omega^2 \tag{3}$$

$$\omega = 2\pi f \tag{4}$$

where ξ is the damping ratio, ω is the angular frequency in rad/s and f is the frequency in Hz.

Solving the Eq. (3) for first and second target frequencies (f_1 and f_2, respectively) and corresponding target damping ratios (ξ_1 and ξ_2) gives the required Rayleigh damping coefficients:

$$\alpha = 2\omega_1\omega_2\frac{\omega_1\xi_2-\omega_2\xi_1}{\omega_1^2-\omega_2^2} \quad \text{and} \quad \beta = 2\frac{\omega_1\xi_1-\omega_2\xi_2}{\omega_1^2-\omega_2^2} \tag{5}$$

$$\omega_1 = 2\pi f_1 \quad \text{and} \quad \omega_2 = 2\pi f_2 \tag{6}$$

$$f_1 = \frac{V_s}{4H} \quad \text{and} \quad f_2 = \frac{3V_s}{4H} \tag{7}$$

Here, α is the Rayleigh coefficient that determines the influence of mass on the damping of the system, β is Rayleigh coefficient that determines the influence of stiffness on the damping of the system.

Material damping of the soft clay was assumed to be 10% (Hardin and Drnevich, 1972). The viscous boundary conditions are assigned to vertical boundaries that can absorb the incident waves, and the base boundary is simulated as a rigid surface. Seismic ground motion has been assigned at the base of the model. The ground motion data of the Loma Prieta earthquake of 1989 and the Kobe earthquake of 1995 were used as a dynamic input motion. It may be noted that deconvolution method should be applied to get proper ground motions at specific site. However, in the present study, a generalized approach is considered instead of site-specific study to show the effect of different ground motions on the behavior of tunnel under seismic loadings with the help of parametric study. The similar methodology of selection of various ground motions as input data irrespective of site-specific study by ignoring deconvolution were also considered by few other researchers in recent past in their analysis (Tsinidis, 2017; Cilingir and Madabhushi, 2011a, 2011b, and 2011c; Kontoe et al., 2011, 2014; Amorosi and Boldini, 2009). The accuracy of the FE analysis depends on the size and distribution of the elements in the mesh. A model is discretized with the triangular 15-noded element. In the dynamic calculation, the size of the elements needs to be chosen according to the characteristics of the input signal and the soil. The adopted average element size is less than one-eighth of the wavelength ($\lambda_s = V_s/f$) of the shear wave that has the lowest velocity in the soil. To achieve the required level of accuracy, the time step in the solving of dynamic equations of motion is determined such that a wave does not cross more than one element per time step. A sensitivity analysis is carried out to check the boundary effect and to determine the required element size. The results of the sensitivity analysis converge well when the width and the depth of the model are 140 m and 75 m, respectively. The simulation of tunnel excavation and construction in numerical analyses requires stepwise calculation, in which the first stage is to generate an initial stress field. Subsequently, the soil is excavated and stabilized by the tunnel lining. The ground volume loss due to the disturbance of the shield is restricted to up to 1% under normal conditions. Thereafter, dynamic loading is applied in terms of acceleration-time history. Under dynamic loading, the undrained state prevails and, thus, Poisson's ratio (ν_s) is, ideally, 0.5. However, to avoid convergence issues in numerical modeling, ν_s is taken as 0.49.