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Stability of a circular tunnel in presence of pseudostatic seismic body forces

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ABSTRACT

The stability of a long circular tunnel in a cohesive frictional soil medium has been determined in the presence of horizontal pseudo-static seismic body forces. The tunnel is supported by means of lining and anchorage system which is assumed to exert uniform internal compressive normal pressure on its periphery. The upper bound finite element limit analysis has been performed to compute the magnitude of the internal compressive pressure required to support the tunnel. The results have been presented in terms of normalized compressive normal stress, defined in terms of σ_i/c; where σ_i is the magnitude of the compressive normal pressure on the periphery of the tunnel and c refers to soil cohesion. The variation of σ_i/c with horizontal earthquake acceleration coefficient (α_h) has been established for different combinations of H/D, $\gamma D/c$ and ϕ where (i) H and D refers to tunnel cover and diameter, respectively, and (ii) γ and ϕ correspond to unit weight and internal friction angle of soil mass, respectively. Nodal velocity patterns have also been plotted for assessing the zones of significant plastic deformation. The analysis clearly reveals that an increase in the magnitude of the earthquake acceleration leads to a significant increment in the magnitude of internal compressive pressure.

1. Introduction

Large underground openings in the form of highway and railway tunnels are often constructed in soils and rocks. Determining the stability of a tunnel forms a major design task. In addition to static forces, the tunnels located in a seismically active zone are also subjected to seismic body forces during the event of an earthquake. A series of investigations have been performed by a number of researchers for evaluating the stability of tunnels and underground openings for static condition (Atkinson and Potts, 1977; Mair, 1979; Davis et al., 1980; Leca and Dormieux, 1990; Sloan and Assadi, 1992; Wu and Lee, 2003; Osman et al., 2006; Klar et al., 2007; Yang and Yang, 2010; Wilson et al., 2011; Yamamoto et al., 2011a,b; Sahoo and Kumar, 2013). By conducting a number of experiments, Atkinson and Potts (1977) have examined the stability of circular tunnels in cohesionless soils supported by means of either compressed air or bentonite slurry. Mair (1979) carried out centrifuge tests on model tunnels constructed in soft clay and supported by means of air pressure from inside. The response of the tunnel was observed as the compressed air pressure within the tunnel was gradually reduced until failure. By performing lower and upper bound limit analysis, Davis et al. (1980) determined the internal support pressure needed to maintain the stability of an underground opening made in a fully cohesive soil medium. Leca and Dormieux (1990) presented solutions for finding the stability of shallow circular tunnels in frictional material based on lower and upper bound limit analysis. With the help of the lower and upper finite element limit analysis in combination with linear programming, Sloan and Assadi (1992) obtained the solution in a bound form for assessing the collapse of a circular tunnel in a clayey medium whose undrained shear strength increases linearly with depth. For a single as well as for a group of parallel tunnels in clay, Wu and Lee (2003) conducted centrifuge model tests to monitor ground movements and the governing collapse mechanism. The compressed air inside the tunnel was used to counteract the overburden stresses acting over the tunnel, and the movement of soil mass was continuously monitored with the gradual reduction of the air pressure until the tunnel finally collapsed. Based on kinematic analysis, Osman et al. (2006) computed ground movements around a tunnel in undrained clay. Klar et al. (2007) derived two and three dimensional upper bound solutions for tunnels formed in soft ground. With the application of the upper bound finite element limit analysis and linear programming, Yang and Yang (2010) computed the internal support pressure on the sides of a shallow

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rectangular tunnel to maintain its stability in a cohesive frictional soil medium. By employing the finite element limit analysis in conjunction with nonlinear programming, Wilson et al. (2011) assessed the stability of a circular tunnel in undrained clay whose cohesion increases linearly with depth. Following the similar limit analysis approach, Yamamoto et al. (2011a,b) carried out the analysis for circular and square tunnels in a cohesive frictional soil medium.

In order to examine the effect of seismic waves on finding the response of tunnels in soils, a few investigations have also been reported in literature (Stamos and Beskos, 1996; Kirzhner and Rosenhouse, 2000; Hashash et al., 2001; Liu and Song, 2005; Pakbaz and Yareevand, 2005; Esmaeili et al., 2006; Merino et al., 2009; Shahrour et al., 2010; Kouretzis et al., 2011; Chen et al., 2012). By employing the boundary element method, for a long circular concrete lined tunnel formed in a soil medium, Stamos and Beskos (1996) computed (i) the normalized displacement amplitudes in radial and axial direction, and (ii) the normalized hoop stress amplitudes on the center line of the tunnel liner due to the occurrence of primary (P) and shear wave (SV) waves. Kirzhner and Rosenhouse (2000) computed the influence of dynamic loads on the development of stresses and displacement fields around the tunnel with the usage of the numerical program FLAC. Based on the post-earthquake analysis of tunnels, Hashash et al. (2001) examined different methods that are used for the seismic design of underground structures. By using the fully coupled dynamic Finite Element code DYNA, Liu and Song (2005) studied the seismic performance of a subway tunnel in saturated liquefiable soils; the effects of vertical earthquake motions and the buried depth of the underground structure on the stability of tunnel were analyzed. Pakbaz and Yareevand (2005) have performed elasto-plastic numerical analysis in a two dimensional domain by using the finite difference method in order to determine the effects of peak acceleration, intensity and duration of earthquake on the tunnel lining and ground interaction behavior. With the help of boundary and finite element method, Esmaeili et al. (2006) tried to examine the stress concentration in a circular lined tunnel subjected to primary and shear seismic waves. Merino et al. (2009) presented closed form solutions for determining displacement, shear force and bending moment at any tunnel section as a function of the seismic excitation, tunnel geometry and material properties. With the application of the elasto-plastic finite element analysis, Shahrour et al. (2010) examined the influence of plasticity and soil dilatancy, on the seismic response of tunnels constructed in a soft clay. Kouretzis et al. (2011) employed 3-D flexible thin shell theory for the strain analysis of near surface long cylindrical underground structures such as buried pipelines and thin-walled tunnels against seismic Rayleigh wave propagation. Chen et al. (2012) carried out model tests on a tunnel which was mounted on a shaking table and subjected to transverse non-uniform earthquake excitation. By employing the upper bound limit analysis, the authors (Sahoo and Kumar, 2012) have recently evaluated the stability of a long unsupported circular tunnel in the presence of horizontal pseudo-static earthquake body force. No exclusive research, however, seems to have been reported in literature to examine the stability of a tunnel which is supported from inside by means of uniform internal pressure and is subjected to seismic body forces. This was the motive behind the present research work. It is intended to determine the magnitude of internal support pressure (σ_i), similar to the compressive air pressure modeled by a number of researchers (Atkinson and Potts, 1977; Mair, 1979; Davis et al., 1980; Leca and Dormieux, 1990; Sloan and Assadi, 1992; Wu and Lee, 2003; Osman et al., 2006; Yang and Yang, 2010; Wilson et al., 2011), needed to maintain the stability of a circular tunnel in a cohesive frictional soil medium with the inclusion of pseudo-static horizontal earthquake body forces. An upper bound finite elements limit analysis in combination with linear optimization has been adopted to perform the analysis. For the purpose of design, the internal support pressure (σ_i) which is needed to maintain the stability of tunnel, is expressed in the form of a dimensionless parameter (σ_i/c) as a function of dimensionless arguments α_h, H/D, $\gamma D/c$ and ϕ; where (i) α_h is the coefficient of horizontal earthquake acceleration, (ii) H and D are the depth and diameter of the tunnel, and (iii) γ, c and ϕ correspond to unit weight, angle of internal friction and cohesion of soil mass, respectively. From the computational results, the variation of (σ_i/c) with α_h for different combinations of H/D, $\gamma D/c$ and ϕ have been established. The nodal velocity patterns have also been plotted for a few cases to explore the effect of the seismic body forces.

2. Problem definition and domain

With reference to Fig. 1(a), a circular tunnel of diameter D is placed at an embedment depth H (cover) below horizontal ground surface in a cohesive-frictional soil medium. The periphery of the tunnel is supported by means of lining and the associated anchorage system which is assumed to exert uniform compressive pressure σ_i. The length of the tunnel is assumed to be very long as compared to its diameter so that a simple plane strain analysis remains applicable. The magnitude of σ_i, which needs to be exerted on the periphery of the tunnel, has to be evaluated for maintaining the stability of the tunnel in the presence of horizontal

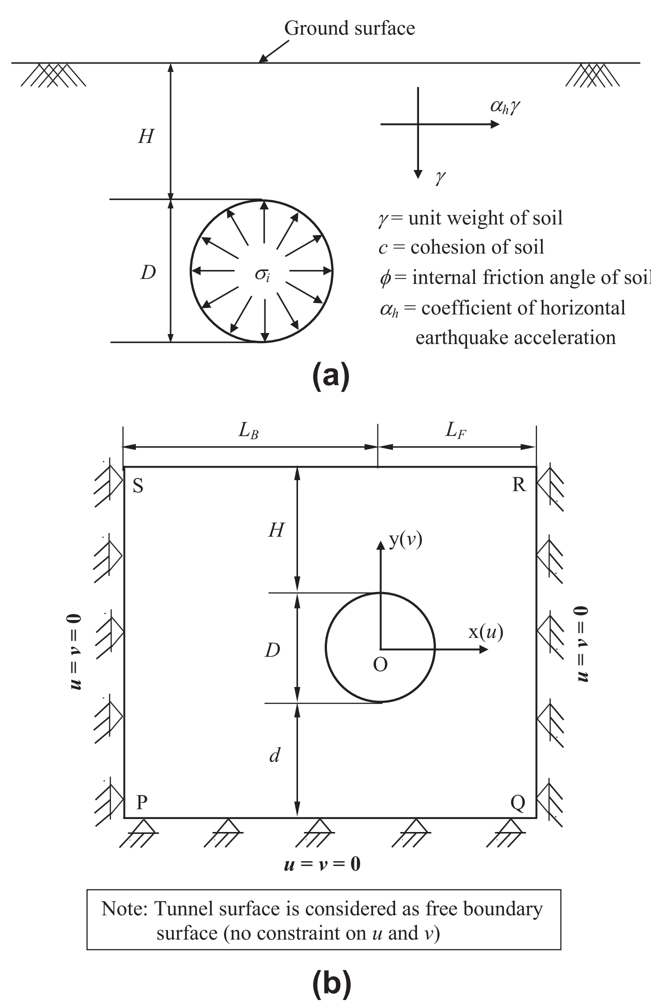

Fig. 1. (a) Definition of the problem and (b) chosen domain and the associated boundary conditions.