Soil Dynamics and Earthquake Engineering 28 (2008) 1063–1077

SOIL DYNAMICS AND EARTHQUAKE ENGINEERING

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Simplified analysis of seismic in-plane stresses in composite and jointed tunnel linings

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Received 30 September 2007; accepted 3 December 2007

Abstract

This paper presents an analytical procedure for evaluating in-plane moments and thrusts in composite and jointed tunnel linings during earthquakes. The analytical procedure treats the tunnel lining as an inner jointed thin-walled shell coupled with an outer thick-walled cylinder embedded in linear elastic soil or rock. The outer thick-walled cylinder can also be used to approximately model a degraded zone around the tunnel lining caused by mechanical disturbance and/or disturbance of the *in situ* stress field due to tunnel construction. The influence of in-plane shear stress is taken into account by assuming the free-field ground response produced during an earthquake is perpendicular to the longitudinal axis of the tunnel. Solutions for moment and thrust are presented for cases involving slip and no slip at the liner–ground interface. A parametric study is performed to investigate the effects of joint flexibility and a degraded annulus of soil or rock around the lining on the seismically induced moments and thrusts.

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Keywords: Analytical solution; Tunnel lining; Joint stiffness; In-plane shear; Weakened zone; Internal forces; Seismic performance

1. Introduction

Seismic effects on buried infrastructure are a major concern in regions that are prone to earthquakes. Consequently, several simplified methods of analysis have been developed to evaluate seismic effects on tunnels and pipelines. For example, Hindy and Novak [1,2] describe an approach to assess axial strains in pipelines caused by seismic waves propagating in the longitudinal direction of a pipeline. Atkinson et al. [3] use a similar approach to evaluate in-plane bending moments in buried pipelines induced by spatial incoherence of seismic waves. Merrit et al. [4] and Wang [5] used a simplified solution for tunnel linings [6] to study various aspects of the global seismic response of tunnels. In addition, Penzien and Wu [7] and Penzien [8] describe analytical procedures for evaluating the effect of in-plane shear stresses on tunnel linings induced by earthquakes. Thus far, these analytical methods are applicable to tunnels with continuous linings constructed in homogenous elastic soil or rock. However, a disturbed or degraded zone can form around bored tunnels due to the effects of construction and/or disturbance of the *in situ* stress field. In addition, jointed tunnel linings are quite common.

This paper presents an analytical approach to evaluate in-plane moments and thrusts in composite and jointed tunnel linings during earthquakes. The tunnel lining is treated as an inner jointed thin-walled shell coupled with an outer continuous thick-walled cylinder embedded in elastic soil or rock (ground). The outer thick-walled cylinder can be used to simulate composite liner behavior (e.g. tunnel supports comprising a primary and secondary lining) or to consider the influence of a degraded zone around the inner tunnel lining. A continuous inner liner can also be assumed. Solutions for moment and thrust are presented for the case of no slip at the lining–ground

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0267-7261/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2007.12.001

interface. In addition, the influence of a weakened or degraded zone around the tunnel is investigated using the equivalent linear approach. The analytical procedures described below extend those of Penzien and Wu [7] and Penzien [8] to new cases of composite and jointed tunnel linings, which should aid in the design of tunnel linings in active seismic regions.

2. The double liner solution

2.1. Problem geometry

El Naggar and Hinchberger [9] developed an analytical solution for the internal forces in composite circular tunnel linings embedded in a homogenous infinite elastic medium and subjected to an initial anisotropic stress field. Fig. 1 shows the problem geometry, where σ_v and σ_h denote the initial vertical and horizontal stresses in the ground, respectively, $\sigma_h = K_o\sigma_v$, and K_o is the coefficient of lateral earth pressure. For the solution, the initial *in situ* stress field (see Fig. 2) is separated into a hydrostatic component, $P_o = (\sigma_v + \sigma_h)/2$ and a deviatoric component, $Q_o = (\sigma_h - \sigma_v)/2$. The moment and thrust are determined in terms of the angle, θ measured counter clockwise with respect to the spring line axis of the tunnel.

As detailed below, it is assumed that the tunnel lining comprises an inner jointed thin-walled shell with elastic modulus E_1, Poisson's ratio ν_1, cross-sectional area A_1, moment of inertia I_1, and joints with rotational stiffness, k_θ. The intrados and extrados of the inner lining are defined by R_1 and R_2, respectively. The inner lining is surrounded by a thick annulus of soil (or a secondary liner

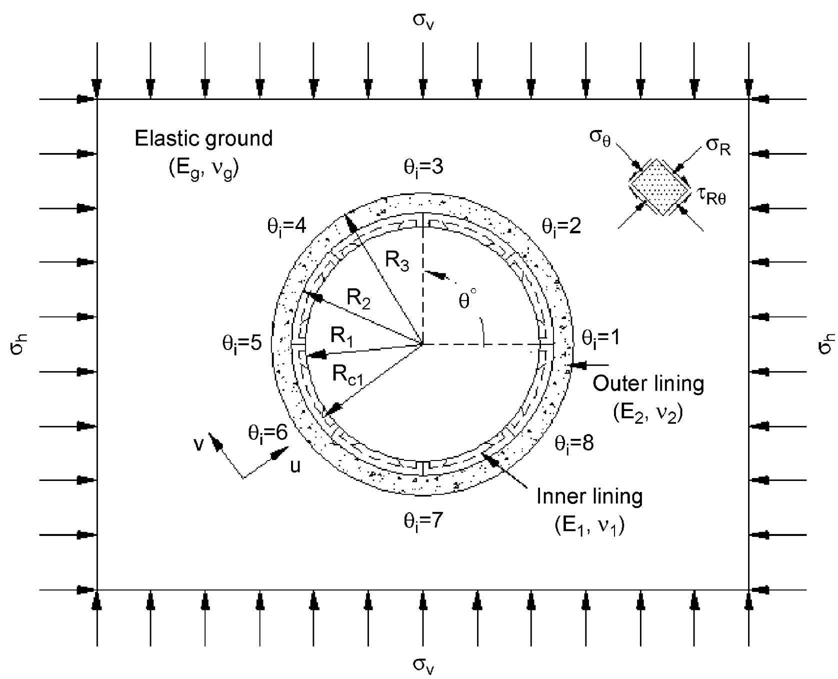

Fig. 1. Problem geometry—jointed double liners system.

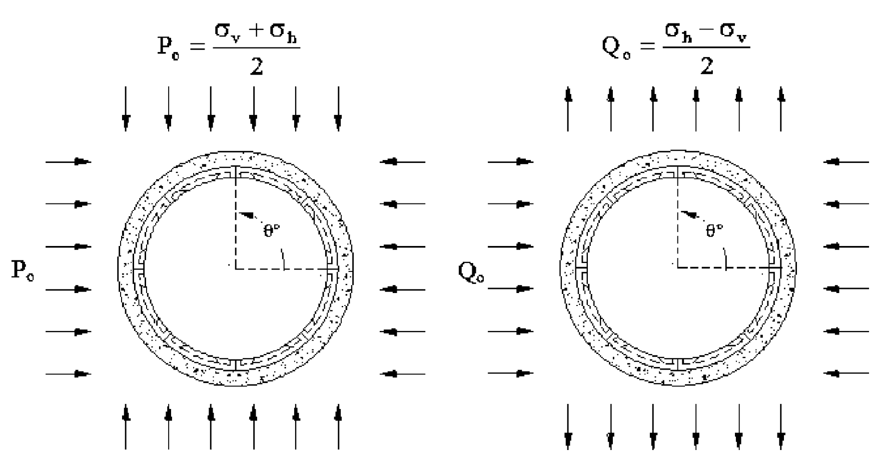

Fig. 2. Hydrostatic and deviatoric components of the solution.

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