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The effect of an explosion in a tunnel on a neighboring buried structure

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ABSTRACT

A comprehensive approach to simulate the effects of an explosion occurring inside a buried infrastructure tunnel on the soil surface and on nearby tunnels is presented. The approach considers all the stages of the complex process: detonation of the internal explosive charge; the shock wave propagation through the air in the tunnel and its following interaction with the cavity's lining; it then examines the soil-structure dynamic interaction, including wave propagation in the surrounding soil medium and their interaction with the nearby tunnels. The soil model takes into account both bulk and shear elastic plastic behavior, including the effect of the soil pressure on the yield strength for the stress tensor deviator. The variational-difference method is applied to solve the problem in the soil and in the lining domains. The developed approach allows studying the effect of the soil and lining properties on the soil-tunnel interaction as well as the explosion effect on a nearby tunnel behavior and on the soil surface response.

1. Introduction

Confined explosions in tunnels may occur due to various reasons and their effects may be extremely severe and lead to serious damage to structural elements and even to their collapse. The confined explosion causes more damage than the damage caused by a similar external free-air explosion, and this damage depends on the geometrical parameters of the space where the explosion occurs (geometrical dimensions, the charge location, the openings' size and location, etc.) as well as on the charge characteristics. The effects of interior explosions inside underground chambers (Ma et al., 2011; Wu et al., 2003a, 2004b; Hao et al., 2001), in storages (Wu et al., 2003b, 2004a; Wu and Hao, 2006; Skjeltorp, 1968) and in tunnels (De et al., 2010; Buonsanti et al., 2011; Wen-ge et al., 2008; Li and Tian, 2004; Liu, 2009; Benselama et al., 2010; Feldgun et al., 2007, 2008a) were studied. A good overview that is highly relevant to the present problem is given in (Zhao et al., 1999). It describes studies that were carried out in Singapore on the effect of underground explosions on the stability of adjacent rock caverns.

Shock waves generated in interior explosions may cause severe damage to nearby public, residential and industrial structures (Wu et al., 2004a). Therefore, the problems of shock waves propagation in rock and soil as well as ground vibrations resulting from various buried explosions are of great interest to experts who are supposed to carry the analysis and design of surface and underground structures (chambers, storages and tunnels). A typical analysis that involves the containing structure, the surrounding soil and the nearby structure, is rather complex. In general, the explosion pressure response of the containing structure's envelope should be coupled with the hydrodynamic processes of the explosion and resulting shock waves hitting the interior face of the envelope, however, when the structural envelope is relatively rigid, its motion does not affect the blast pressure time history and the analysis maybe uncoupled (Feldgun et al., 2011a).

Most of the publications, dealing with these problems refer to a rather simple case of a single tunnel buried in soil. The present problem examines the results of the occurrence of an interior explosion in a tunnel and the instantly released large amount of energy as blast waves (Tian and Li, 2008; Li et al., 2006), on its surroundings. This is because a severe explosion may cause not only damage to the confining tunnel but also strongly affect adjacent tunnels and aboveground structures. In a special case where there exists an intermediate tunnel between the confining tunnel and the ground surface, the traveling shock waves, when obstructed by another tunnel that is placed in between the explosion tunnel and an aboveground structure, will be reflected and refracted around the intermediate tunnel and this will affect the dynamic response of the above ground structure (Tian and Li, 2004; Yu et al., 1996). This problem of other underground and above ground structures, interacting with the results of an explosion in a confining tunnel, is rather complex and has not been sufficiently investigated. A very small number of reported works on the above subject

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has been published. The three-dimensional finite element software ABAQUS was used (Liu, 2009) to analyze the dynamic response and assess the damage of subway structures in different ground media. The elasto-plasticity of the ground media, the possible damage of the lining material and the nonlinear interaction between the lining and the ground were taken into account in the numerical models. Blast loading was modeled as a specific impulse and peak blast pressure using CONWEP. Dynamic response of the soil surface and of a multi-story building that is founded on the top surface to a ground shock induced by an in-tunnel explosion were numerically analyzed in another paper (Tian and Li, 2008). The effect of an adjacent parallel tunnel is also considered in the analysis. Different methods, such as the eight-node iso-parametric finite element and mass-lumped system, were used to establish the coupling model consisting of the two adjacent tunnels, the surrounding soil medium and the multi-storey building. A numerical simulation of the vibration resulted from blasting construction of an underpass tunnel that was located a short distance away from an existing tunnel, was conducted with LS DYNA, and field testing was carried out in another paper (Wen-ge et al., 2008). The effect of an adjacent parallel tunnel is also studied in (Li et al., 2013). The surrounding rock mass is considered to deform elastically. The stress distribution around the adjacent tunnel wall is analyzed. Obviously, the research effort given to this problem is rather limited. A detailed analysis is needed to study the effects of an internal explosion on the response of a tunnel and on the effects on the surrounding soil, as well as the effects on an adjacent tunnel and on the soil top surface and on aboveground structures. The present paper aims at providing a comprehensive approach to simulate the stated problem considering all its aspects that are mentioned above. The developed approach considers all the aspects of the process including the interior explosion and its effect on the confining tunnel lining, soil-structure dynamic interaction due to the blast action on the lining's interior face, wave propagation in the surrounding soil medium and the waves interactions with the nearby tunnels. The soil model takes into account both bulk and shear elastic plastic behavior, including the effect of soil pressure on the yield strength for the stress tensor deviator. The variational-difference method is applied to solve the problem in the soil and in the tunnel lining domains and takes into consideration the possible soil-lining separation in tension.

In previous recent investigations the authors examined the effect of the soil and lining properties on the response of a single tunnel buried in soil and its interaction with the surrounding soil (Feldgun et al., 2007, 2008a, 2008b, 2009, 2011c, 2013a, 2013b, 2013c; Karinski et al., 2009, 2012; Yankelevsky et al., 2008, 2011, 2012). The present 2D approach is extended to include a nearby lined tunnel and investigate the effects of an internal explosion in one tunnel on the response of the adjacent tunnel as well as their effect on the response of the top surface.

2. The model

Consider two long tunnels with rectangular cross section dimensions $a_1 \times b_1$ and $a_2 \times b_2$ respectively (Fig. 1) that are buried in a soft soil at depths H_1 and H_2 respectively. The first tunnel is subjected to an interior blast loading resulting from an internal explosion of a line charge (Fig. 1). The line explosive is assumed to have a square cross section with the cross section dimensions $R_E \times R_E$. The center of mass of the charge is placed at distances a_E and b_E from the tunnel walls as shown in Fig. 1a. Thus, the line charge loading density is $\rho_E(R_E)^2$ where ρ_E is the reference density of the explosive. The explosion effect on the soil free surface and on the neighboring (second) tunnel is examined for specified values of the above mentioned parameters (Fig. 1). This problem may be formulated as a 2-D plain strain problem, and its solution may utilize a 2-D code that had been developed through a series of studies. The 2-D solution may provide much insight into this complex problem and provide an effective and relatively fast solution. It should be noted that the comprehensive method which is proposed in the present paper allows considering tunnels and charges with any arbitrary shapes.

The dry soft soil is considered as an infinite homogeneous isotropic irreversible compressible elastic plastic medium (Grigoryan, 1960; Grujicic et al., 2006; Luccioni and Ambrosini, 2006; Luccioni et al., 2009). The pressure–density relationship is schematically shown in Fig. 2.

The bulk behavior of this material is described by an initial linear elastic behavior (segment A_1A) that is small and generally can be disregarded. This elastic segment is followed by a zone of elastic plastic bulk compaction (segment ABC) with hardening caused by the closure of the internal pores. A non-linear elastic model (segments B_1B, C_1C) that is different from the active loading line ABC represents unloading and reloading at this stage. The unloading line is uniquely determined by the maximum soil density ρ^* that is attained in the process of active loading. This irreversible process occurs as long as the density is smaller than the full compaction value ρ_{FC} (point C) corresponding to the full closure of the internal pores. Thereafter the medium behaves as a non-linear elastic material (segments CD_1, CD_2 or CD_3). This zone corresponds to a constant ρ^* and, therefore, $\rho_1 \leqslant \rho^* \leqslant \rho_{FC}$. The model allows describing the range of pressure values from low pressures (for the case of a far explosion) to very high pressures (for the case of a nearby explosion).

The soil spherical (hydrostatic) pressure takes the form (see Fig. 2):

$$p = f(\rho,\rho^*) = \begin{cases} f_L(\rho) & \text{for the active loading} \quad (A_1ABCD) \\ f_U(\rho,\rho^*) & \text{for unloading and reloading} \quad (B_1B, C_1C) \end{cases} \tag{1}$$

where ρ is the soil current density.

The functions f_L and f_U in Eq. (1) depend on the type of the medium and may be obtained from dynamic compression tests (Forestal et al., 1984; Bragov et al., 1996).

Fig. 2 shows three different possible loading branches to describe the material behavior beyond the point of full compaction: a linear extension (C–D_3), a polynomial branch (C–D_2) and a full locking branch (C–D_1). In most references mentioned above a polynomial branch is adopted. The polynomial branch may have a more moderate curvature when it is closer to the linear branch or it may be steeper when it approaches the full locking branch. The linear and the full locking branches may be considered as the lower and upper bounds of the polynomial branch. The level of steepness is quantified by the polynomial degree. For the full locking (shock Hugoniot) soil, the following functions have been chosen (Bazhenov et al., 2001; Zukas, 2004; Yankelevsky et al., 2008):

$$\begin{aligned} &f_L(\rho) = \rho_0 c_0^2 \frac{\varepsilon_V}{(1-\beta\varepsilon_V)^2} \\ &,f_U(\rho,\rho^*) = f_L(\rho^*) + c_U^2(\rho^*)(\rho-\rho^*) \\ &,c_U(\rho^*) = \frac{c_0\rho_0}{\rho^*}\sqrt{\frac{1+\beta\varepsilon_V^*}{(1-\beta\varepsilon_V^*)^3}} \end{aligned} \tag{2}$$

where ρ_0 and c_0 are the initial density and sound velocity, $\varepsilon_V = 1 - \rho_0/\rho$ is the bulk strain ($0 \leqslant \varepsilon_V < 1/\beta$), $1/\beta$ is a full locking bulk strain (Fig. 2), $c_U(\rho^*)$ is the current sound velocity and $c_{FC} = \sqrt{df_L(\rho)/d\rho}|_{\rho=\rho_{FC}}$ is the sound velocity at the state of full compaction.