Tunnelling and Underground Space Technology 66 (2017) 64–76

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Assessment of damage to an underground box tunnel by a surface explosion

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ARTICLE INFO

Keywords:
Underground box tunnel
Explosive charge weight
Lining thickness
Burial depth
Damage levels

ABSTRACT

Recently, external terrorist activities have become one of the most influential events on tunnel structure safety because of the absence of proper mechanisms to detect these events in time to take preventive action. The present study used ANSYS/LS-DYNA software to investigate the damage behaviour of an underground box frame tunnel caused by a surface explosion of a sedan, van, small delivery truck (SDT), and container carrying 227, 454, 1814, and 4536 kg, respectively, of TNT charge weight. The Arbitrary Lagrangian Eulerian (ALE) technique was used to simulate and monitor the propagation of the blast pressure waves into the soil. The validation results indicated that the pressure waves propagated into the soil as hemispherical waves, and the peak pressure values closely matched the predicted values of the technical design manual TM5-855-1, except for large distances. Therefore, an equation was derived to calculate the values of the peak pressure at large distances for each explosion case. Intensive parametric studies were conducted to evaluate the interaction between the explosive charge weight, the tunnel lining thickness and the burial depth, which has a significant effect on tunnel safety. The assessment of the damage levels using the single degree of freedom (SDOF) approach proved that the tunnel experienced little damage when the explosive charge is a sedan or van with a lining thickness of 250, 500 or 750 mm at burial depths of 4, 6, or 8 m. However, tunnel collapse occurred when the lining thickness was 250 mm, and the tunnel was subjected to an explosion of an SDT or container at all investigated depths, as well as the case for a lining thickness of 500 mm at a depth of 4 m for the container explosion. The tunnel lining with a thickness of 750 mm appeared to be highly resistant to the explosion of an SDT or container for all the investigated depths, and the best resistance was achieved at a depth of 8 m, which should be considered by designers to ensure the safety of an underground box tunnel when subjected to an incredible surface explosion.

1. Introduction

Throughout the years, underground tunnels have offered a quick and cost effective alternative to address transportation requirements in many countries. Terrorist attacks, such as the bombing of the Moscow Metro in 2004, London Subway in 2005, and Belarus in 2011, highlight that these structures should be carefully designed to withstand such events. The main method terrorists used to implement these attacks is using a vehicle bomb because of its enormous charge power, high success rate and serious demolition (Kong et al., 2007).

Tunnel structures can be exposed to internal or external explosions. The internal explosions are less likely to occur because it is hard to get an explosive material inside a tunnel because of modern security and control systems inside subway tunnels that can easily detect such explosive devices. Nevertheless, scholars have studied the dynamic response of underground tunnels subjected to internal explosions (Feldgun et al., 2008, 2014; Jiang and Zhou, 2012; Papanikolaou and Kappos, 2014). On the other hand, external blasts are more likely to occur and cause more destruction because of the difficulties in monitoring and preventing such events before they occur. In this research field, there are no databases on full-scale field experiments to investigate the tunnel dynamic response for a surface blast because such an experiment is extremely risky, costly and unachievable in civilian research because of the requirement of a large quantity of explosives. However, some researchers (Kutter et al., 1988; Davies, 1991, 1994; Davies and Williams, 1992) used scaled-down centrifuge modelling techniques to determine the dynamic responses of tunnels. They observed that centrifuge tests are a valid method to model the effects of an explosion in soil. De (2012) and De et al. (2013) carried out several centrifuge tests to describe the influence of a surface detonation on a cylindrical structure buried in dry sand. These experiments provided quantitative data for the effect of surface explosions on buried tunnels.

Recently, numerical techniques have been used, and they represent

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http://dx.doi.org/10.1016/j.tust.2017.04.001
Received 13 June 2016; Received in revised form 16 November 2016; Accepted 2 April 2017

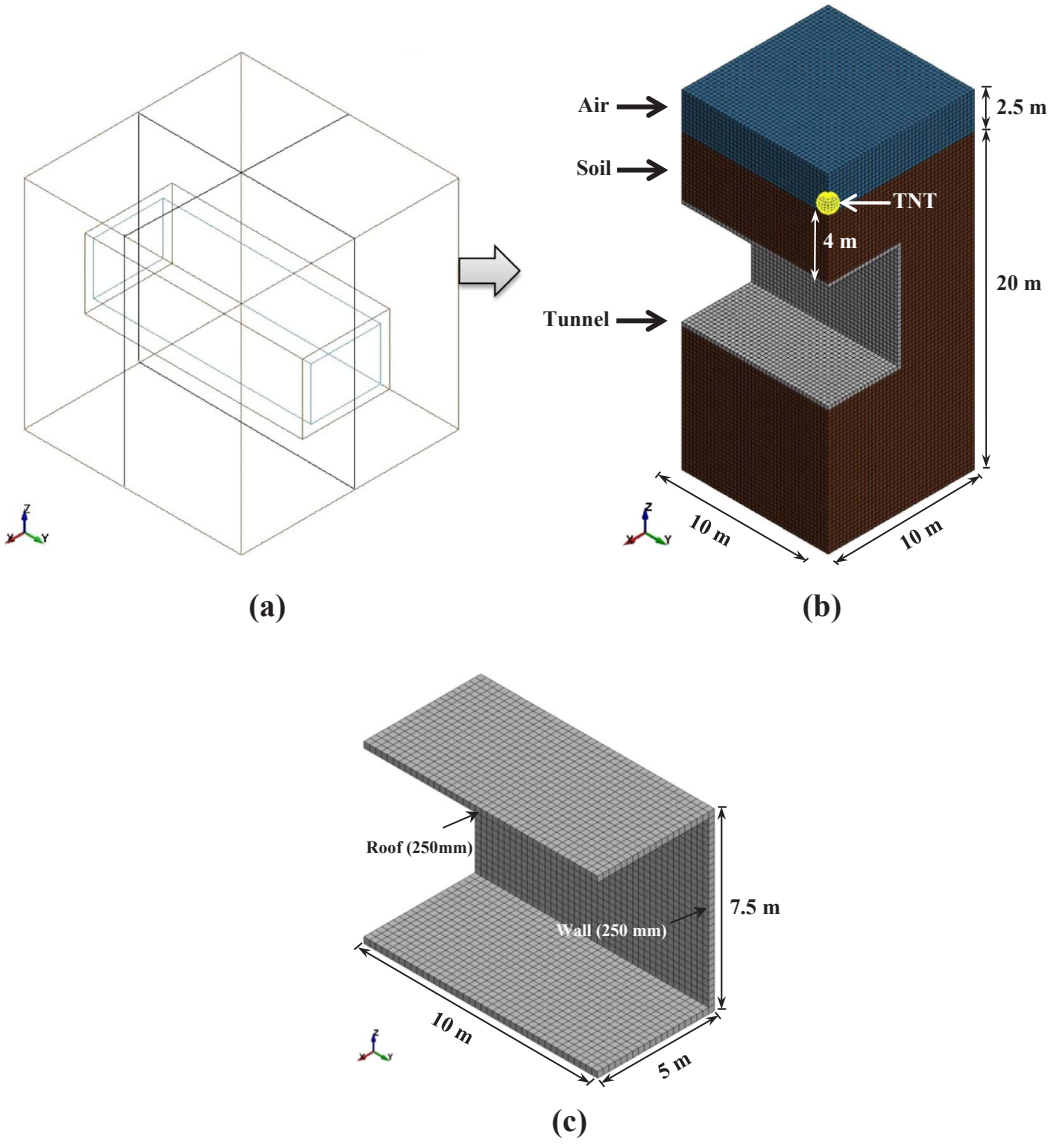

Fig. 1. Geometry of the numerical model: (a) full scale, (b) 1/4 symmetric geometrical model, and (c) tunnel dimensions.

Table 1
Weight of explosive (TNT equivalent) to fill a vehicle.

Type of vehicles	Vehicle description	Explosives materials capacity (kg)
	Sedan	227
	SUV/van	454
	Small Delivery truck	1814
	Container/water truck	4536
	Semi-trailer	27,216

a good alternative to provide valuable information in a timely and cost-effective manner. Wang and Lu (2003), Wang et al. (2004) created a numerical three-phase soil model that is able to simulate an explosion wave propagation into soils. Lu et al. (2005) and Wang et al. (2005) utilized this model to study the response of buried structures subjected to underground explosions.

Luo et al. (2007) analysed the dynamic response of a circular underground tunnel to a surface explosions of 100 and 300 kg of TNT charges in sandy soils. The numerical results indicated that the top part and the centre at the bottom of the subway section are the most damaged zones. The tunnel was safe when 100 kg of TNT explodes at a height of 1.5 m. Yang et al. (2010) estimated the dynamic behaviour of a circular metro tunnel exposed to a surface detonation using the Arbitrary Lagrangian-Eulerian (ALE) method in which the Eulerian meshes were applied to the air, soil and TNT while the Lagrangian mesh was applied to the tunnel. The results showed that the upper part of the tunnel lining is more vulnerable compared to other parts, and the tunnel with a lining thickness of 350 mm is safe for depths greater than 7 m for surface explosions containing less than 500 kg of TNT.

Tiwari et al. (2014) performed a coupled Eulerian-Lagrangian (CEL) analysis using Abaqus software on circular underground tunnels subjected to an internal blast. The outcomes demonstrated that damage in