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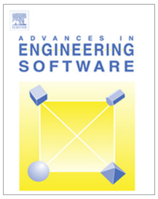

Response of segmented bored transit tunnels to surface blast

Sivalingam Koneshwaran, David P. Thambiratnam*, Chaminda Gallage

Science & Engineering Faculty, Queensland University of Technology, Australia

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ABSTRACT

Increasing threat of terrorism highlights the importance of enhancing the resilience of underground tunnels to all hazards. This paper develops, applies and compares the Arbitrary Lagrangian Eulerian (ALE) and Smooth Particle Hydrodynamics (SPH) techniques to treat the response of buried tunnels to surface explosions. The results and outcomes of the two techniques were compared, along with results from existing test data. The comparison shows that the ALE technique is a better method for describing the tunnel response for above ground explosion with regards to modeling accuracy and computational efficiency. The ALE technique was then applied to treat the blast response of different types of segmented bored tunnels buried in dry sand. Results indicate that the most used modern ring type segmented tunnels were more flexible for in-plane response, however, they suffered permanent drifts between the rings. Hexagonal segmented tunnels responded with negligible drifts in the longitudinal direction, but the magnitudes of in-plane drifts were large and hence hazardous for the tunnel. Interlocking segmented tunnels suffered from permanent drifts in both the longitudinal and transverse directions. Multi-surface radial joints in both the hexagonal and interlocking segments affected the flexibility of the tunnel in the transverse direction. The findings offer significant new information in the behavior of segmented bored tunnels to guide their future implementation in civil engineering applications.

1. Introduction

Underground transit tunnel systems provide a quick and cost effective alternative to laying surface rails and roads and play an essential role in addressing transportation needs in many cities. Increasing blast attacks highlight that these underground transit tunnels are vulnerable to potential terrorist attacks with possible failure causing loss of lives, transit network interruptions and considerable financial implications. Transit tunnels must therefore be designed to withstand ground shocks transmitted from credible explosions. It is desirable that if such an explosion did occur, the tunnel should be able to return to service as soon as possible with minor repairs.

The central part of a rapid transit network in cities is usually built in tunnels. These tunnels are mostly bored tunnels constructed using tunnel boring machines (TBM) with the support of permanent linings. The principle of bored tunnel construction has been known for a long time. The tunnels constructed in the beginning of the nineteenth century are still in use in many cities. They have a direct relationship with the identity of the city as they illustrate its history, culture, and its economic, political and social states. This also highlights the importance of protecting such structures.

Bored tunnel consist of prefabricated reinforced concrete segments placed together with bolts in both the longitudinal and transverse directions. In order to prevent water from entering the tunnel through the joints, the segments are provided with an inside groove to accommodate a watertight gasket. The primary load resisted by the segments is circumferential (hoop) stress induced by external pressure from the surrounding ground acting on the circumference of the tunnel. The segments are generally designed to resist the axial bearing loads and buckling from the TBM thrust loads. Under geostatic conditions, the segments transfer load across the joints without damage in the concrete segments. However, the response of the segments under blast loads is more complex as the tunnel system employs the flexibility of its segmented linings to resist the blast load. In segmented tunnels, the segments resist the blast load by allowing the joints to rotate, slide and dissipate energy in order to achieve equilibrium before the concrete segments are damaged. Structural analysis of segmented tunnel under static and earthquake loads has been the subject of several studies. However, there is inadequate information on the blast response of bored tunnels. Nasri Munfah [1] described that thin precast segmented tunnel linings are more vulnerable to blast loads than thick cast in place concrete tunnels.

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* Corresponding author at: School of Civil Engineering & Built Environment, Queensland University of Technology, GPO Box 2434, Brisbane, Queensland 4001, Australia. Tel.: +61 7 3138 1467; fax: +61 7 3138 1170.

E-mail address: d.thambiratnam@qut.edu.au (D.P. Thambiratnam).

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In this research field, explosive tests with real physical models are extremely risky and expensive to investigate the tunnel response. A limited number of studies however have been conducted using scaled-down centrifuge modeling techniques to investigate the tunnel response under surface blast loading. The centrifuge modeling is useful for scale modeling of large-scale nonlinear problems in geotechnical engineering. Studies [2–7] have shown the successful implementation of centrifuge modeling to simulate the blast response of buried structures. De et al. [2,3] described a recent series of centrifuge tests to examine the surface blast effect on a buried copper pipe in dry sand. During this process, the gravitational acceleration increases with radial distance along the rotating arm of the centrifuge and hence the gravitational field is not constant across the depth of the model in the test bucket. This limitation controls the centrifuge testing to smaller models. Scaled-down modeling of large structures such as bored tunnels with segments may be impossible due to the size limitation. Moreover, it may not be feasible to investigate the effect of contact joints using the scaled-down models.

The possible alternative therefore is to use numerical modeling techniques which can provide valuable data in a timely and cost effective manner to enable the development of design tools and retrofit measures. Several studies [3,8–12] have treated the simulation of the blast response of transit tunnels. De [3] used the coupled fluid–structure interaction (FSI) approach in Arbitrary Lagrangian Eulerian (ALE) algorithm to study the surface blast induced tunnel response using Autodyn. Eulerian meshes were used to model the air and explosive while the soil and the tunnel were modeled with Lagrangian meshes. Yang et al. [9] studied the blast response of a metro tunnel in Shanghai using an advanced general purpose multi-physics computer software LS-DYNA [13]. The study also used ALE method, but the interface between Eulerian soil meshes and Lagrangian tunnel meshes was merged at the common nodes. The modeling was unable to simulate the ground-lining interaction and subsequent separation, re-contact and sliding at the contact interface. Bessette [14] simulated the Conventional Weapon Effect Backfill test [15] using FSI approach in ALE to investigate the blast response of a reinforced concrete box structure buried in various backfill conditions. In this study, the test structure was modeled using Lagrangian meshes while the other three materials, soil, air and explosive, were modeled as Eulerian meshes. Wang et al. [16] used a fully coupled procedure involving the Smooth Particles Hydrodynamics (SPH) method and the Finite Element Method (FEM) for analyzing the response of buried cut-and-cover tunnel subjected to blast loading using Autodyn.SPH particles were used to model the explosive and near field soil while Lagrangian meshes were used to model the rest of the soil and the tunnel. The techniques discussed above have the capability to simulate the sequences of phases, such as explosion, crater formation, shockwave propagation and the tunnel response. However, the numerical techniques need to be thoroughly validated in order to investigate a real problem.

This paper first compares ALE and SPH numerical techniques to investigate the above ground explosion and the subsequence tunnel response with regards to the modeling aspects of numerical prediction and computational efficiency reported in Koneshwaran et al. [17]. This study identified the better numerical technique which was then employed to treat the blast response of segmented bored tunnels buried in dry sand. This particular study was extended from previous investigation reported in Koneshwaran et al. [17]. The commercially available non-linear finite element software package LS-DYNA is used in this study. Tunnels with different types of segments were further compared in the present study to investigate the flexibility and drifting effects of the segmented tunnels.

2. Numerical simulations

Numerical simulations divide the system into finite elements, a process called discretization which occurs with respect to time (temporal) and space (spatial). The temporal discretization uses the explicit method which calculates the state of a system at a later time as a function of time step from the current state of the system. To describe any activities within an element, the time step should comply with the Courant–Friedrich–Levy (CFL) function such that the time step (Δt) is less than the period for sound to travel across the smallest element. For blast problems in LS-DYNA, it is recommended to use a Safety Factor (SF) of 0.67. This function can be generally described as below:

$$0 < \Delta t \leqslant N\frac{l}{c} \quad (1)$$

where N is the safety factor, l is the least element size and c is the speed of sound through the element.

2.1. ALE method

Computer hydrocodes include two types of spatial discretization solvers which are the Largrangian and Eulerian solvers. In the Lagrangian solver, the elements move with the material during the distortion. This is mainly used in structural mechanics where the distortion is represented by the mesh distortion. The Lagrangian solver provides easy tracking of free surfaces and interaction between different materials. This solver often suffers severe element distortion during large deformation which can result in very small time steps and grid tangling. The Eulerian solver, in which the mesh is fixed in space while the material flows freely through the mesh, is broadly used in fluid dynamics. Eulerian solver can also be used for solid materials to handle large distortions, but it is unable to define the material boundary conditions involving surface slippage in contact [16].

Arbitrary Lagrangian–Eulerian (ALE) approach was developed combing the best features of the above solvers, while reducing their respective weaknesses. ALE is capable of solving problems in fluid dynamics, solid mechanics and coupled problems describing fluid–structure interaction (FSI). Coupled FSI in ALE is a multi-physics simulation process for solving highly non-linear problems with large distortions such as those resulting from an explosion. It allows modeling the explosive and its surrounding using ALE meshes, in which deformable structures are modeled using Largrangian meshes. Firstly, the computation searches for the intersections of the ALE with Lagrangian meshes. When the Lagrangian surface is detected inside the ALE mesh, the coupling algorithm initiates the computation of the penetration of the ALE material across the Lagrangian surface. The interaction forces are calculated during every computational step for their resultant penetration of both materials. The ALE algorithm satisfies the governing equations describing the conservation of mass, momentum and energy [18].

2.2. SPH method

SPH is a meshless computational Lagrangian hydrodynamic particle method developed for astrophysics problems [19,20] in 1977. It initially dealt with modeling of interacting fluid masses in vacuum without boundaries. It was then improved as a deterministic meshless particle method and implemented to continuum solid and fluid mechanics [21,22]. SPH is free from mesh tangling encountered in large deformation problems. It is based on interpolation theory of kernel approximation of a function [18], which is adequately smooth for higher order derivatives to deliver stable and accurate results.

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