Soil-Tunnel Interaction under Medium Internal Blast Loading

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Abstract

A series of numerical simulations were carried out to study the interaction between subway tunnels and soils subjected to medium internal blast loading (< 200 kg of TNT equivalent). The excess pore-water pressure was studied with an existing soil model (FHWA) that can simulate pore-water pressure and effective soil pressure. A recently developed blast loading scheme that removes the necessity of modeling the explosive in the numerical models but still maintains the advantages of nonlinear fluid-structure interaction was used to study the process of blast wave propagation in the air domain inside the tunnel.

Keywords: soil-tunnel interaction, blast, underground structures, Finite Element method

1 Introduction

US transportation system has 337 highway tunnels and 211 transit tunnels in 2003 according to the Blue Ribbon Panel (BRP) on Bridge and Tunnel Security assigned by AASHTO [1]. These tunnels are facing threats of internal explosion which will cause large socioeconomic losses. However, mechanism of saturated ground-tunnel interaction under medium internal blast loading is still not well understood. There is no validated design guideline for tunnel linings in saturated soil due to medium blast loading.

Many transportation tunnels run through saturated soils [1]. Saturated soils subjected to blast loading generate drastic changes of compressive strain and excess pore pressure. Especially the residue of excess pore pressure will reduce effective stress and may result in soil liquefaction. The existing knowledge on explosion-induced compressive strain and pore pressure in saturated soil does...
not directly apply herein because explosion does not occur in soil and the tunnel modifies the characteristics of blast loading on soil [3].

Analyzing the effects of blast on tunnels and soils is a difficult task, as it involves highly nonlinear fluid dynamics, structural dynamics and fluid-structure interaction. At present, most blast resistant analyses make use of simplistic blast loading and structure models [2], but their accuracy cannot be guaranteed when complicated structure and loading scenarios are involved. The existing blast loading equations are focused on the free air blast, blast effect on plane rigid surface, or blast effect inside a rectangular structure [2]. The effects of confinement from tunnels on the blast loading are not studied or investigated thoroughly.

This research aims to study on the interaction between circular subway tunnels and saturated soils subjected to medium internal blast loading to improve the design and rehabilitation of transportation tunnels.

2 Literature Review

Responses of underground structures subjected to explosive loading have been extensively studied [e.g. 4-9] for its military importance. For explosions outside underground structures, most of the studies focused on cratering, earth pressure on underground structures, and corresponding structure damage.

Only few of these studies considered the coupling of pore fluid and soil particles [4], not to mention the change of effective stress and its effect on underground structures.

For explosions inside underground structures, air-blast, ground blast wave, blast pressure, collapse and debris of underground structures have been investigated. These studies are mostly related to large-scale explosions inside underground ammunition storages in rock mass, the findings of which cannot be directly applied to tunnels in saturated soils.

Few studies on the responses of underground structures subjected to internal blast loading [4] can be found. The subjects of Chille et al. [6] and Choi et al. [7] were both underground structures in rock masses. Preece et al. [9] investigated the response of a 13-ft-diameter aluminum tunnel in moist soil subjected to internal blast loading from 6600 pounds of TNT using centrifuge test, which is not realistic for the hazard facing general transportation tunnels. Port Authority of New York and New Jersey and several other transportation agencies investigated the blast vulnerability of specific tunnels after 9/11 but unfortunately their results are not released. Liu [4] found that under single blast loading, the tunnel vibrated drastically and applied multiple shocks to the ground media, which coincided with the finding of Feldgun et al. [8]

3 Finite Element Model

The blast loading was simulated with a new blast loading scheme (Load_Blast_Enhanced) available in LS-DYNA [10]. The air immediately around the tunnel lining is modeled by Eulerian air elements. A layer of special Eulerian elements works as the blast wave resource, which is herein referred to as the ambient layer. Time histories of incident blast pressure applied to the ambient layer are derived from embedded CONWEP in LSDYNA. The validity of this numerical approach was discussed by Han and Liu[11].

3.1 Base Model

As shown in the Figure 1, the Finite Element model consists of soil, soil-tunnel interface, tunnel lining, air and ambient layer. Due to symmetry, 1/4 model was simulated to save computer resources.
The prototype model is based on single-track subway tunnels in New York City. The diameter of the tunnel was assumed to be 5 m and the tunnel was buried 7.5 m below the ground surface. The thickness of saturated soil layer was assumed to be 15 m, the base of which was stiff bed rock and fixed in the Finite Element model. The length of the tunnel in the model was 30 m. The width of the model was 25 m. The lining thickness was assumed to be 6 cm based on the parameters of cast-iron subway tunnels in New York City. The Finite Element model was fixed at the base and roller boundaries were applied to the side planes. Centrifuge technique was used in the simulations to save computer resource.

3.2 Constitutive Model of Soil

The dense saturated soil was modeled by FHWA Soil Model. Most of the default parameters in LS-DYNA were employed in this study, which were calibrated by the model developer for dense granular soil with cohesive fines [12]. Table 1 shows the model parameters. The thin-layer elements between soil and lining were also modeled by FHWA soil model, but their shear modulus and shear strength were assumed as two thirds of those of soil.

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*Table 1 Material model parameters of the saturated soil (unit system: cm, g, μs)*

3.3 Constitutive Model of Tunnel

An isotropic elastic-plastic material in LSDYNA was used to simulate the cast-iron tunnel lining in the numerical analysis. In this model yield stress versus plastic strain curves can be defined for
compression and tension. Thus this model can simulate the cast-iron whose compressive strength is much larger than tensile strength.

The stress-strain behavior follows one curve in compression and another in tension. The sign of the mean stress determines the state where a positive mean stress (i.e., a negative pressure) is indicative of tension. Two load curves, \( f_t(p) \) and \( f_c(p) \) are defined, which give the yield stress \( \sigma_y \), versus effective plastic strain for both the tension and compression regimes. The two pressure values \( p_t \) and \( p_c \) when exceeded, determine if the tension curve or the compression curve is followed, respectively. If the pressure \( p \) falls between these two values, a weighted average of the two curves is used:

If \(-p_t \leq p \leq p_c\)

\[
\begin{cases}
    scale = \frac{p_c - p}{p_t + p_c} \\
    \sigma_y = scale \cdot f_t(p) + (1 - scale) \cdot f_c(p)
\end{cases}
\]

Strain rate is accounted for using the Cowper and Symonds model, which scales the yield stress with the factor

\[1 + \left(\frac{\dot{\varepsilon}}{\varepsilon_c}\right)^{1/p}\]

where \(\dot{\varepsilon}\) is the strain rate.

Figure 2 shows the stress and strain relations in tension and compression. The Young’s modulus of cast iron tunnel is 100Gpa. In the tensile direction, the tunnel is in the elastic domain before the strain reaches 0.001. The failure stress is 150 Mpa when the tensile strain equals to 0.004. In the compressive direction the yield stress of tunnel is 600 Mpa. In the numerical analysis failure flag was set up to plastic strain limit control. When the plastic strain reaches the limit value, the element is deleted from the calculation.

![Stress-strain relation in compression](image1)

![Stress-strain Relation in Tension](image2)

\[\text{Figure 2: Stress strain relation of tunnel lining}\]

Thin-layer elements are used to simulate the interface between soil and tunnel. The concept has been employed extensively in analyses of soil-structure interactions [18]. Ordinary solid elements was used to simulate the interfaces, but the thickness was about 0.01~0.1 of the longer dimension. Material model of the thin-layer elements was the same as that of the soil, but with reduced strength and shear modulus.
3.4 Constitutive Model of Air and Ambient Layer

The air in all the numerical simulations was modeled using linear 3D solid elements in LS-DYNA. The elements were 8-node hexahedron elements integrated using 8-point Gaussian method. The air and the ambient layer was assumed to be ideal gas and modeled using the MAT_NULL material model, the equation of state of which is given as:

\[ p = (\gamma - 1) \rho_0 E_0 \]  

Here \( \gamma \) is the ratio of specific heat and was assumed as 1.4 according to previous numerical experiences [13]. \( \rho_0 \) is the initial density of air and was assumed to be 0.00129 g/cm\(^3\). This value was increased in some of the analyses to investigate its effect. \( E_0 \) was given a value of 2.5e-1 MPa according to Schwer [13] and assuming an initial air temperature of 20 °C.

In the numerical simulations, gravity load was firstly applied, followed by the ignition of the explosive charge. Time-step in the second stage was set as 5µs to capture the response of the soil-tunnel system. The length of analyses in the model scale was set as 15 ms, at the end of which the main event of last loading was over. In the dynamic analysis, 5% viscous damping was considered for the geological materials while 2% was considered for the tunnel lining.

4 Results of Simulations

4.1 Impact Loading on Tunnel Lining

The peak pressure and specific impulse on the lining elements that did not fail are shown in Figure 3. The peak pressures were smaller than the reflected one on a rigid plane while the impulses were larger. This difference was caused by the tunnel deformation and the multiple reflections of air pressure in this analysis.

![Figure 3: Peak reflected pressure and impulse on the lining](image)

4.2 Tunnel Failure

A series of numerical simulations were carried out to investigate the failure mechanisms of circular tunnels due to different amount of explosives. As shown in Figure 4, the failure modes of tunnel lining
are different with various levels of blast loading. In the 200kg TNT case the analysis terminated at 9.42ms due to extensive failure in the tunnel lining while the analysis time of 50kg and 100kg TNT cases is 15ms.

Under the blast loading of 200kg TNT, the Mises stress in the lining increased dramatically due to internal blast loading as shown in Figure 4(a). When a lining element reached the failure stress of 220Mpa, it failed and was deleted from further analysis. The failure occurred first at the section close to the explosive due to large hoop stress in tension. It then propagated to the adjacent section, and extended as far as 10 m away from the cross-section where the explosive was located.

![Figure 4: Lining failures due to different amount of explosives (Deformation enlarged 30 times)](image)

Under the blast loading of 100kg TNT, the lining failure was not as severe as the case with 200kg TNT. The fracture area was about 0.19m² which was much smaller than the 200kg case (13.05m²) in prototype model. The fracture concentrated at the top and bottom of the tunnel, as shown in Figure 4(b). Fracture emerged at 1.5ms after the explosion. This fracture was caused by the phase lag of vibration that resulted in large tensile stress in the axial direction. This phase lag was mostly initiated by the different moments of blast loading on the lining.

Under the blast loading of 50kg TNT, the lining had no fracture, but some lining elements on the outside surface failed, as shown in Figure 4(c). Close to the explosive, the lining experienced very large acceleration in the shrinking direction, which must have led to large bending stress on the outside surface of the lining, and resulted tensile failure.

4.3 Response of Soils

The main influence of blast loading occurred in the soil not far away from the explosive. The soil expanded first and then vibrated. Some soil elements were penetrated by the fractured tunnel lining. Soil liquefaction occurred with blast loading from 50-200 kg TNT equivalent. Soil had progressive failure due to both vibration of the tunnel and blast loading. Liquefied soil distribution due to different amount of explosives is shown in Figure 5.

![Figure 5: liquefied soil distribution due to different amount of explosives (The blue parts are liquefied soil elements)](image)

With large amount of explosive and extensive lining failure, only a small portion of blast energy propagated into the soil, and the extension of soil liquefaction was actually smaller. In contrast the soil
Liquefaction might be more extensive when the lining failure was less severe. The lining vibrated more significantly and propagated more energy to the surrounding soil.

However, the excess water pressure generated in the FHWA soil material model was not 100% accurate after the soil liquefied and underwent large shear deformation. Unrealistic dilation of model soil with large shear deformation led to unrealistic increase of effective stress and shear strength. Tunnel might experience more failure due to the soil liquefaction, but it could not be reproduced in this study. More work is needed to improve the material model and the numerical scheme.

5 Conclusion

- The failure modes of tunnel lining were different due to different amounts of explosive. With relatively large amount of explosive, severe rupture firstly appeared in the domain close to the explosive, and then propagated to farther distance due to lining vibration. The failure was governed by the tensile strength of the material. When the blast loading were reduced, only a little fractures occurred. The lining fracture was caused by the phase lag of vibration. This phase lag was mostly initiated by the different moments of blast loading on the lining. Overall the damage and failure of the tunnel lining was progressive in nature. The damage and failure occurred mainly during the lining vibration when the main event of blast loading was over.

- The main influence of blast loading occurred in the soil not far away from the explosive. Soil liquefaction occurred with blast loading from 50-200 kg TNT equivalents. Soil had progressive failure due to both vibration of the tunnel and blast loading.

- With large amount of explosive and extensive lining failure, only a small portion of blast energy propagated into the soil, and the extension of soil liquefaction was actually smaller. In contrast the soil liquefactions might be more extensive when the lining failure was less severe. The lining vibrated more significantly and propagated more energy to the surrounding soil.

References

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