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ADVANCED DYNAMIC RESPONSE ANALYSIS OF UNDER-GROUND TUNNEL AFFECTED BY BLAST GROUND DISTANCE

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Abstract

The study aimed to investigate the dynamic response of underground box tunnel subjected to a surface explosion of 1000 kg TNT charge weight located at 4 and 8 m from the tunnel centreline. An Arbitrary Lagrangian-Eularian (ALE) technique was used to analyse and monitor the propagation of blast load into sandy loam soil. The results revealed a good consistency with the technical manual TM5-855-1 and proved that the blast waves transmitted into soil as hemispherical shape in all the investigated cases of blast ground distance. Moreover, the reflected pressure, effective stress and velocity at tunnel centre were significantly reduced with the increment of blast ground distance. The lateral displacement index of tunnel proved that the explosion at tunnel centreline was the most critical state on tunnel safety due to the high speed of blast waves which could increase the vibration of tunnel. The damage assessment approach demonstrated that the tunnel was safe in all the investigated cases of blast ground distance.

Keywords: ALE technique, Box tunnel, Ground distance, Reflected pressure.

1. Introduction

During last decades, terrorist activities become the main threat for underground structures such as tunnels. These incidents caused a severe damages in tunnel structures and many losses of lives such as the attack on Paris and Moscow subways in 1995 and 2004, respectively [1]. Thus, a proper tunnel design would significantly reduce the implications resulted from internal and surface tunnel explosions. In this area, experimental tests are extremely risky and expensive; therefore, the numerical analysis may consider as a best alternative.

The new technology considerably decreases the risks of internal explosions by using modern security systems which can easily detect the explosions materials. Nevertheless, several scholars studied the dynamic behavior of tunnel under internal explosions [2-5]. The surface explosions unfortunately are highly expected to occur because the absence of proper devices to detect it before exploded. Kun-Sheng et al. [6] found out that the top part and centre of circular shaped tunnel are the most damaged zones under surface blast loads range between 100 and 300 kg TNT charge weight. Fan et al. [7] studied the response of shallow-buried structure under surface explosion and determined that sidewall of the structure could withstand a direct surface explosion more than the roof.

Yang et al. [8] analysed the dynamic behaviour of circular metro tunnel by using the Arbitrary Lagrangian-Eulerian (ALE) method and the results appeared that the upper part of the tunnel lining under the explosion centre is the most vulnerable part compared to others. Koneshwaran [9] studied the effect of blast ground distance on the dynamic response of a circular tunnel and the results showed that a tunnel was safe when the blast load placed at two times of tunnel diameter and subjected to 750 kg TNT charge weight. Mobaraki and Vaghefi [10] studied the effect of burial depth on the box shaped tunnels and revealed that the roof and wall center are the most critical parts. Mussa et al. [11] assessed the damage behavior of box shaped tunnel affected by tunnel burial depth, lining thickness, and charge weight. The results indicated that the roof and wall center were the most destruction parts and the maximum resistance occurred at depth 8 m with lining thickness of 750 mm subjected to 4536 kg of TNT charge weight.

In the present study, the effect of blast ground distance on box tunnel was evaluated by using ANSYS/LS-DYNA software. The results were compared with the analytical formula of technical manual TM 5 -855-1 to ensure the accuracy of the numerical model [12].

2. Finite Element Model

Underground railway tunnel with dimensions of 10 m × 10 m × 7.5 m and burial depth 4 m was modeled [13]. Eight node elements SOLID 164 was used to create a quarter symmetrical model of 10 m × 10 m × 17.5 m due to the symmetry about YX and YZ planes as shown in Fig. 1. The tunnel was placed at 4 meter depth *(D)* underground the explosion center of 1000 kg TNT charge weight. Initial volume fraction geometry command simulated the charge weight as spherical shape by specifying its radius and detonation point [14].

To ensure the accuracy of the numerical model, a convergence test was performed by using meshes with element sizes of 250, 500, and 750 mm. The results showed that the mesh with an element size of 250 mm was quite sufficient and gave an accurate solution to the problem. MAT_high_explosive_burn was used to model TNT charge weight with Jones– Wilkens–Lee (JWL) equation of state [13]. For simplicity, the entire sandy loam soil was modelled as MAT_Soil_and_Foam and its properties were described by Mussa and Mutalib [13].

MAT_Null was used to model the air with a linear polynomial equation of state [14]. The tunnel lining was built by *C50* concrete and modelled as MAT_plastic_kinematic which consider a cost effective model and suited to simulate the isotropic and kinematic hardening plasticity with the option of including strain rate effects [8, 10]. The movements of nodes perpendicular to the symmetry planes XZ and YZ were fixed. A non-reflection-boundary was applied to the other two lateral surfaces to decrease the stress wave reflection at these computational boundaries. A free boundary condition is used for the upper surface, and the base was fixed in all directions to signify bed rock [9]. Arbitrary Lagrangian Eulerian (ALE) technique was used due to its ability to gather the best features of pure Lagrangian and Eulerian solvers [15]. TNT, air and soil were modelled as Eulerian meshes while the tunnel lining was modelled using a pure Lagrangian mesh. The coupling between the Lagrangian meshes and Eulerian meshes was achieved using Constrained_ Lagrange_In_Solid, where a penalty factor governs the penetration of the explosive-air volume fraction into the Lagrangian mesh [14].

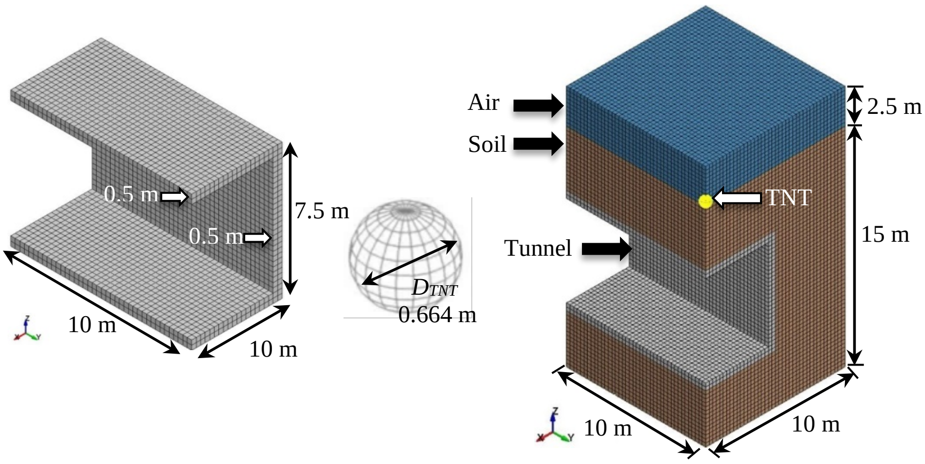


Fig. 1. Finite element model.

3. Results and Discussions

3.1. Validation results

TM5-855-1 includes an equation to estimate the peak pressures of ground shock waves into soil as follows:

$$P_P = 0.407 f \rho_c \left(\frac{R}{w^{\frac{1}{3}}}\right)^{-n} \tag{1}$$

where P_p is the peak pressure, *f* is the coupling factor, which is recommended to be 0.14 for an explosion in air, ρ_c and *n* are the acoustic impedance and attenuation coefficient for sandy loam soil which equal to 4.972 and 2.75 [12], R is the distance to the explosion centre, and W is the charge weight. Figures 2 and 3 pointed that the peak pressures gradually reduced far away from the explosion centre and demonstrated a good consistency with TM5 by difference of 2.631% at depth 4 m. However, the deepest points recorded large differences reach up to 35.996% at depth of 10 m due to the location of charge weight at the same ground level which 53% of explosion energy capable to disperse into the air [16].

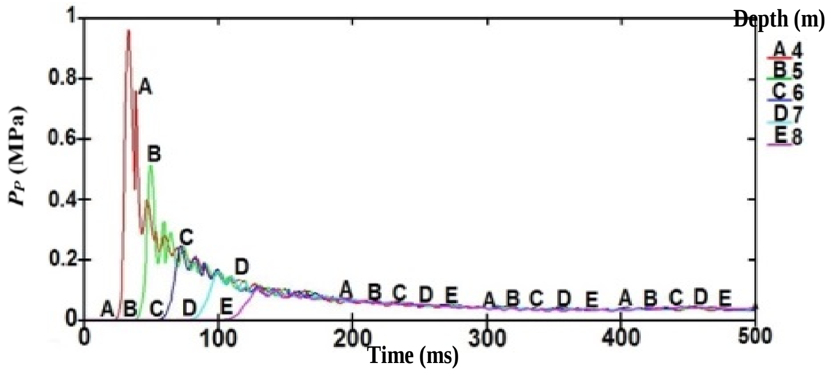


Fig. 2. Time histories of blast peak pressure into soil at different depths.

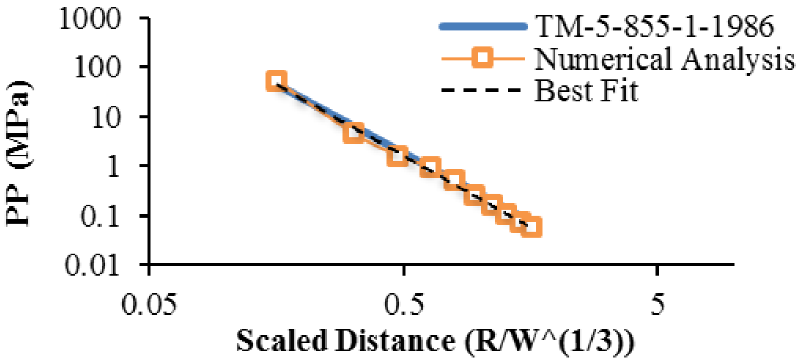


Fig. 3. Comparison between numerical and TM5 results.

3.2. Effect of blast ground distance

3.2.1. Propagation of blast waves into soil

The propagation of blast waves into soil was evaluated for surface explosions located at tunnel centreline (GD = 0 m), and ground distances of 1D and 2D as shown in Fig. 4. where D is the burial depth of tunnel, R is the distance of explosion to tunnel centreline and GD is the blast ground distance, where $0 \leq GD \leq 2D$.

The results indicated that the blast waves were propagated into sandy loam soil as hemispherical shape in all the studied cases of ground distance as shown in Fig. 5.

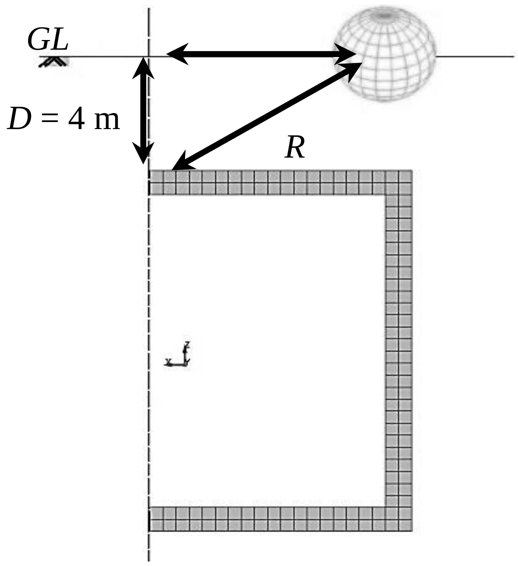
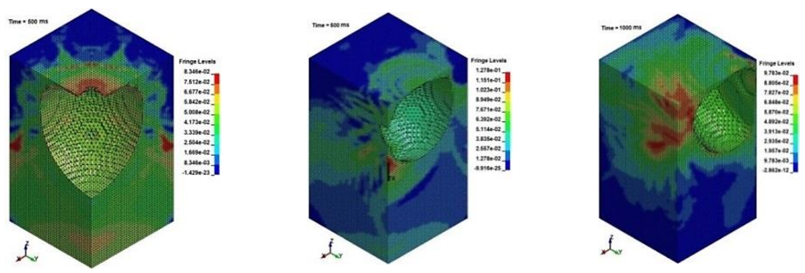


Fig. 4. Variation of blast ground distance.



(a) *GD* = 0 **(b) *GD* = 4 m** **(c) *GD* = 8 m**

Fig. 5. Propagation of blast waves into soil at various ground distance.

The effect of blast ground distance on the shock waves mechanism into soil were evaluated at 4 meter depth under tunnel centreline, whereas, the most critical values of peak pressure, velocity (*V*), and acceleration (*A*) of shock waves were found at tunnel centreline and gradually decreased with the increment of ground distance due to diminution of blast waves into soil as described in Table 1.

Table 1. Mechanism of blast waves into soil under tunnel centreline at different ground distance.

GD (m)	P_P (MPa)	*V* (mm/ms)	*A* (mm/ms^2)
0	0.962	39.539	37.767
4	0.313	10.088	0.911
8	0.102	2.347	0.074

3.2.2. Tunnel response

3.2.2.1. Reflected pressure

Figure 6 indicated that the blast ground distance could have notable effect on the pattern of reflected pressure distribution, whereas the tunnel corner appeared a great response to reflected pressure whenever the blast ground distance increased due to the elements located far away from the tunnel centre could affected by the nonlinearity properties of concrete as stated by [17, 18].

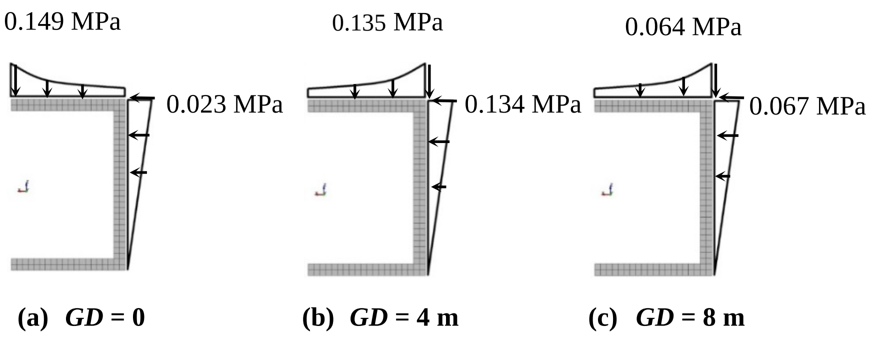


Fig. 6. Reflected pressure (MPa) of tunnel at different blast ground distance.

3.2.2.2. Effective stress, velocity and displacement

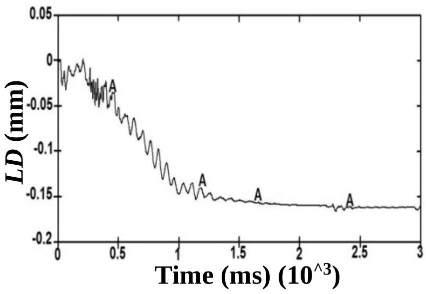
The effective stress, velocity and lateral displacement *(LD)* were evaluated for the tunnel center, corner and wall center which were considered as the most affected parts from the variation of blast ground distance as shown in Table 2. The results revealed that the blast ground distance considerable affected on the values of effective stress and velocity at the tunnel center which were gradually reduced when the blast ground distance increased. Similar trend had observed by Koneshwaran [9] for the center of circular tunnel which was safe at ground distance equal two times of tunnel diameter.

Table 2.Effective stress and velocity of tunnel at different blast ground distance.

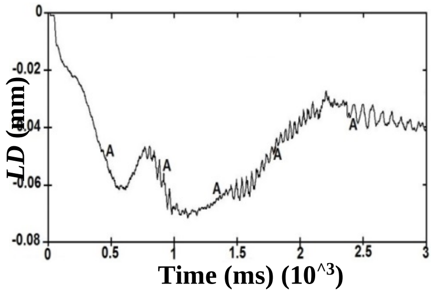
GD (m)	Effective stress (MPa)			*V* (mm/ms)		
	Center	Corner	Wall	Center	Corner	Wall
0	0.2195	0.0527	0.0029	81.677	2.2056	0.042
4	0.189	0.2422	0.010	10.367	29.524	0.573
8	0.039	0.1040	0.013	1.5201	18.388	1.113

The time histories of lateral displacement for the selected elements proved that the explosion at tunnel centerline was the most critical state on tunnel safety due to the high speed of blast waves, which could increase the vibration of tunnel as shown in Table 2. Figure 7 indicated that the increment of blast ground distance could significantly reduce the lateral displacement of tunnel center by

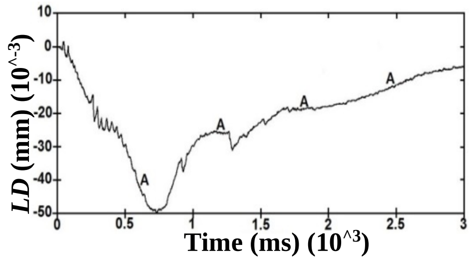
133.80 and 238.77% at distances of 4 and 8 m, respectively, as compared with blast at tunnel centerline.



(a) *GD* = 0 m



(b) *GD* = 4 m

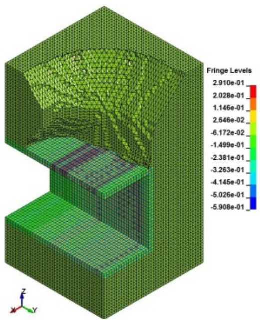


(c) *GD* = 8 m

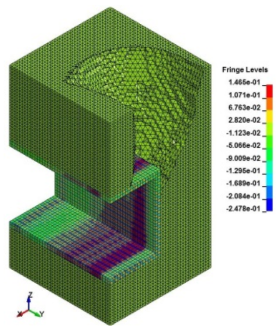
Fig. 7. Time histories of lateral displacement for tunnel center at various blast ground distance.

3.2.2.3. Failure mode

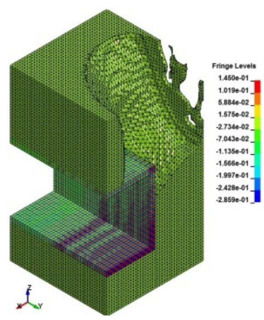
Figure 8 proved that the tunnel was safe in all the investigated cases of blast ground distance. These results were in a good accordance with Mussa et al. [11] which simplified the tunnel structure to a single degree of freedom (SDOF) model and assess the failure based on the mid displacement of tunnel roof and wall.



(a) *GD* = 0



(b) *GD* = 4 m



(c) *GD* = 8 m

Fig. 8. Lateral displacement contours of tunnel at different blast ground distance.

4. Conclusions

The results of study were concluded as following:

- The verification results were in a good agreement with TM5-855-1 and indicated that the blast waves propagated into soil as hemispherical shape in all the investigated cases of ground distance.
- The reflected pressure, effective stress and velocity at tunnel centre were gradually reduced with the increment of ground blast distance
- Lateral displacement index for tunnel proved that the explosion at tunnel centreline was the most critical on tunnel safety.
- Damage assessment approach revealed that the tunnel was safe in all the investigated cases of blast ground distance.

Acknowledgments

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