Empirical Models for External Tunnel Explosion

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Abstract

The objective of this study employed the C4 explosive to evaluate the overpressure response in the portal tunnel with different explosive scaled distance. Both experimental and numerical methods were used and the predicted models were established. In experiment part, several amount of C4 charge from 50 g to 175 g were detonated in front of the tunnel. In numerical part, the overpressures were obtained by the finite element code LS-DYNA with the arbitrary Lagrangian-Eulerian (ALE) algorithm. Simulation results for the scaled distance from 2.15 to 3.26 m/kg$^{1/3}$ exhibited the overpressure predicted by proposed method show good agreement with the experimental results and the relative differences were less than 5%. This study also presented several empirical models for external tunnel explosion. The empirical formulas can use for tunnel design reference.

Keywords: Tunnel, Overpressure, LS-DYNA

1. Introduction

Most major military facilities and command posts of countries are established underground or within tunnels to enhance defense. With the development and advancement of weapon precision, various missiles and weapons can now hit the portal of a tunnel directly. In addition, the impact of an explosion is sufficient to constitute great threat to internal personnel and equipment, and even lead to equipment damages and personnel casualties. Therefore, it is necessary to evaluate the techniques applied for explosions at portals. In 1993, Scheklinski-Glück [1] conducted 0-90 degrees explosion tests at different distances within a radius five times of the diameter from the portals using different amounts of charges. The experiments were implemented in a circular tunnel with a diameter of 3.6 m and 4000, 2000 and 1000 kg of columned RDX charges, and in a small scaled tunnel with a diameter of 9 cm and 64, 32 and 16 g of columned RDX charges. The results showed that the blast pressure within the tunnels attenuated with the increase of distance. In 2004, McMahon et al. [2] used 0.177 kg and 1.77 kg of spherical B charges on a circular tunnel with a diameter of 0.298 m and a length of 54.3. The experiments were conducted with explosives placed at the portal and 60, 30, 15 cm from the portal. The results showed that the blast pressure within the tunnel attenuated with the increase of distance, and that the impulse may be considered as a fixed value. In 2005, Welch et al. [3] discussed the relation between tests of scaled and full-sized explosions, and the results showed a high relevance, indicating that scaled explosion tests can substitute for full-sized ones effectively. Study of dynamic response of structures to airblast forces has also received a lot of attention in the last decades [4-11]. This study aims at investigating the airblast propagation of explosions outside portals of tunnels, and simulating the airblast within tunnels from explosions outside using LS-DYNA. By explosion test methods, results of the tests and numerical simulations are analyzed and compared to verify the correctness and viability of numerical simulation, which is further used as basis in establishing relevant empirical equations and numerical models for reference and assessment of protective designs.

2. Analytical. model

2.1 Near surface burst experiments

For near surface burst experiments, C4 charges weighing 50, 100, 120, 150 and 175 g were used with the center of charge 15 cm from the ground, and a free field blast pressure pencil probe was set 120 cm from the center of charge to measure blast pressure, as shown in Fig. 1.

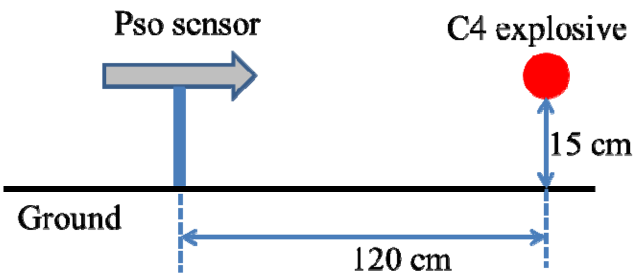

Fig. 1 Near surface burst experiments

2.2 External tunnel explosion experiments

Steel plates 2 cm thick with an inside diameter of 30×30×120 cm were welded together to assemble the tunnel for prevention from blast leakage. In order to be consistent with the actual tunnel form, steel plates were added above and at both sides of the portal on the outside to ensure that the blast pressure generated by external explosion can enter the portal sufficiently. The explosion experiments outside the portal used small scaled tunnel model and 50-175 g of C4 charges. The explosions occurred 120 cm from the portal with the center of charge 15 cm from the ground. The pressure sensor was set on the right side wall in the tunnel 2, 30, 60 and 90 cm from the portal. Layout of explosion experiment outside the tunnel is shown in Fig. 2. The scaled distance Z of portal overpressure was between 2.15 to 3.26 m/kg$^{1/3}$. The scaled distance Z is expressed as follows:

$$Z=R/W^{1/3} \tag{1}$$

, where R is the standoff distance (m), and W is the mass of explosive (kg).

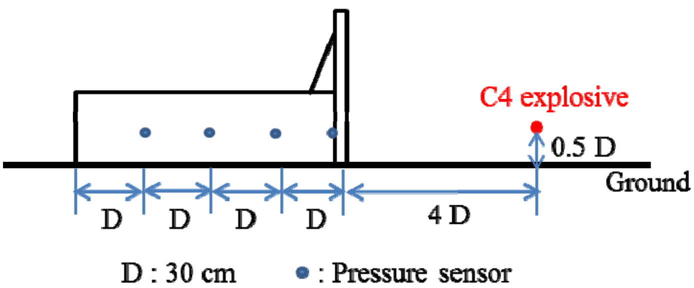

Fig. 2 External tunnel explosion experiments

A C4 explosive charge is an US made M5A1 pack, of which charges can be formed into various shapes, suitable for multiple applications. M6 detonators were used which were connected to C4 explosive charges, as shown in Fig. 3.

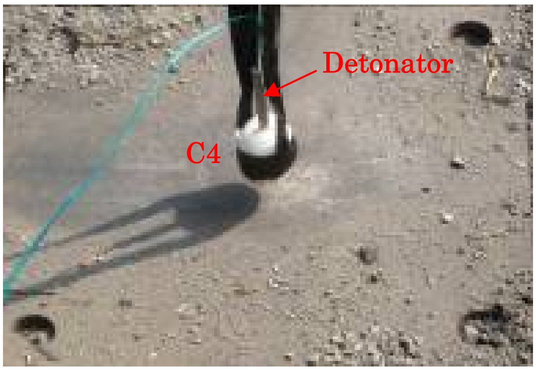

Fig. 3 M6 detonator connected to C4 explosive

For measurement of the explosions, the 137A23 free field blast pressure pencil probe made by US PCB Corporation was used, of which the maximum pressure was 345 kPa, approximately 3.4 folds of atmospheric pressure. The 113A23 pressure sensor, also from PCB, installed inside the tunnel had a maximum pressure of 103,420 kPa. The 5000 Oscilloscope made by US Agilent Technologies was used for signal acquisition, of which the maximum bandwidth was 100 MHz and the maximum sampling rate was 2×109(1/s).

2.3 Numerical simulation

Numerical simulations of explosion outside the tunnel were conducted using LS-DYNA software, and the model was divided into air (MAT_NULL) [12], explosive charge (MAT HIGH EXPLOSIVE BURN) [13], soil ground (MAT RIGID) [14] and tunnel (MAT PLASTIC KINEMATIC) [11]. Arbitrary-Lagrangian-Eulerian (ALE) algorithm for Fluid-Structure-Interaction model was adopted. Air and charges applied the Eulerian meshes of which the elements had 1 cm sides, and the tunnel and ground applied the Lagrangian meshes of which the elements had 2cm sides, the tunnel structure used shell elements. The numerical simulation model was shown in Fig. 4.

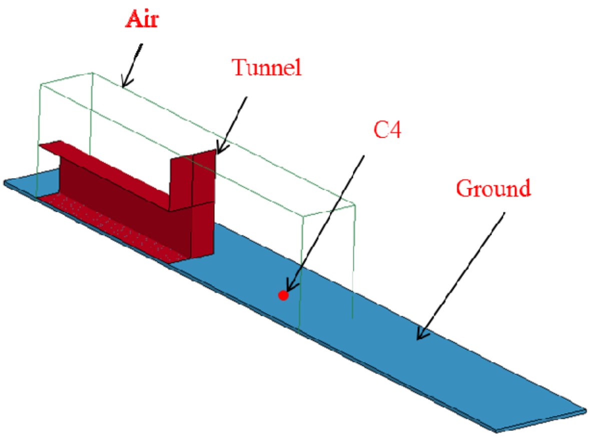

Fig. 4 Numerical simulation model

3. Result

3.1 Near surface burst experiments

A total of 45 effective data resulted from the near surface burst experiments, as shown in Fig. 5 The correlation coefficient of scaled distance and peak overpressure (kPa) was -0.93, indicating a highly negative correlation.

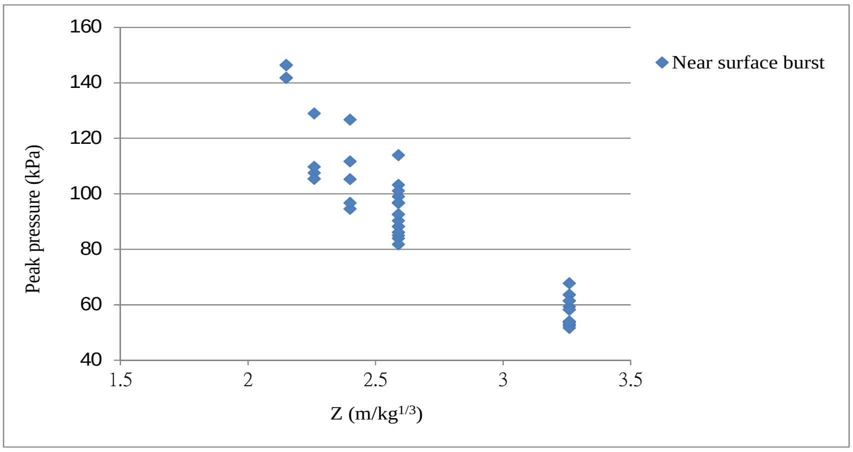

Fig. 5 Peak side-on overpressure vs. scaled distance

In order to determine the degrees of dispersion of each blast in this experiment, the mean, standard deviation and coefficient of variance of Z=2.15 to 3.26 m/kg$^{1/3}$ are shown in Table 1. It can be observed that the coefficient of variance is between 1.76 to 14.8%, indicating there is no significant dispersion in the data of this experiment.

Table 1: Coefficient of Variation for near surface burst experiments

Z (m/kg$^{1/3}$)	P_{so} (kPa)	Standard deviation (kPa)	Coefficient of variation (%)
3.26	57.97	5.06	8.73
2.59	92.81	8.53	9.19
2.40	106.97	12.98	14.80
2.26	113.37	9.97	8.96
2.15	143.61	2.53	1.76

To determine the regression analysis of near surface burst experiments, the external tunnel overpressures were used in five regression models selected by Excel, including linear, logistic, polynomial, power and exponential. The power regression model with a maximum coefficient of determination, R-squared, of 0.92 was the best fitting regression formula, which can be used as empirical equation for near surface burst at portal of tunnel. The power formula as follow:

$$P_{so}=629.06Z^{-2.02} \quad (2)$$

Where $Z=R/W^{1/3}$ (m/kg$^{1/3}$) , P_{so} is the peak side-on pressure (kPa), R is the standoff distance between explosive and measurement point (m), W is explosive weight (kg).

3.2 Portal overpressure

A total of 38 effective data resulted from the blast experiments at the portal, as shown in Fig. 6. The correlation coefficient of scaled distance and portal pressure was -0.92, indicating highly negative correlation. The mean, standard deviation and coefficient of variance of each data set are shown in Table 2. It can be observed that the coefficient of variance is between 5-8%, indicating there is no significant dispersion in the data of this experiment. The appropriate scaled distance is between Z=2.15 to 3.26 m/kg$^{1/3}$.

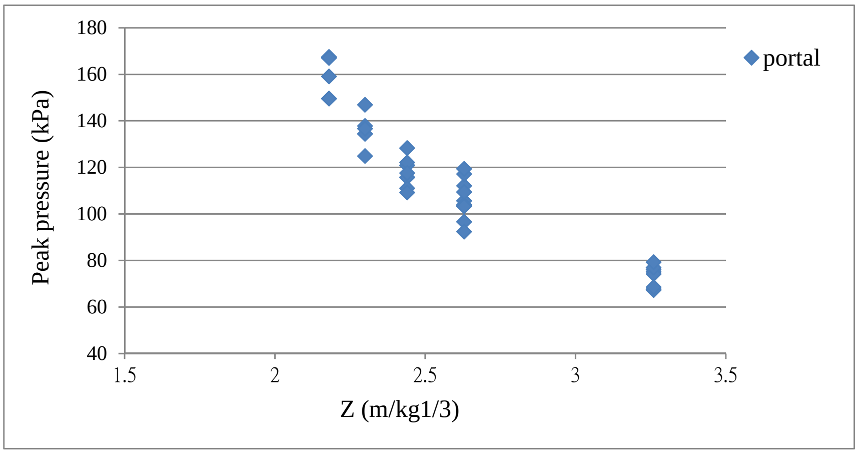

Fig. 6 Peak side-on overpressure vs. scaled distance

Table 2 Coefficient of variation for portal overpressure

Z ($m/kg^{1/3}$)	P_{portal} (kPa)	Standard deviation (kPa)	Coefficient of variation (%)
3.26	72.49	4.70	6.48
2.59	106.32	8.46	7.95
2.40	117.91	5.86	4.97
2.26	136.10	7.90	5.81
2.15	162.04	7.83	4.83

To determine the regression analysis of portal overpressure were used in five regression models selected by Excel. The power regression model with a maximum coefficient of determination, R-squared, of 0.94 was the best fitting regression formula, which can be used as empirical equation for near surface burst at portal of tunnel. The power formula as follow:

$$P_{portal}=652.88Z^{-1.87} \quad (3)$$

Where $Z=R/W^{1/3}$ ($m/kg^{1/3}$) , P_{portal} is the peak side-on pressure (kPa), R is the standoff distance between explosive and measurement point (m), W is explosive weight (kg).

3.3 Internal tunnel overpressure

Pressure sensors were set at 2, 30, 60 and 90 cm in the tunnel to measure internal overpressure. The locations of the pressure sensors are divided by the diameter of the tunnel (30 cm) to be dimensionless, resulting in 0.067, 1, 2 and 3, respectively, and are expressed by portal section, L/D=1, 2 and 3. Fig. 7 compares the blast pressures measured at portal section and L/D=1, 2 and 3 using different amounts of C4 charges. When the shock wave is between portal section and L/D=1, the blast pressure is attenuated, but it increases as the shock wave enters L/D=2, which might be due to reflection waves and superposition generated by blast waves on the inner walls, causing the blast pressure measured at that position to be greater than other measuring points. The blast pressure is attenuated at L/D=3.

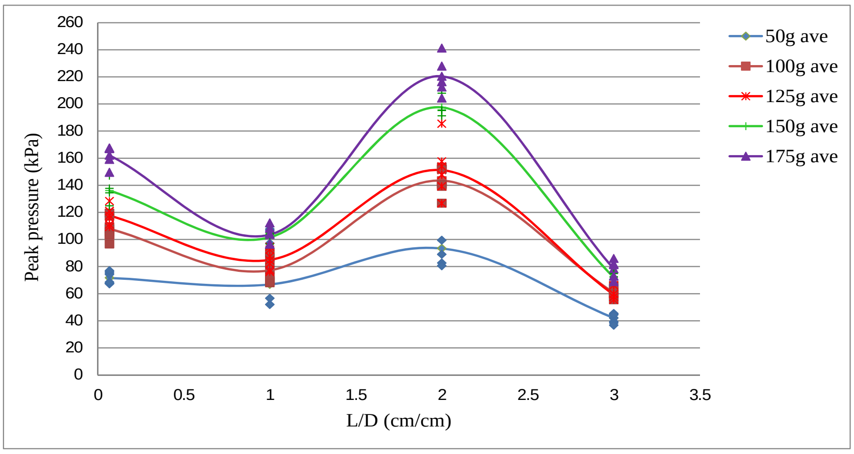

Fig. 7 Internal overpressure vs. L/D

For comparing the relation between peak pressure measured by sensors in the tunnel and portal section, the peak pressure measured by sensors were normalized and that of the portal section was set at 1. The peak pressure of L/D=1, 2 and 3 were compared with the portal section, as shown in Fig. 8. The cubic polynomial regression equation of maximum coefficient of determination R-squared 0.93 was used as the best regression equation for internal overpressure ratio, as shown in Eq. (4).

$$P_{so}' = -0.39Y^3+1.65Y^2-1.62Y+1.10 \quad (4)$$

Where Y=L/D, $P_{so}' = P_{internal}/P_{portal}$, L is the standoff distance between explosive and portal (cm), D is the diameter of the tunnel (cm).

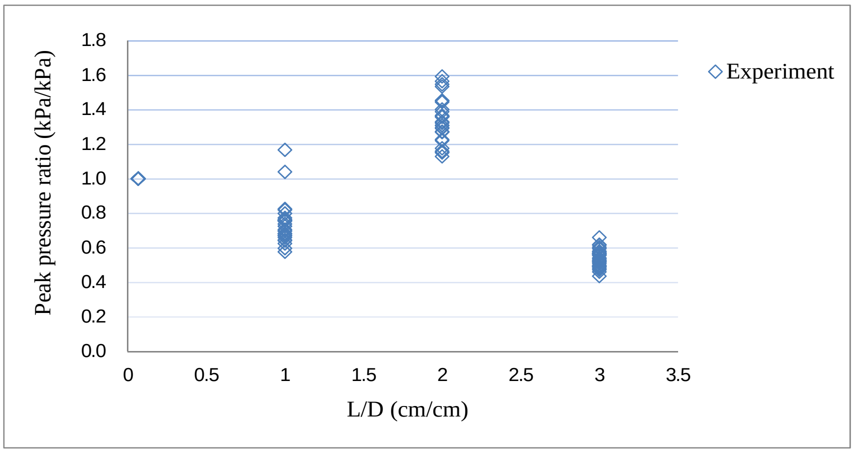

Fig. 8 Peak overpressure ratio vs. L/D

It can be observed in Table 3 that the near surface burst pressure was smaller than the portal with a variance of -9.28% to -20.03%. This might be because the shock wave was compressed or diffracted when entering the portal, which lead to an increment in blast pressure at the portal. However, if the pressure ratio is taken into consideration, the results are as shown in Table 14. The blast pressure at portal is approximately 1.17 folds of the ratio average of near surface burst experiment, and the appropriate scaled distance is Z=2.15 to 3.26 m/kg$^{1/3}$, as shown in Eq. (5).

$$P_{portal}=1.17\times P_{so} \quad (5)$$

Table 3 Comparison overpressure between P_{so} and P_{portal}

Z (m/kg$^{1/3}$)	P_{so} (kPa)	P_{portal} (kPa)	Relative difference[*1] (%)	Ratio[*2]
3.26	57.97	72.49	-20.03	1.25
2.59	92.81	106.32	-12.71	1.15
2.40	106.97	117.91	-9.28	1.10
2.26	113.37	136.1	-16.70	1.20
2.15	143.61	162.04	-11.37	1.13

[*1] ：$(P_{so}- P_{portal})/ P_{portal}\times 100$

[*2] ：P_{portal}/ P_{so}

3.4 Numerical simulation results

Table 4 shows the results of portal blast experiment and numerical simulation. The study results indicate that, for the overpressure by portal in external explosion, the outcomes of the numerical simulation and the experiment were consistent. This means that as the scaled distance increased, the pressure attenuated. In Z=2.15 to 3.26 m/kg$^{1/3}$, the relative difference between numerical simulation and experiment were both within 5%, indicating that the portal overpressure from external blast in the numerical simulation had a better analysis result, which is beneficial to future studies on prediction of blast pressure at portals from external blasts.

Table 4 Comparison overpressure between $P_{LS\text{-}DYNA}$ and P_{portal}

Z (m/kg$^{1/3}$)	$P_{LS\text{-}DYNA}$ (kPa)	P_{portal} (kPa)	Relative difference[*1] (%)
3.26	75.81	72.49	4.58
2.59	108.45	106.32	2.00
2.40	123.39	117.91	4.65
2.26	139.59	136.1	2.56
2.15	154.48	162.04	-4.67

[*1] ： $(P_{LS\text{-}DYNA}- P_{portal})/ P_{portal}\times 100$

3.5 Establishment of internal tunnel overpressure predicting model

This study provides two kinds of empirical formulas that can be estimated internal tunnel overpressure values.

3.5.1 Method 1

(1) Use Eq. (2) in Section 3.1 to determine the overpressure of near surface burst.
(2) Use Eq. (5) in Section 3.3, which indicates the blast pressure at portal is 1.17 folds of near surface burst, to determine the portal pressure.
(3) Use Eq. (4) in Section 3.3, which indicates the relation between the peak pressures measured by each pressure sensor and at the portal section, to determine the in-tunnel pressure, as shown in Eq. (6).

3.5.2 Method 2

(1) By using Eq. (3) in Section 3.2, which indicates the power regression equation of blast pressure at portal, the portal pressure may be determined.
(2) Topped with Eq. (6) in Section 3.3, which indicates the relation between the peak pressures

measured by each pressure sensor and at the portal section, the in-tunnel pressure may be determined.

4. Conclusions

This study used small amounts of explosive charges and small sized tunnel specimens and conducted external blast experiments to measure the blast pressure at portals. The results of experiment and the numerical simulation were analytically compared, and the correctness of results was checked by verifying numerical simulation. The outcomes are applied as basis for establishing empirical equations and numerical models for portal pressures in external blasts to provide reference for evaluating protective designs. The study results are as follows:
(1) Provide empirical equation for overpressure in near surface burst experiment.
(2) Provide empirical equation for overpressure of experiment at portal.
(3) Provide the relation between ratio of near surface burst and portal overpressure.
(4) Provide two empirical equations for internal tunnel overpressure.

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