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Analysis of Blast Wave Propagation Inside Tunnel*

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Abstract: The explosion inside tunnel would generate blast wave which transmits through the longitudinal tunnel. Because of the close-in effects of the tunnel and the reflection by the confining tunnel structure, blast wave propagation inside tunnel is distinguished from that in air. When the explosion happens inside tunnel, the overpressure peak is higher than that of explosion happening in air. The continuance time of the blast wave also becomes longer. With the help of the numerical simulation finite element software LS-DYNA, a three-dimensional nonlinear dynamic simulation analysis for an explosion experiment inside tunnel was carried out. LS-DYNA is a fully integrated analysis program specifically designed for nonlinear dynamics and large strain problems. Compared with the experimental results, the simulation results have made the material parameters of numerical simulation model available. By using the model and the same material parameters, many results were adopted by calculating the model under different TNT explosion dynamites. Then the method of dimensional analysis was used for the simulation results. As overpressures of the explosion blast wave are the governing factor in the tunnel responses, a formula for the explosion blast wave overpressure at a certain distance from the detonation center point inside the tunnel was derived by using the dimensional analysis theory. By comparing the results computed by the formula with experimental results which were obtained before, the formula was proved to be very applicable at some instance. The research may be helpful to estimate rapidly the effect of internal explosion of tunnel on the structure.

Keywords: explosion inside tunnel; blast wave; overpressure peak; dimensional analysis

The tunnel structures are widely used in the military and civil engineering. In the military engineering, the possibility that the dynamite explodes in the tunnel is increasing with the development of precision guidance technology and the improvement of earth penetrating weapon[1]. In the civil engineering, thus, the likelihood that the bomb explodes in the tunnel by the terrorist or accidentally is also increasing with the development of the subway and underground structure. The analysis of blast wave propagation inside tunnel has great significance. The blast wave reflects repeatedly in the tunnel because of the limit of tunnel wall when the dynamite explodes in tunnel. The tunnel close-in effect makes the overpressure of tunnel blast wave increase and continuance time of the blast wave longer. The law of the blast transmitting in the tunnel is different from that in the air. A lot of experiments and simulation were made to study the law of the blast inside tunnel abroad and in. The Third Research Institute of the Corps of Engineers carried out many explosion experiments inside tunnel and got lots of shock waves time histories. They also gave formulas for overpressure decline of the blast wave as the experimental results[2−4]. Yang *et al*[1] supposed numerical simulation for flow field of chemical explosion inside tunnel by means of three-dimensional numerical simulation, formulas for shock wave overpressure peak and duration, which were verified by experimental results, were obtained. US army engineer waterways experiment station made the experiment that the dynamite explodes at internal and external steel tunnel model with inter radius of 24.3 cm[5]. Choi calculated a real subway tunnel subjected to different dynamite explosions by using numerical simulation dynamic software-AUTODYN[6]. Also they gave the blast wave declining curve and simple-method to get the structure strain.

In this paper, the numerical simulation calculation

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for the explosion inside tunnel was made by means of LS-DYNA. The finite element model and parameters of material were proved to be appropriate by comparing the simulation results with experimental results. Combining the simulation results with the dimensional analysis, the blast wave overpressure decline formula at a certain distance from the dynamite center was derived. Also comparison between the formula results and the experimental results were discussed. We hope that could be useful to the analysis of blast wave propagation inside tunnels.

1 Finite element model and parameters of material

1.1 Finite element model

Due to the papers about the explosion experiments inside tunnel are limited, we use the experiment in Ref.[7]. The length of the finite element model is 10 m. The section is arch-roofed underground tunnel (see Fig.1).

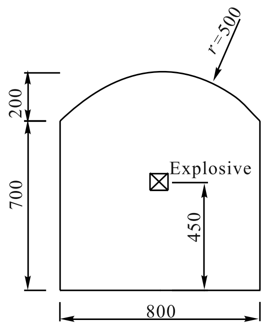


Fig.1 Tunnel section (unit:mm)

The dynamite is 0.6 kg and the distance from dynamite center to the ground is 0.45 m. The mesh of the section is shown in Fig.2. Considering the symmetry of the model, half of the model was taken to calculate for saving time.

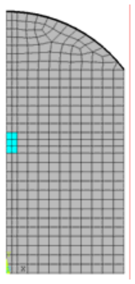


Fig.2 Mesh of the tunnel section

1.2 Parameters of material

The parameters of material are very important for numerical simulation. The main parameters of material are about the dynamite and the air[8]. In the simulation MAT_HIGH_EXPLOSIVE is adopted for the dynamite and MAT_NULL for the air. The pressure is calculated by the JWL station equation as follows:

$$p = A(1-1/R_1)e^{-R_1 v} + B(1-1/R_2)e^{-R_2 v} + \omega E/v \quad (1)$$

where p is pressure; v is initial relative volume, $v = V/V_0$; V_0 is initial volume.

The air is considered as ideal gas. The air pressure is calculated by linear polynomial.

$$p = (\gamma - 1)\rho_0 E_0 \quad (2)$$

where ρ_0 is air relative density; E_0 is initial energy per unit reference specific volume. The parameters of material used in this paper are shown in Tab.1 and Tab.2.

Tab. 1 Parameters of material

TNT dynamite(MAT_HIGH_EXPLOSIVE_BURN)			Air(MAT_NULL)		
ρ_0/(kg · m^{-3})	D/m	p_{CJ}/ Pa	ρ_0/(kg · m^{-3})	D/m	p_{cJ}/ Pa
1 600	7 000	2.55×10^{10}	1.29	0	0

Tab. 2 Equations of state

TNT dynamite(EOS_JWL)						
A/Pa	B/Pa	R_1	R_2	ω	E_0/Pa	V_0
5.409×10^{11}	$0.093\ 72\times10^{9}$	4.5	1.1	0.35	8.0×10^{9}	1.00

Air(EOS_LINEAR_POLYNOMIAL)								
C_0	C_1	C_2	C_3	C_4	C_5	C_6	E_0/Pa	V_0
0.00	0.00	0.00	0.00	0.40	0.40	0.00	2.5×10^{5}	1.00

2 Comparison between the FEM calculation and the experimental results

The pressure-time history comparison between the FEM calculation and the experimental results is illustrated in Figs.3—6. The experimental points are 2.25 m and 6.25 m to the dynamite center respectively.

Tab.3 shows the comparison of the overpressure peak and the arriving time between the numerical simulation and experiment.

The relative error between the FEM calculation and the experimental results is less than 20%, which proves the finite model and the parameters of material are appropriate.

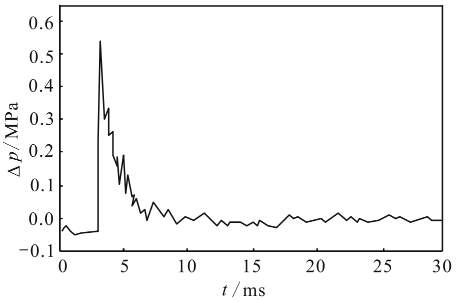


Fig.3 Pressure-time curve of experiment point (2.25 m to the detonation)

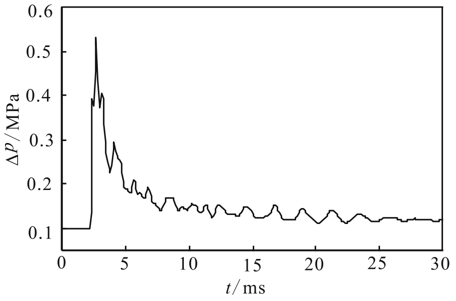


Fig.4 Pressure-time curve of FEM calculation (2.25 m to the detonation)

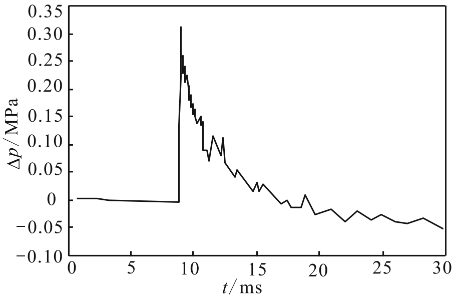


Fig.5 Pressure-time curve of experiment point (6.25 m to the detonation)

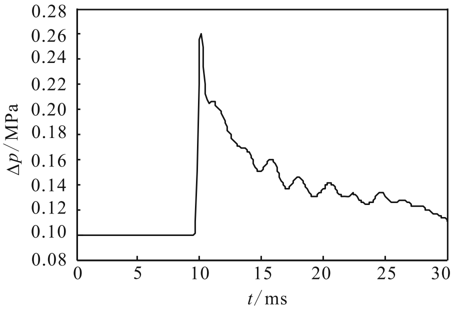
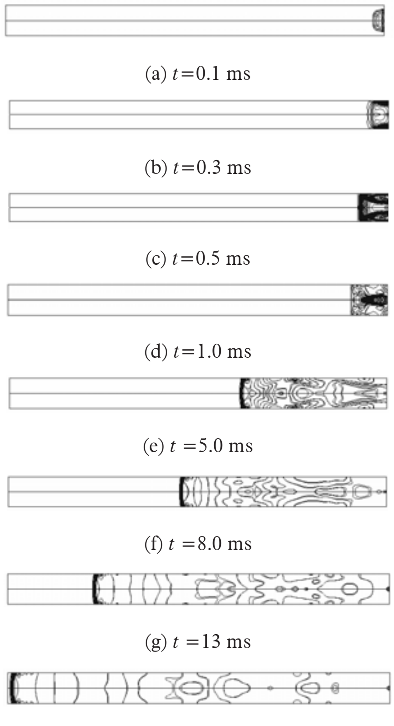


Fig.6 Pressure-time curve of FEM calculation (6.25 m to the detonation)

The changing process of isobaric pressure line is shown in Fig.7. At the initial time of the explosion, the explosive flow filed is complex as the blast shock wave reflects repeatedly in the tunnel. When the blast wave exceeds a certain distance, the steady plane wave forms.

Tab.3 Comparison of the overpressure peak and the arriving time between the experiment and the numerical simulation

Distance to the detonation	Item	Overpressure peak/MPa	Arriving time/ms
2.25 m	Experiment	0.53	3.1
	FEM	0.53	2.7
	Relative error/%	0.00	12.9
6.25 m	Experiment	0.31	8.9
	FEM	0.26	10.0
	Relative error/%	16.1	12.4



(a) t=0.1 ms

(b) t=0.3 ms

(c) t=0.5 ms

(d) t=1.0 ms

(e) t =5.0 ms

(f) t =8.0 ms

(g) t =13 ms

(h) t =18.2 ms

Fig.7 Changing process of isobaric pressure line

3 Attenuation law of overpressure peak of blast wave in tunnel

Firstly, we need to make sure of the main impact parameters on overpressure peak of the blast wave before analyzing the attenuation law of blast wave overpressure peak in tunnel. Then based on the dimensional analysis, the constant parameters should be ascertained. Finally, the math relation of overpressure peak with constant parameters is fixed by varying the constant parameters.

It has been known that the main impact parameters on the overpressure peak Δp are dynamite energy Q , the air pressure p_0, equivalent diameter of the tunnel D, the distance to detonation point L and the effective volume $V=SL$. Using LMT unit, we can get four constant parameters by π theorem : $\pi_1=\Delta p/p_0$, $\pi_2=p_0L_3/Q$, $\pi_3=V/L^3$, $\pi_4=D/L$. To eliminate L, we use $\pi_2'=\pi_2\bullet\pi_3=p_0V/Q$, $\pi_3'=\pi_2^{1/3}\bullet\pi_4=p_0^{1/3}D/Q^{1/3}$. Moreover, the expression is $\Delta p/p_0=f(p_0V/Q,\ p_0^{1/3}D/Q^{1/3})$. When the dynamite explodes in the air, $p_0=1$, so the expression is $\Delta p=f(LS/Q,\ D/Q^{1/3})$. The dynamite energy is proportional to the dynamite mass, which is expressed as $Q=mQ_v$, where Q_v is explosion heat. Then the dynamite energy Q in overpressure function can be replaced by the dynamite mass m. The finite model is calculated by changing dynamite mass to fit the overpressure peak function. The relationships between overpressure peak and the distance to the detonation point under different TNT masses (the coordinate is the double logarithm) are shown in Figs.8—11.

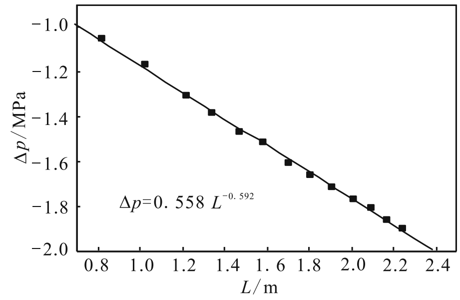


Fig. 8 Overpressure peak fit curve(m=0.42 kg)

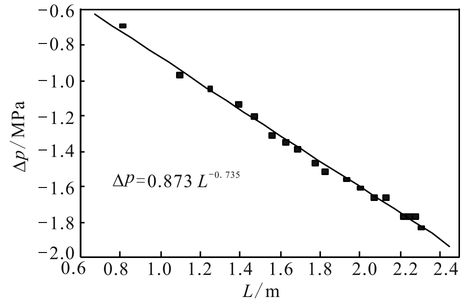


Fig.9 Overpressure peak fit curve(m=0.60 kg)

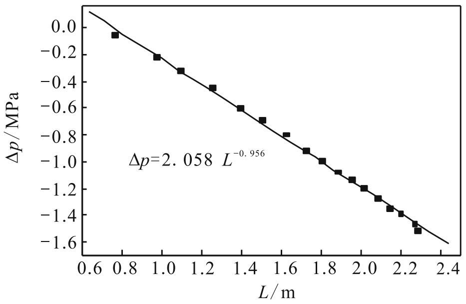


Fig.10 Overpressure peak fit curve(m=1.29 kg)

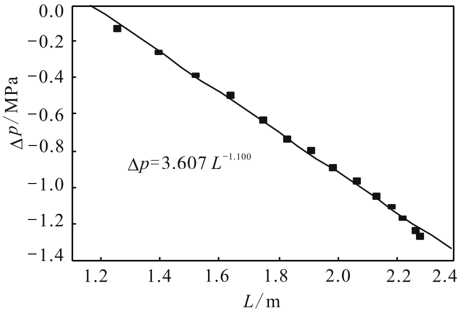


Fig.11 Overpressure peak fit curve(m=1.82 kg)

The fit curves illustrate that the relationship between the air overpressure peak and the transmitting distance is linear in the double logarithm coordinate system under different equivalent TNT mass. The air overpressure peak at the same point varies, according to different dynamite masses presented in Fig.12. While at the same point, the fit curve demonstrates that the relationship between the overpressure peak and the dynamite mass is also linear in the double logarithm coordinate system. According to the function of the fit curve, when the scaled distance is larger than 1, the formula for air overpressure peak Δp is given as follows:

$$\Delta p=1.40\left(\frac{LS}{m}\right)^{-0.846}\left(\frac{D}{m^{1/3}}\right)^{0.563} \tag{3}$$

where Δp is overpressure peak, MPa; m is equivalent TNT mass, kg; S is the tunnel section area, m^2; L is the distance to the detonation point, m; D is equivalent diameter of the tunnel, m.

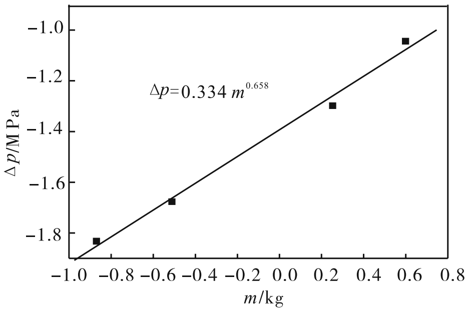


Fig.12 Overpressure peak fit curve

To verify the formula, the overpressure peak calculated by Eq.(3) is compared with the experimental results illustrated in Fig.13 and Fig.14. Experimental results in Fig.13 and Fig.14 were obtained by the Third Research Institute of the Corps of Engineers (TRICE), and US Army Engineer Waterways Experiment Station (WES), respectively.

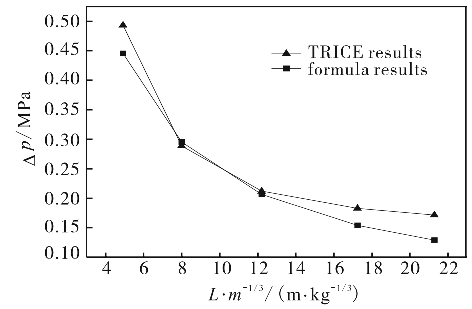


Fig.13 Comparison of formula results with experimental results obtained by TRICE

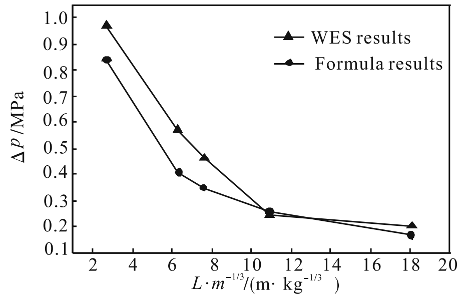


Fig.14 Comparison of formula results with experimental results obtained by WES

When the scaled distance($L \cdot m^{-1/3}$) from the overpressure point to the detonation point is larger than 1, the biggest relative error between Eq. (3) results and the experimental results obtained by TRICE is 29%, and the biggest relative error between Eq. (3) results and the experimental results obtained by WES is 28%. The biggest relative error of the formula can be accepted for the explosion in tunnel. It is referential for the internal explosion protection project.

4 Conclusions

When the dynamite explodes in tunnel, the blast wave reflects and superposes on tunnel wall. The overpressure peak and continuance time of blast wave would increase more than those exploding in the air. Also the damage made by the blast wave is larger than that in the air. At the initial time of the explosion, the explosive flow filed is complex as the blast shock wave reflects repeatedly in the tunnel. When the blast wave exceeds a certain distance, the steady plane wave forms. The experimental results were numerically simulated by means of the software LS_DYNA and it proves that the finite model and parameters of material are suitable. Then the overpressure peak attenuation formula was derived by calculating the finite model under different equivalent TNT masses. Comparison of formula results with experimental results reveals that the overpressure peak can be predicted by the formula achieved in this paper when scale distance ($L \cdot m^{-1/3}$) is larger than 1.

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