Study on the shock wave effect and engineering algorithm in the tunnel after structure damage under different explosion conditions

X HE¹, G JSUN¹, F LIU¹, X J REN¹, X WANG¹, L CHEN¹

¹ Institute of Defense Engineering, Academy of Military Science, PLA China, Luoyang 471023, China

*Corresponding author, E-mail: hyhq@foxmail.com

Abstract. In this paper, according to dimensional analysis, the dimensionless function of the intensity of the air shock wave overpressure of the explosion in structure leaking into a tunnel is established. Forty-eight experiments were carried out focusing on some influencing factors such as explosive charge, explosive depth, ratio of reinforcement, concrete matrix strength, and existence of the structure, revealing the influence laws of explosive charge, explosive height, ratio of reinforcement and concrete matrix strength on the overpressure intensity of air shock wave. Then, engineering calculation methods for leak shock wave effect are obtained, which include the overpressure distribution of shock wave in explosive tunnel in structure, equivalent coefficient of explosive charge compared with explosion in tunnel as well as the reduction factor of shock wave with or without structure.

1. Introduction
Tunnel fortification is usually adopted to protect goods, materials, and equipment from the damage of conventional earth-penetrating weapons. With the improvement of hit precision and penetration capability, it is very likely that an earth-penetrating weapon directly hits the structure right above the fortification and penetrates structure to induce an explosion. The structure is an important protective barrier for tunnel fortification, and its antiknock function plays a vital role in protecting the safety of structure, personnel, and equipment in the tunnel. According to the differences of earth-penetrating weapons coming to attack in penetration capability, explosive power, and resistance level of tunnel fortification, the damage of a tunnel fortification can be classified into the following three typical modes. (1) Mode 1: the explosion do not penetrate and do not torn the structure, and no shock wave propagation forms in tunnel; (2) Mode 2: the explosion torn the structure without penetrating it, and the shock wave propagation generates in tunnel; (3) Mode 3: the structure is penetrated, and explosion in tunnel forms. Among the three modes, in Mode 1 most energy of the explosive causes certain damage to the structure, produces ground shock waves and seismic oscillation, but the shock wave propagated into structure can be neglected; in Mode 2, part of the energy of the explosive damages the structure while the remaining energy converts to shock waves and propagates into the structure. Mode 3 is about explosion in structure, most energy of the explosive converts to shock waves. Investigations on Mode 1 and Mode 3 are relatively systematic and mature, while those on Mode 2 mainly concentrate on spalling failure of structure[1~3]. However, those on the leak air shock wave after the structure is damaged are very limited. As to Mode 2, if the explosion causes havoc and complete removal of structure material in a certain range from the explosive point to lower surface of structure
and a propagation channel of detonation products forms, detonation products together with fractured structure fragments pass the path, swarm into tunnel and generate shock waves. The waves propagating through the tunnel damage hit structure, the people, and the equipment. Therefore, part of the energy of the explosives damages the structure, while the remaining energy generates leak shock waves in tunnel. At present, the outstanding issue is the insufficient understanding of allocation pattern of the explosive energy; no calculation method is still available for internally exploded shock wave propagation of an explosion in structure that leaks into tunnel[4–8], which directly affects the damage evaluation for tunnel fortification in this mode.

This type of problem can thus be regarded as a typical near-region explosion problem with many influencing factors, related to the propagation and distribution of the explosive load and associated with structural damage. The sole theoretical analysis can hardly provide analytical solution. However, the accuracy of numerical simulation relies heavily on the selection of material model and structure damage criterion. Compared with numerical simulation and theoretical analysis, an experimental test remains the most intuitive and the most reliable approach to studying the engineering method mentioned above. According to serial experiments on the shock wave effect of explosion in structure leaked into tunnel, this paper mainly studies the engineering calculation methods for air shock wave effect when explosive energy flows into main tunnel as the explosion causes collapse penetration, including the overpressure distribution of the leak shock wave of explosive tunnel in structure, the equivalent coefficient of explosive charge in comparison with explosion in tunnel, and the quantitative analysis of antiknock protection function of the structure.

2. Dimensional analysis

To scientifically design the experimental tests and promote and apply the test results to different situations, it is necessary to perform dimensional analysis on a targeted explosive wave problem to properly select the dimensionless main parameter set, find the dependency between undetermined parameters and dimensionless main parameter set, and derive general equations of relationships of explosive shock wave parameters. Then, based on explosion test data, the concrete form of the functions is determined, and the dimensionless parameters in the functions are obtained, thus establishing the reduced parametric engineering model that reflects the real dynamics process and is suitable for engineering applications. The empirical formula of explosive shock wave parameters obtained in this way has universal significance and can be promoted and applied to different situations. In the explosive tunnel in structure, the overpressure peak value of a shock wave at different locations \( \Delta P \) depends on multiple factors including explosive charge \( Q \), charge density \( \rho_0 \), charge slenderness ratio \( L_0/D_0 \), charge angle \( \alpha \), equivalent diameter of tunnel \( D \), horizontal distance between measure point and explosion center \( L \), height of explosion center \( H \), test specimen density \( \rho_s \), steel bar strength \( f_y \), reinforcement ratio \( \rho \), and matrix strength of test specimen \( \sigma_c \).

\[
\Delta P = F\left( Q, \frac{L_0}{D_0}, \alpha, D, L, H, \rho_0, \rho, f_y, \sigma_c \right)
\]  

Since the high number of factors affecting the overpressure of a shock wave, solving Eq.(1) requires a considerable amount of tests. The present experimental tests mainly investigate primary factors and neglect the secondary ones or leave them to later research. For concrete of regular strength, the conventional ratio scheme used in engineering is adopted, so the density \( \rho_0 \) is approximately constant and negligible. TNT is usually used in experiments as charge, the density of which is not changed, and in practical application other types of charge can be equivalent to TNT charge, so they can be ignored for the moment. The present experiments adopt aggregate charging, so the effects of charge slenderness ratio \( L_0/D_0 \) and charge angle \( \alpha \) can be neglected. Thus, Eq.(1) simplifies as:

\[
\Delta P = F\left( Q, D, L, H, \rho, f_y, \sigma_c \right)
\]  

Through dimensional analysis, the following relationship can be obtained:
\[ \Delta P = f \left( \rho, \frac{H}{Q^{1/3}}, \frac{D}{Q^{1/3}}, \frac{\sigma_c}{f_y}, L \right) \]  

(3)

3. Design of experiments

The test rig consists of precast structure specimens and a modular steel model tunnel (figure 1). The following three types of structure specimens are designed to carry out tests. Type I: size specimen of 1000×1000×500 mm (WxLxH), with Ø8HPB335 reinforcing bar, and volumetric ratio of reinforcement of 1%. Type II: specimen of same dimension as Type I, and volumetric ratio of reinforcement is 2%. After pouring of both types, each edge of the square specimens is extended by 40 cm. The outer edges are constrained by 2-mm-thick light steel sheet, and C30 plain concrete is filled between the sheet and the original specimen. The purpose of increasing geometric dimensions of specimen and constraint by sheet is to increase the maximum charge of damage and to reduce the border effect of specimen. Type III: cylinder-shaped specimen with diameter of 162 cm (wall thickness of steel die is of 1 cm), and 75 cm high. Concrete marks of specimens of Types I and II vary in the range of C20–C80, while that of Type III is C30. All types use Ø8HPB335 reinforcing bars. The horizontal bar spacing and the vertical one of both Type I and Type II specimens are 150 mm and 100 mm, respectively. Type III uses Ø14 deformed steel bar internally, and the horizontal spacing is 15 cm. Binding wires connect seven layers of the mesh reinforcement. Spot welding for mesh is applied to four erection bars, and vertical spacing was 12 cm.

The steel model tunnel has a total length of 21 m, consisting of 21 assembly-type steel structure units. Each unit is 100 cm long, has a net section of 60 ×60 cm, and the wall is 2 cm thick. Figure 2 shows the real tunnel. In order to sustain the air tightness of the model tunnel during the experiment, the units are connected by high-strength bolts with seal rings between units, and both ends of the tunnel are open.

The tests mainly investigate the influences of different values of charge amount (200–2600 g), burial depth (30–68 cm) and the ratio of reinforcement (1% and 2%), and matrix strength of concrete (C30–C80) on the overpressure of leak shock wave in tunnel. A total of 40 tests were carried out. Before the damage test in structure, also air blast comparison tests were carried out. TNT aggregating charge was used in the air blast tests, and the explosion occurred at the geometric center of the external rim of steel structure at the opening of tunnel (figure 4). Through measuring the overpressure of shock wave at the sidewalls of main tunnel, the distribution and attenuation laws on shock wave of the air blast above the opening of tunnel could be analyzed to provide comparison standards for investigating the antiknock protection function of the structure. Eight air blast comparison tests were carried out.

![Test specimen of structure](image)

**Figure 1.** Schematic of the test rig.
Tapped holes were preliminarily laid out at different distances from the opening of the steel model tunnel; air pressure transducers were screwed inside before tests, and the sensing faces were aligned with the internal wall of tunnel. Air pressure transducers measure the air shock wave effects propagating along the tunnel. In the real tests, to facilitate the stability of tunnel and protection of measurement cables, the tunnel was embedded in the soil, and the upper edge of tunnel was aligned with the ground surface (figure 3).

4. Test results and analyses
Due to space limitations, this paper only presents the waveforms of air shock waves for the tests without structure specimen (figure 5 and figure 6), the damage patterns of explosive structure, and the measured waveforms of air shock waves in the tunnel for three different tests (figure 7~figure 12).
Figure 7. Test No. 040202, damage pattern of structure.

Figure 8. Test No. 040202, R=503 cm measured waveform.

Figure 9. Test No. 040902, damage pattern of structure.

Figure 10. Test No. 040902, R=303 cm measured waveform.

Figure 11. Test No. 052501, damage pattern of structure.

Figure 12. Test No. 052501, R=303 cm measured waveform.

Figure 13~ figure 17 show the effects of charge amount, burial depth of charge (explosive distance), the reinforcement ration of specimen, matrix strength, and existence of structure specimen, respectively, on the overpressure of air shock wave in tunnel.
The analyses of factors influencing the overpressure of shock wave highlight that the overpressure peak value of shock wave is sensitive to charge amount and burial depth in the tested range, and less sensitive to the ratio of reinforcement and matrix strength, i.e., the sensitivities to charge parameters are greater than those to structure parameters. The fluctuations of overpressure peak values of the shock waves in a relatively limited range and the increasing trend instead of the expected decrease (figure 13- figure 17) are individual phenomena preliminarily considered due to the measurement error. The measurement uncertainty of the overpressure of air shock wave is about 15%. When the variation amplitude of investigated influencing factor is small, that of the measurement result may be commensurate to the measurement error, and thus the phenomena of above are caused.

5. Calculation formulas for the effects of leak air shock wave

5.1. Engineering algorithm for overpressure of leak air shock wave

The test results of shock waves were fitted according to Eq. 3, and the following relationship can be obtained:

$$\Delta P = 1.707 \cdot e^{-0.164\rho - 6.783 \frac{H}{Q^{0.3}}} \left( \frac{D}{Q^{0.3}} \right)^{0.147} \left( \frac{\sigma_c}{f_y} \right)^{0.0474} \left( \frac{L}{Q^{0.3}} \right)^{-0.975}$$

(4)
Correlation index and standard deviation are R=0.970 SD=0.129, respectively. The scope of application is 0< ρ ≤2, 0.041≤ H/Q \(1/3\)≤0.297, 0.492≤ D/Q \(1/3\)≤0.919, 20 ≤ σ \(c\) ≤80 MPa, and 2.405≤ L/Q \(1/3\)≤9.203. The mean relative error of the fitting is 7.4%.

5.2. Calculation formula for the equivalent charge amount
The amount of equivalent charge is the charge amount corresponding to the overpressure effect of the explosion in a tunnel identical to that of the charge explosion in structure leaking to the same location in tunnel. Thus, the calculation formula (4) for the overpressure peak value of an air shock wave generated by the explosion in tunnel obtained by the present systematic study can be used to calculate the overpressure peak value of air shock wave of explosion in structure leaking into tunnel.
Concerning explosion in a straight tunnel, the overpressure of near-region air shock wave can be calculated by:

\[
\Delta P = 4.81 \left( \frac{L}{Q^{1/3}} \right)^{-1.855} \left( \frac{D}{Q^{2/3}} \right)^{-3.3}
\]

where, \(L/D\leq6\), \(D/Q^{1/3}=0.4~1.1\); \(Q\) is the explosive charge equivalent to TNT (kg); \(\Delta P\) is overpressure of air shock wave (MPa); \(L\) is distance from center of explosion, and \(D\) is equivalent diameter of tunnel, (m).

As for far zones, the overpressure of the air shock wave can be calculated by:

\[
\Delta P = 1.314 \left( \frac{L S}{Q} \right)^{-0.883} \left( \frac{D}{Q^{1/3}} \right)^{0.321}
\]

Where, \(L/D \geq 6\), \(D/Q^{1/3}=0.4~1.1\); \(S\) is sectional area of tunnel (m²). The measured overpressure of shock wave is calculated according to the calculation formula for the overpressure of explosive shock wave in tunnel, and the equivalent charge amount \(\omega\) of identical overpressure generated at the same location under explosion at the center of tunnel opening. The equivalent charge amount \(\omega\) is associated with experimental charge amount \(Q\), equivalent diameter of tunnel \(D\), height of explosion center \(H\), matrix compressive strength \(\sigma\), and ratio of reinforcement of structure \(\rho\). From dimensional analysis:

\[
\frac{\omega}{Q} = f \left( \frac{D}{Q^{1/3}}, \frac{\sigma}{f_y}, \rho, \frac{H}{Q^{1/3}} \right)
\]

According to the calculated \(\omega\) by back-calculation, through the fitting, the equivalent charge amount can be obtained:

\[
\frac{\omega}{Q} = 0.679 \left( \frac{D}{Q^{1/3}} \right)^{2.515} \left( \frac{\sigma}{f_y} \right)^{0.049} \cdot e^{-0.184 \rho - 4.255 \frac{H}{Q^{1/3}}}
\]

Correlation index and standard deviation are R=0.941 and SD=0.248, respectively. The scope of application of this formula is 0< \(\rho\) ≤2, 20 ≤ \(\sigma\) ≤80 MPa, 0.041 ≤ \(H/Q^{1/3}\) ≤0.325, and 0.521 ≤ \(D/Q^{1/3}\) ≤1.158. The mean relative error of the fitting result is 13.5%.

5.3. Quantitative analysis of antiknock protection function of the structure
The overpressure reduction factor \(\eta\) is introduced to evaluate the antiknock protection function of structure directly. It is defined as \(\eta = \Delta P_i/\Delta P_0\), where \(\Delta P_i\) is overpressure peak values at measuring
points of different distances in the explosive tunnel with structure specimen, and \( \Delta P_0 \) is overpressure peak values at measuring points of the same location in the tunnel without structure specimen. The working condition of test without structure specimen is the same as that with structure specimen in the tests, i.e., identical charge amount and burial depth. The overpressure reduction factor \( \eta \) is a function of test charge amount \( Q \), height of explosion center \( H \), equivalent diameter of tunnel \( D \), horizontal distance between measuring point and explosion center \( L \), ratio of reinforcement of specimen \( \rho \) and matrix compressive strength of specimen \( \sigma_c \).

Through dimensional analysis, the following relationship can be obtained:

\[
\frac{\Delta P_1}{\Delta P_0} = f\left[ \rho, \frac{H}{Q^{1/3}}, \frac{D}{Q^{1/3}}, \frac{L}{Q^{1/3}}, \frac{\sigma_c}{f_y} \right]
\]

The expression of overpressure reduction factor of experimental results of shock waves with and without the structure specimen is as follows:

\[
\eta = \frac{\Delta P_1}{\Delta P_0} = 0.180 \cdot e^{-0.118 \rho - 4.890 \frac{H}{Q^{1/3}} - 0.642 \left( \frac{D}{Q^{1/3}} \right) - 0.475 \left( \frac{L}{Q^{1/3}} \right) - 0.260 \left( \frac{\sigma_c}{f_y} \right)}
\]

Correlation index and standard deviation are \( R=0.927 \) and \( SD=0.157 \), respectively. The scope of the application of Eq. (10) is \( 0<\rho \leq 2 \), \( 0.041 \leq H/Q^{1/3} \leq 0.325 \), \( 0.492 \leq D/Q^{1/3} \leq 1.158 \), \( 20 \leq \sigma_c \leq 80 \) MPa, and \( 2.405 \leq L/Q^{1/3} \leq 9.203 \). The calculated mean relative error is 8.6%.

6. Conclusions

Based on measurement results of tests of shock wave propagation in a tunnel which the explosion in structure leaks into, together with dimensional analysis, engineering calculation methods are obtained for leak shock wave effects, including overpressure distribution of shock wave caused by explosion in structure leaked into tunnel, equivalent coefficient of explosive charge in comparison with explosion in tunnel, and reduction factor of overpressure of shock wave with or without structure. The calculated mean errors of the algorithms of above are 7.4%, 13.5%, and 8.6%, respectively, demonstrating the results from the algorithm, and the measurements are in good agreement.

References

[1] ZHENG Quanping, ZHOU Zaosheng, QIAN Qihu, et al. 2003, Chinese Journal of Rock Mechanics and Engineering, Spallation in protective structures. vol 22(8): pp 1393-1398

[2] ZHANG Xiangbai, YANG Xiumin, CHEN Zhaoyuan, et al. 2006, Journal of Tsinghua University: Science & Technology, Explosion spalling of reinforced concrete slabs with contact detonations. vol 46(6): pp 765-768

[3] YUE Songlin, WANG Mingyang, ZHANG Ning, et al. 2016, Explosion and Shock Waves, A method for calculating critical spalling and perforating thicknesses of concrete slabs subjected to contact explosion. vol 36(4): pp 472-482

[4] YANG Yadong, LI Xiangdong, WANG Xiaoming. 2016, Acta Armamentarii, An analytical model for propagation and superposition of internal explosion shockwaves in closed cuboid structure. Vol 37(8): pp 1449-1455

[5] YANG Kezhi, YANG Xiumin. 2003, Explosion and Shock Waves, Shock waves propagation inside tunnels., vol 23(1): pp 37-40

[6] CHENG Liangyu, LONG Yuan, MAO Yiming, et al. 2017, Journal of Vibration and Shock, An experimental study on large-diameter high-pressure pipeline physical explosions shock wave propagation. vol 36(22): pp 40-44
[7] HU Hongwei, SONG Pu, ZHAO Shengxiang, et al. 2013, *Chinese Journal of Energetic Materials, Progress in explosion in confined space*. vol 21(4): pp 539-546

[8] TIAN Zhimin, WU Yubin, LUO Qifeng. 2011, *Journal of Vibration and Shock, Characteristics of in-tunnel explosion-induced air shock wave and distribution law of reflected shock wave load*. vol 30(1): pp 21-26