Study on the air shock wave effect and engineering algorithm in the tunnel after the damage of protective door under different explosion conditions

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Abstract. In this study, the effect of an air shock wave discharged into a tunnel when an explosion occurs in front of a protective door was experimentally examined and the actual air shock waveforms in the tunnels with and without a protective door were analyzed and compared. It was found that both the waveform structure and the characteristic parameters of the air shock wave, such as the peak and the action time, were significantly changed after a protective door was installed. Moreover, by combining with dimensional analysis results, some detailed engineering algorithms of the residual shock wave effect, namely, the engineering algorithm of the overpressure peak of the residual shock wave in the tunnel, the equivalent explosive coefficient in the case without protective door, and the shock wave reduction coefficient with and without a protective door, were derived.

1. Introduction

A protective door, generally located at the mouth of an underground tunnelling project, is specially used to block the produced shock wave. The explosion energy produced by charged explosives in enclosed underground tunnels is mostly transformed into an air shock wave. However, in cases where the explosions take place in adjacent structures and cause certain damages, the energy conversion and damage effect are quite complex [1-3]. The explosion in this type of environment exhibits the following distinguishing features: (1) the explosion near the charging position does not form a stable air shock wave in front of the structure, and the load acting on the structure is mainly induced by the produced detonation products; (2) under the detonation pressure, the structure gets damaged to a certain degree and is seriously penetrated, such that some detonation products may rush in the back of the structure; (3) the detonated products that have rushed in the back of the structure continue to move and the formed residual air shock wave propagates; (4) due to the restriction and obstruction from the structure, some explosive energy causes damages to structures, while some energy translates into an air shock wave; (5) compared with the condition without structure, the anti-explosion protective body of the structure consumes most of the explosive energy, which reduces significantly the strength of the shock wave at the back of the structure and protects the personnel and equipment to certain degree. In other words, the protective body can be sacrificed to save others. Investigating the effect of the propagated residual shock wave along the tunnel in front of a protective door is typical of this type of explosion environments. The enormous released explosion energy from the explosives not only causes damages to the internal structures and the protective door in the tunnel, but also converts partly into a
residual air shock wave behind the door, which may injure the personnel and destroy the equipment after passing through the screen of the protective door. Currently, scholars place emphasis on the impact-resistance design of protective doors, as well as on their damage mode and dynamic response [4-8], however, the residual shock wave effect behind the protective door from the perspective of damage is rarely investigated. Zheng Yin et al. examined the propagation rules of the residual shock wave after the protective door was damaged [9]. Liao Zhen et al. performed numerical simulations on the propagation rules of the residual shock wave after the protective door of a tunnel was damaged. They found that the peak pressure of the shock wave with the protective door was approximately 4.0%~10.0% of the value without the protective door [10]. According to their results, the protective door effectively prevented the propagation of the air shock wave and greatly reduced its damage power. However, a practical engineering calculation method of the residual air shock wave effect is still in blank.

The residual shock wave effect produced in the explosion in front of a protective door and propagated along a tunnel can be regarded as a typical near-zone explosion problem. There exist a lot of influence factors, including mainly the propagation and distribution of the explosion load, as well as the structural damages. Analytical solutions can hardly be obtained through pure theoretical analysis. Numerical simulation accuracy heavily relies on the selection of material mode and structural damage criterion. Compared to numerical simulation and theoretical analysis methods, experiments still prove to be the most direct and reliable research means for this type of problems. In this study, experiments were performed on the shock wave effect that was produced from an explosion in front of a reinforced concrete protective door and propagated along the tunnel, and reasonable functions were concluded via dimensional analysis. Next, the experimental data were fitted for acquiring the engineering calculation method of the residual shock wave in a tunnel. The present research results can provide insightful reference for damage assessment and structural design in tunnels.

2. Experimental arrangement and operating condition

13 sets of experiments in total were carried out for examining the residual shock wave effect in a tunnel after an explosion in front of a protective door, among which the reinforced concrete protective door was installed in 7 sets of experiments, while the rest experiments were performed without the protective door. 7 reinforced concrete protective door specimens were prepared before testing. Reinforced concrete specimens, with a C30 strength grade and a size of 0.6m×0.6m×0.1m were used. The related reinforcement ratio per unit volume was 1.0%. During the tests, the prepared reinforced concrete protective door specimens were placed at the outer edge of the combined steel tunnel mouth using groove steel constraints. The steel tunnel was 15 m in length and 60 cm×60 cm in net sectional area. The charged explosive was placed right ahead of the specimen and the explosion center pointed right at the geometrical center. The explosive was placed at a certain distance away from the specimen (figure 1). Soil bags were piled up above the specimen to reduce the boundary effect. Threaded holes were opened at different distances away from the steel tunnel opening. Before the experiment, air pressure sensors were screwed in the holes and the sensitive surfaces were aligned with the inner wall of the tunnel. After the TNT explosives were detonated, the damage morphology of the specimen was observed and air shock wave pressure on the side wall of the tunnel behind the specimen was measured. Table 1 lists the basic operating conditions used in the present experiments. The explosive charging conditions remained unchanged in the damage tests with and without a reinforced concrete protective door.
Figure 1. Testing arrangement.

Table 1. Operating conditions applied in the damage experiments with and without a reinforced concrete protective door.

| Serial number | Explosive charge/g | Horizontal distance from the explosion center to the specimen surface/cm | With/without a protective door |
|---------------|--------------------|------------------------------------------------------------------------|-------------------------------|
| 1             | 1800               | 23.75                                                                  | With a protective door        |
| 2             | 600                | 23.75                                                                  | With a protective door        |
| 3             | 1200               | 23.75                                                                  | With a protective door        |
| 4             | 1200               | 17.75                                                                  | With a protective door        |
| 5             | 800                | 16.5                                                                   | With a protective door        |
| 6             | 400                | 16.5                                                                   | With a protective door        |
| 7             | 600                | 16.5                                                                   | With a protective door        |
| 8             | 400                | 16.5                                                                   | Without a protective door     |
| 9             | 800                | 16.5                                                                   | Without a protective door     |
| 10            | 1200               | 17.75                                                                  | Without a protective door     |
| 11            | 1200               | 23.75                                                                  | Without a protective door     |
| 12            | 600                | 23.75                                                                  | Without a protective door     |
| 13            | 1800               | 23.75                                                                  | Without a protective door     |

3. Experimental arrangement and operating condition
After the tests were performed, the damage effect on the RC protective door was observed, and the overpressure curves of the produced air shock wave measured at the same location with and without the RC protective door were plotted and compared. Figure 2 displays the overpressure curves of the air shock wave under an explosive charge of 800 g and at an explosive center distance of 16.5 cm. Figure 3 displays the overpressure curves under an explosive charge of 1800 g and at an explosive center distance of 16.5 cm. Figure 4 displays the attenuation rules of the overpressure peak of the shock wave at the back of a protective door when the explosion distance was fixed (R=0.238m) and the explosive charge varied (Q=0.6, 1.2, and 1.8kg). Figure 5 displays the attenuation rules of the overpressure peak of the shock wave at the back of a protective door when the explosive charge was fixed (Q=1.2kg) and the explosion distance was set at different values (R=0.178, 0.238m).
Figure 2. Air shock waveforms measured at the same point with and without a protective door (W=800g and r=16.5cm).

Figure 3. Air shock waveforms measured at the same point with and without a protective door (W=1800g and r=16.5cm).

Figure 4. Attenuation rules of the shock wave overpressure at a fixed distance under different explosive charges.

Figure 5. Attenuation rules of the shock wave overpressure under a fixed explosive charge at different explosion distances.
Contrary to the air shock wave formed in the tunnel when no RC protective door was installed, the air shock wave in the tunnel with a RC protective door exhibited the following apparent characteristics:

1. The overpressure peak of the shock wave was significantly reduced. At a same measuring position, the overpressure peak of the air shock wave after the addition of the RC protective door was reduced by over 90%, and simultaneously, the action time was greatly increased by approximately 2~3 times. This is practically consistent with the research conclusions described in [4].

2. The waveform peak of the shock wave in the tunnel after placing a protective door underwent obvious oscillation. When a protective door was installed, a great number of concrete fragments, particles, and dust produced during the explosion spread in the tunnel and then acted on the sensors, leading thereby to drastic waveform fluctuations.

3. In the cases with a protective door, a peak pressure with a magnitude of approximately 0.01~0.02 MPa appeared before the peak of the shock wave, which lasted for a short time (of the order of ms). The peak pressure may have been caused by the transient intensive deformation of the protective door before damage or by the induced air shock wave when the air was compressed. Under explosion-induced punching or collapse action, the reinforced concrete in the region of damage moved rapidly away from the original, leading thereby to the compression of air. Next, when the formed great air shock wave propagated across the tunnel and was discharged into the damaged passage, a residual air shock wave was formed and propagated. The shock wave pressure rose steeply to the maximum. In other words, the peak pressure lasted for a short time, and then, the residual pressure shock wave that was produced in the explosion arrived and superposed on the peak pressure waveform.

4. After a protective door was installed, the overpressure peak of the shock wave measured at the same point dropped as the explosion distance increased and the explosive charge decreased, as shown in figure 4 and figure 5, respectively.

4. Engineering algorithm of the residual shock wave effect

4.1. Engineering algorithm of the overpressure peak of the residual shock wave

The detonation of the explosives next to the RC protective door caused damages to the protective door to a certain degree. For the protective doors with same size, the strength of the residual shock wave discharged into the tunnel, after the protective door was torn, was related to the explosive charge Q, the explosion distance R, the tunnel cross-sectional area S (the equivalent diameter D), and the horizontal distance X between the measuring point and the protective door (figure 6).

Figure 6. Illustration of the explosion experiments in the tunnel (a) with and (b) without a protective door.
When protective doors with same size were used, the effect of the parameters related to the protective door on the strength of the residual shock wave was not taken into account. Based on the test conditions, a dimensional analysis was performed:

$$\Delta P = f\left(\frac{X}{Q^{1/3}}, \frac{D}{Q^{1/3}}, \frac{R}{Q^{1/3}}\right)$$

By fitting the shock wave pressure measured on the side wall of the tunnel when the RC protective door was damaged to a certain degree under different conditions (different explosive charges and explosion distances), the overpressure peak of the residual shock wave behind the protective door can be calculated as:

$$\Delta P = 0.517 \cdot \left(\frac{X}{Q^{1/3}}\right)^{-1.997} \cdot \left(\frac{D}{Q^{1/3}}\right)^{-0.558} \cdot \left(\frac{R}{Q^{1/3}}\right)^{-0.319}$$

Where $\Delta P$ denotes the overpressure peak of the shock wave in the tunnel (MPa); $Q$ denotes the original explosive charge (kg); $X$ denotes the distance between the measuring point and the mouth edge of the tunnel (m); $D$ denotes the equivalent diameter of the tunnel (m); and $R$ denotes the distance between the explosion center and the mouth edge of the tunnel (m).

The correlation coefficient and the standard deviation of the fitting results were $R=0.941$ and $SD=0.1406$, respectively. The application range of Eq. (2) can be described as:

- $\frac{D}{Q^{1/3}} = 0.556 \sim 0.919$
- $\frac{R}{Q^{1/3}} = 0.167 \sim 0.282$
- $\frac{X}{Q^{1/3}} = 2.038 \sim 6.026$

By taking the 2nd and the 9th sets of experiments as an example, the overpressure peaks of the shock waves were calculated according to Eq. (2), and were also compared to the measured results (figure 7 and figure 8). Apparently, the calculated results fit well with the measured data. The mean error between the calculated overpressure peaks of the residual shock wave and the measured values was 16.8%.

**Figure 7.** Comparison between the calculated overpressures of the residual shock wave and the results from the 2nd experiment.

**Figure 8.** Comparison between the calculated overpressures of the residual shock wave and the results from the 9th experiment.
4.2. Engineering algorithm of the explosive equivalent coefficient

The equivalent explosive charge refers to the required explosive charge in the tunnel without a protective door when the same overpressure effect can be achieved at the same position in the tunnel with a protective door. Accordingly, using the calculated formula for the overpressure peak of the explosion air shock wave that has been systematically investigated, the overpressure peak of the residual shock wave in the tunnel with a protective door can be calculated as:

\[
\Delta P = 0.258 \left( \frac{XS}{Q} \right)^{-0.519} \left( \frac{D}{Q^{1/3}} \right)^{-1.58} e^{-0.642 \frac{R}{Q^{1/3}}}
\]

The related application range can be written as:

- \( \frac{D}{Q^{1/3}} = 0.4 \sim 1.1 \)
- \( \frac{R}{Q^{1/3}} = 0 \sim 1 \)

By combining Eq. (3) with the measured data, the required explosive charge \( \omega \), corresponding to the same overpressure peak at the same position in the tunnel, can be derived, which can be used as the equivalent explosive charge in the tunnel without a protective door (figure 1b). Then, the equivalent coefficient of the charge, denoted as \( \frac{\omega}{Q} \), can be calculated. Through dimensional analysis, the following expression can be acquired:

\[
\frac{\omega}{Q} = f \left( \frac{XS}{Q}, \frac{D}{Q^{1/3}}, \frac{R}{Q^{1/3}} \right)
\]

(4)

According to the above converted equivalent explosive charge, the following expression can be obtained through formula fitting:

\[
\frac{\omega}{Q} = 0.148 \cdot \left( \frac{XS}{Q} \right)^{-0.943} \cdot \left( \frac{D}{Q^{1/3}} \right)^{2.379} \cdot \left( \frac{R}{Q^{1/3}} \right)^{-1.017}
\]

(5)

The correlation coefficient and the standard deviation of the fitting results were \( R=0.935 \) and \( \text{SD}=0.051 \), respectively. The formula is applicable under the following conditions: \( 0.496 \leq \frac{XS}{Q} \leq 3.86 \), \( 0.556 \leq \frac{D}{Q^{1/3}} \leq 0.919 \), and \( 0.167 \leq \frac{R}{Q^{1/3}} \leq 0.282 \). The fitted mean relative error was equal to 8.8%.

4.3. Anti-explosion protective effect of the RC protective door

The overpressure reduction coefficient was introduced in order to directly evaluate the anti-explosion protection effect of the protective door. The overpressure reduction coefficient can be defined as

\[
\eta = \frac{\Delta P_1}{\Delta P_0}, \text{ where } \Delta P_1 \text{ denotes the overpressure peaks at different measuring points in the tunnel with a protective door, and } \Delta P_0 \text{ denotes the overpressure peaks at the same measuring points in the tunnel without a protective door under same explosive charging conditions (i.e., the explosive charge and the buried depth remained unchanged). Through dimensional analysis, the following expression can be derived:}
\]
Based on the overpressure peak ratio of the shock wave in the tunnel with and without a protective door, the overpressure reduction coefficient of the RC protective door can be fitted as:

$$\eta = \frac{\Delta P}{\Delta P_0} = f\left(\frac{XS}{Q^{1/3}}, \frac{D}{Q^{1/3}}, \frac{R}{Q^{1/3}}\right)$$

(6)

The correlation coefficient and the standard deviation of the fitting results were $R=0.919$ and $SD=0.0807$, respectively.

The above formula is applicable under the following conditions: $0.652 \leq \frac{XS}{Q} \leq 3.861$, $0.556 \leq \frac{1/3}{D} \leq 0.919$, $0.167 \leq \frac{1/3}{R} \leq 0.282$. The fitted mean relative error was equal to 10.9%.

5. Conclusions

This study experimentally investigated the air shock wave effect when the explosion in front of the RC protective door was discharged into a tunnel, and compared the measured waveforms of the air shock waves produced in the tunnel with and without a protective door. After a protective door was installed, both the waveform shape and characteristic parameters, such as the peak and the action time of the air shock wave, were significantly changed. In combination with dimensional analysis results, some engineering algorithms of the residual shock wave effect were derived, including the engineering algorithm of the overpressure peak of the residual shock wave in the tunnel, the equivalent explosive charge coefficient, corresponding to the case without a protective door, and the reduction overpressure coefficient after a protective door was installed. Using these algorithms, the mean errors were 16.8%, 8.8% and 10.9%, respectively, which confirmed a good consistency between calculated and measured results.

Due to limited research conditions and research period, the experiments in this study were conducted only on one type of RC protective door. Actually, the strength of the residual shock wave is not only related to explosive charging parameters and tunnel geometry parameters, but it also depends on the type and the properties of the protective door. It can be reasonably predicted that a novel protective door with higher strength would possess stronger anti-explosion protection effect. The conclusions of the present research can provide insight into the analysis of anti-explosion performances of other protective doors and into the calculation of the residual shock wave strength.

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