Numerical Simulation about the Effect of Tunnel Expansion Chamber on the Shock Wave Attenuation

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Abstract. Setting up an expansion chamber in the local tunnel can accelerate the attenuation speed of the shock wave, which is of great importance for safety protection of the tunnel staff. Under the same simplified conditions, the reliability of the numerical model was verified according to the theoretical formula calculation results. The simulation results of the long straight tunnel and the tunnel with expansion chamber were compared. Results show that the overpressure in the tunnel with expansion chamber is lower than that in the long straight tunnel at the same distance. Then, the length-width ratio was changed. Taking both the protection performance and construction cost into consideration, it is concluded that expansion chamber with the length-width ratio of 2.5 is relatively appropriate. The study can offer effective reference for structure design of the underground tunnel.

Introduction

Explosion shock wave is a kind of strong compression wave, the propagation of which is supersonic. Therefore, increasing the cross-sectional area of the tunnel can effectively reduce the shock wave pressure. In engineering practice, the cross section shape of the tunnel will be limited by several factors, setting up an expansion chamber in the local tunnel is an effective way to solve the above problem.

In recent years, a series of progress has been made by domestic and foreign scholars in this area. Jia Zhiwei et al.[1] proposed the expression of wave front parameters after the mutation of the sectional area; Zhang Shouzhong et al.[2] preliminary discussed the attenuation characteristics of shock wave by carrying out explosion experiments in tunnels with different sectional areas. Igra et al.[3] extended their computation to demonstrate the contribution of the expansion chamber volume to shock wave attenuation. The previous studies lack specific analysis of the shock wave flow field and also fail to give a conclusion with application value.

In this paper, an underground tunnel is taken as the research object, the numerical simulation is carried out based on ANSYS/LS-DYNA, the propagation of the shock wave in tunnel with expansion chamber is analyzed using the knowledge of fluid mechanics and the size of expansion chamber is given which is most beneficial to shock wave attenuation.

The theoretical analysis

The explosion shock wave propagates in a tunnel at the speed of V. When it reaches the surface of AB, the wave front intensity suddenly changes as the increase of the sectional area [4], which is shown in figure 1. In order to conveniently analyze the physical parameters of the wave front before and after mutation, it is assumed that the shock wave reaches surface CD from surface AB in unit time. In fact, surface AB and CD is coincident in geometry. Since the elastic-plastic deformation of the tunnel wall is very small, it is regarded to be smooth and rigid. The quality and viscosity of the air are also ignored.

Before mutation, the sectional area of the tunnel is S_1, the wave front AB is characterized by the physical parameters of u_1, ρ_1, P_1; After mutation, the sectional area of the tunnel is S_2, the wave front CD is characterized by the physical parameters of u_2, ρ_2, P_2. The coordinate system which synchronously moves with velocity V is taken as the reference coordinate system.

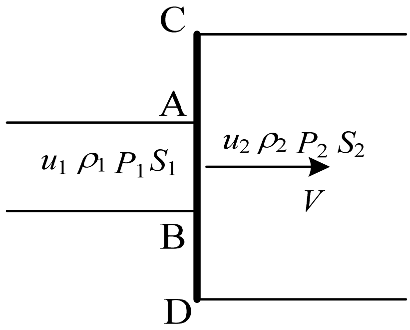


Fig.1. Wave front before and after the sectional area mutation

According to the mass conservation equation:

$$\rho_1(V-u_1)S_1=\rho_2(V-u_2)S_2 \tag{1}$$

According to the momentum conservation equation:

$$\rho_1(V-u_1)^2S_1+P_1S_1=\rho_2(V-u_2)^2S_2+P_2S_2 \tag{2}$$

According to the energy conservation equation:

$$e_1+\frac{1}{2}(V-u_1)^2S_1+\frac{P_1}{\rho_1}S_1=e_2+\frac{1}{2}(V-u_2)^2S_2+\frac{P_2}{\rho_2}S_2 \tag{3}$$

According to the equation of state:

$$e_1=\frac{P_1}{(\gamma-1)\rho_1} \tag{4}$$

$$e_2=\frac{P_2}{(\gamma-1)\rho_2} \tag{5}$$

Where, γ is the adiabatic coefficient of the air; e is the internal energy.

For the above equations, the number of unknowns is greater than the number of equations, it is impossible to obtain an analytic solution. In reference [5], the pressure P_1 of wave front AB is considered to be a known quantity, the pressure P_2 of wave front CD is derived by eliminating unknowns:

$$P_2=P_1-\frac{(P_1-P_0)(\frac{S_2}{S_1}-1)[(\gamma+1)P_0+(\gamma-1)\frac{S_1}{S_2}P_1]}{[(\gamma+1)-(\gamma-1)\frac{S_1}{S_2}]P_1+[(\gamma-1)\frac{S_2}{S_1}-(\gamma+1)]P_0} \tag{6}$$

Where, γ is 1.4; P_0 represents the initial pressure of air in the tunnel which is 0.1MPa in this paper.

The simulation model

The length of the tunnel is 82 m, the cross section is rectangle with the area of 3.5 m × 8.5 m. The expansion chamber is set up 20 m from the entrance of which length is 30 m and width is 10 m, as is shown in figure 2 (the length unit is cm). When establishing the simulation model, a wave front of 0.4 MPa produced by explosion outside the tunnel is simplified as a pressure load, which is applied to the normal direction of the tunnel entrance.

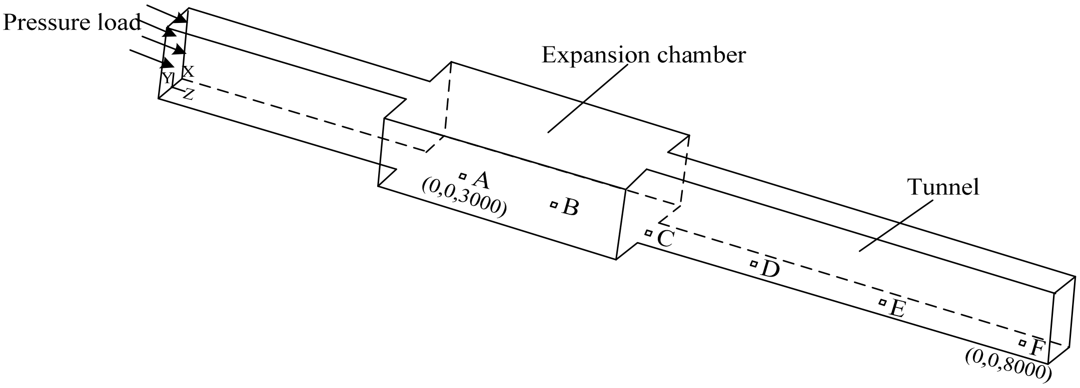


Fig.2. The diagram of simulation model

In order to establish a rigid wall, the zero displacement boundary condition is set up by constraining the air particle movement in the normal direction [6]. And also air is regarded as ideal gas in order to ignore the influence of quality and viscosity.

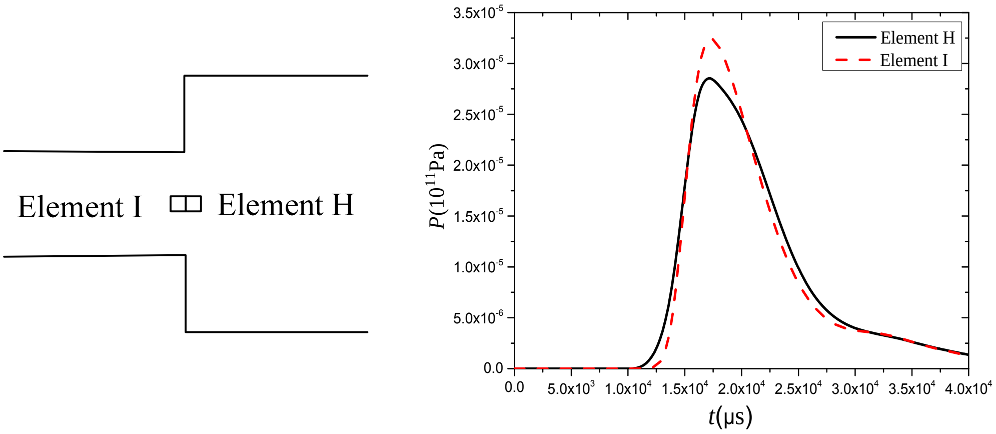
The simulation model only consists of air, which is described by a kind of material model called MAT_NULL and linear polynomial equation of state named EOS_LNIEAR_ POLYNOMIAL.

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E \qquad （7）$$

Where, $\mu = \frac{\rho}{\rho_0} - 1$, ρ is the current density, ρ_0 is the initial density, E is internal energy of material, C_0, C_1, C_2, C_3, C_4, C_5, C_6 are parameters of the state equation [7]. For the ideal gas, $C_0= C_1= C_2= C_3= C_6=0$，$C_4= C_5=0.4$.

The simulation verification

To further verify the reliability of the simulation model, element H and I are taken before and after the wave front, both elements locate on the central axis of the tunnel. The overpressure-time curve is obtained according to the simulation results, as is illustrated in figure 3. By the overpressure-time curve, it is found that the overpressure suddenly decreases when the sectional area enlarges. The peak overpressure of element I reaches up to 3.39 MPa, while the peak overpressure of element H falls to 2.92 MPa.



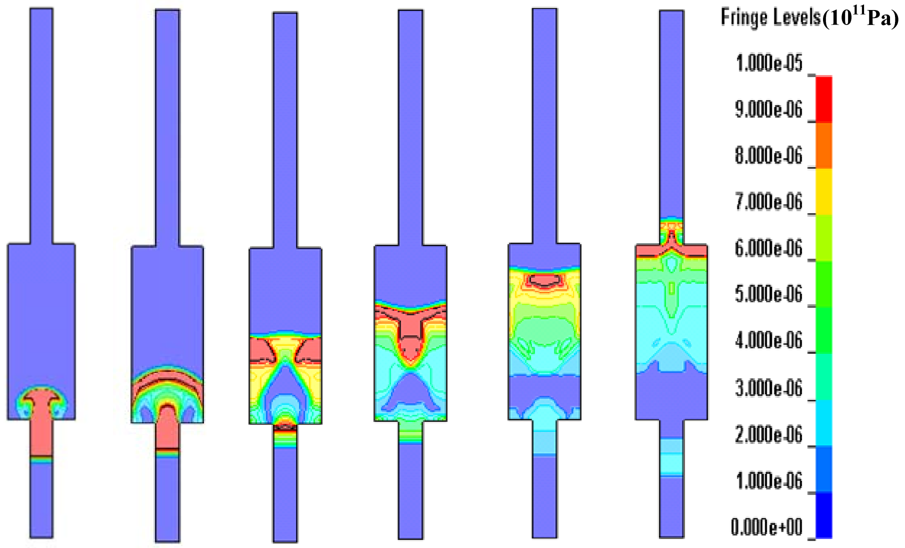
a) b）

Fig.3. The location of two elements and their overpressure-time curve

The peak overpressure of element H is regarded as P_1 of the wave front AB, the peak overpressure of element I is regarded as P_2 of the wave front CD. The pressure P_1 of 3.39 MPa is substituted into the equation (6). It can be obtained that P_2 is 2.83 MPa. Comparing the calculation result of 2.83 MPa with the simulation result of 2.92 MPa, the relative error is 3.2%. The causes of the error may be that in the formula derivation process AB and CD are assumed to be the ideal plane waves, while in numerical simulation the shock wave will be reflected and superimposed resulting in the pressure intensity enhancement. On the whole, the error lies in an acceptable range proving the simulation model is reliable.

Results and discussion

After setting up an expansion chamber in the tunnel, the propagation process has a big difference from that in the long straight tunnel. The pressure flow field at different times is shown in figure 4, in which the propagation of shock waves can be clearly observed. *t*=15ms, the shock wave spread into the expansion chamber experiencing the first sectional mutation. Due to the inertia, the middle of the wave kept its original shape and the edge extended into the surrounding space forming a fan-shaped surface. *t*=17ms, there existed two low pressure areas at the right-angled bends. During the process of continuous propagation, the shock wave was reflected back and forth between the walls. At the same time, the reflected wave and the incident wave superimposed with each other. Two high pressure areas developed on both sides of the wall. *t*=25ms, the high pressure areas continued to increase and converged near the central axis. Gradually, the high pressure air mass restored to a smooth wave front.



t=15ms *t*=17ms *t*=22ms *t*=25ms *t*=29ms *t*=35ms

Fig.4. The pressure flow field at different times

In order to further verify the effect of expansion chamber on shock wave attenuation, a long straight tunnel with the same length and sectional area was established on which the same pressure load was applied. As is shown in figure 1, six elements are located along the tunnel's central axis, which are separated by 10 m each. The elements are named from A to F, their corresponding overpressures are P_A～P_F.

The simulation results of the long straight tunnel and the tunnel with an expansion chamber are summarized in table 1. The long straight tunnel is named tunnel 1, the tunnel with an expansion chamber is named tunnel 2. Overall, the overpressure in two tunnels was both diminishing with the increase of the distance. However, a small rise occurred near element B in tunnel 2, which is consistent with the phenomenon of high pressure area converging in the flow field analysis. After setting up an expansion chamber, the geometric space of the tunnel enlarged, the wave front become wider, the energy distribution on unit area reduced and the quantity of compressed air increased. The kinetic energy of the air particles promoted leading to an augment of the irreversible energy loss. Thus, the overpressure in the tunnel with an expansion chamber is lower than that in the long straight tunnel at the same distance.

Table 1 the overpressures of six elements in two tunnels

	P_A	P_B	P_C	P_D	P_E	P_F
Tunnel 1(MPa)	1.25	1.17	1.09	0.92	0.81	0.77
Tunnel 2(MPa)	0.76	0.88	0.79	0.71	0.60	0.57
Decrease rate(%)	39.2	24.8	27.5	22.8	25.9	26.0

In engineering construction, it is ensured that the protective performance should meet the requirements and the costs should reduce to the greatest extent, therefore, the size of expansion chamber which is most beneficial to shock wave attenuation need to be found out. Keeping the tunnel length of 82 m, the opening position b=20m, the chamber width d=10m unchanged, the chamber length l is changed making the length-width ratio l/d between 1～5.5, as is shown in figure 5.Multiple sets of numerical simulations were carried out by 0.5 each.

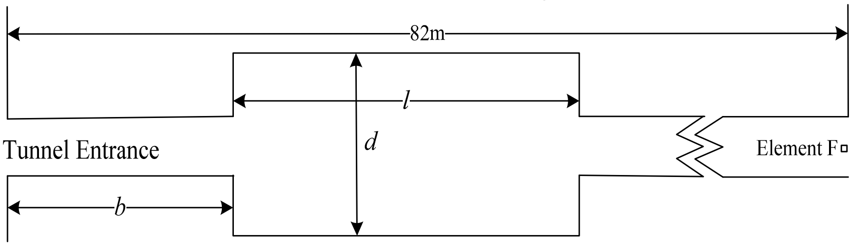


Fig.5. Top view of the tunnel with expansion chamber

In case of accidental explosion, the staff will escape through the tunnel exit, therefore, the overpressure of element F need to be focused on. The curve of the relationship between overpressure and length-width ratio is illustrated in figure6. It can be seen that the overpressure of element F is not monotonically decreasing with the increase of the chamber volume. $1\leqslant l/d\leqslant 2.5$, the overpressure shows obvious downward trend; l/d =2.5, the overpressure reaches a minimum of 0.62 MPa; $2.5\leqslant l/d\leqslant 4.5$, the overpressure decreases slowly after a small increase, which is still greater than the minimum.

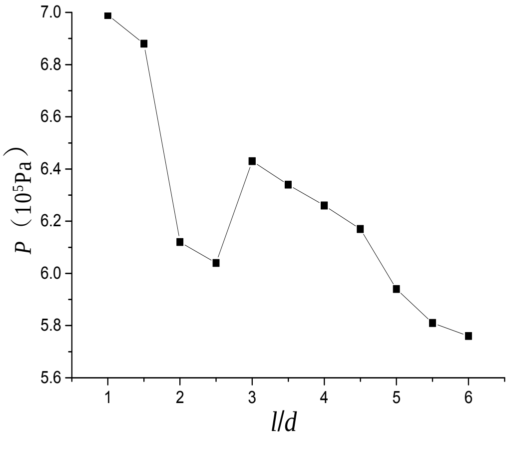


Fig.6. The curve of the relationship between overpressure and length-width ratio

Under different conditions, the overpressure of shock waves which just enter the expansion chamber is the same. With the difference in chamber length, the reflection effect between shock wave and walls is different. When the length lies in a certain range, the reflection will continue after the high pressure area converges. If the energy supplement is greater than the dissipation, the overpressure will enhance.

Giving priority to the construction cost, the expansion chamber with the length-width ratio of 2.5 is relatively appropriate. Several measures can be taken to reduce the overpressure, such as adding multilevel gallery and installing interference plates.

Conclusion

The reliability of the numerical model was verified by comparing with the formula calculation. Subsequently, the propagation law of shock wave in the tunnel with expansion chamber was studied. The following conclusions were drawn.

1) The overpressure in the tunnel with expansion chamber is lower than that in the long straight tunnel at the same distance.

2) Giving priority to the construction cost, the expansion chamber with the length-width ratio of 2.5 is relatively appropriate for the underground tunnel.

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