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A numerical study of the evolution of the blast wave shape in rectangular tunnels

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ABSTRACT

When the explosion of condensed materials occurs in square or circular cross-section tunnel, the subsequent blast wave reveals two patterns: three-dimensional close to the explosive charge and one-dimensional far from the explosion. Pressure decays for these two patterns have been thoroughly studied. However, when the explosion occurs in rectangular cross-section tunnel, which is the most regular geometry for underground networks, the blast wave exhibits a third, two-dimensional, patterns. In order to assess the range of these three patterns, several numerical simulation of blast waves were carried out varying the width and the height of the rectangular cross-section as well as the mass of the charge. Laws are presented to localize the transition zones between the 3D and the 2D patterns, and between the 2D and the 1D patterns, as functions of non-dimensional width and height. The numerical results of the overpressure are compared to existing 3D and 1D laws. An overpressure decay law is proposed to represent the 2D pattern. Knowing the two transition zones and the overpressure decays within these zones, an algorithm is presented to efficiently predict an overpressure map. This algorithm is validated by comparison with experimental data.

1. Introduction

Blast wave is a topical research subject as shown by the several recent works (Igra et al., 2013; Langlet et al., 2014; Kim et al., 2014), and in particular confined blast wave (Song and Ge, 2013; Buonsanti and Leonardi, 2013). One of the application of the confined domain is the underground network. Underground networks such as subway station have rectangular cross-section. Typically, the height is smaller than the width. Therefore, blast waves occurring in such a domain exhibit three patterns: (a) a free-field pattern, known to yield fast overpressure decay, while the blast wave does not reach any obstacle; (b) a two-dimensional (2D) pattern after the first reflection (vertical: in the direction of the height) and (c) a one-dimensional (1D) pattern after the second reflection (transversal: in the direction of the width). 2D and 1D patterns obviously induced lower overpressure decays involving more dramatical damages not only for the structures but also for the peoples. The knowledge of the global behavior of blast waves in such a confined domain is thus decisive for safety reasons.

The first pattern cited above, ie. the free-field pattern, is indubitably the most studied. From these studies, scaling laws were derived, as the laws from Baker et al. (1983), Mills (1987), Brode (1959) or Henrych (1979) relating the maximum overpressure peak to the distance from the explosive charge. In fact, Henrych (1979) proposed one of the most common free-field decay law, which is expressed as:

$$\begin{cases} \left.\dfrac{\Delta P_{max}}{P_{ref}}\right|_{Henrych} = \dfrac{14.072}{Z} + \dfrac{5.54}{Z^2} - \dfrac{0.357}{Z^3} + \dfrac{0.00625}{Z^4} \text{ if } 0.05 \le Z \le 0.3 \\ \left.\dfrac{\Delta P_{max}}{P_{ref}}\right|_{Henrych} = \dfrac{6.194}{Z} - \dfrac{0.326}{Z^2} + \dfrac{2.132}{Z^3} \text{ if } 0.3 \le Z \le 1 \\ \left.\dfrac{\Delta P_{max}}{P_{ref}}\right|_{Henrych} = \dfrac{0.662}{Z} + \dfrac{4.05}{Z^2} + \dfrac{3.288}{Z^3} \text{ if } 1 \le Z. \end{cases} \quad (1)$$

The third propagation pattern is the case of a confined explosion, which considers that the blast wave propagates inside a confined space that is strong enough to withstand the explosive

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Nomenclature

Greek letters

$\alpha_x = 100d_c/x$	ratio of the explosive diameter d_c to the tunnel hydraulic diameter d_H, height H, width H or $W-H$
Δx	mesh cell size (m)
λ	mesh wavenumber, $\lambda = m_c^{1/3}/\Delta x$ ($kg^{1/3}/m$)
ω	constant for Jones-Wilkins-Lee (JWL) equation of state
Φ	tunnel cross-section diameter (m)
ρ	density (kg/m^3)

Latin letters

A	tunnel cross-sectional area (m^2)
A, B, C, R_1, R_2	constants for the JWL equation of state
C_p	pressure coefficient $C_p = (p-p_0)/p_0$
d	diameter (m)
E	total specific internal energy, $E = e + 1/2(u^2 + v^2 + w^2)$ (J/kg)
e	specific internal energy (J/kg)
H	height of the tunnel (m)
L	length of the tunnel (m)
M	Mach number
p	pressure (Pa)
r	radial coordinate (m)
T	total simulation time (s)
t	time (s)
W	width of the tunnel (m)
Z	reduced distance, $Z = r/m_c^{1/3}$ ($m/kg^{1/3}$)
Z_x	position of transition zones between 3D and 2D patterns ($x = H$), and between 2D and 1D patterns ($x = W$). $Z_{W-H} = Z_W - Z_H$ ($m/kg^{1/3}$)
m	weight (kg)

Indices

0	reference conditions
c	explosive charge
H	height
h	hydraulic
Trans	transition
W	width

charge impulse (e.g., a tunnel). Among the few reported experiments investigating air detonation in underground environments, some gave overpressure decays laws during this third pattern. Curran (1996) proposed the following pressure-distance law for various explosives weights:

$$\frac{\Delta p}{p_0} = \left(\frac{M}{\Phi^2 x}\right)^{0.8}. \tag{2}$$

Smith and Sapko (2005) determined the following overpressure-distance decay relationship:

$$\frac{\Delta p}{p_0} = 7.028\left(\frac{M}{Ar}\right)^{0.514}. \tag{3}$$

Applying the energy concentration concept (ECF), which is detailed in Section 2.3, (Silvestrini et al., 2009) the very similar law:

$$\frac{\Delta p}{p_0} = 7.43538\left(\frac{M}{Ar}\right)^{0.51}. \tag{4}$$

Benselama et al. (2010) have investigated the position of the transition zone between the three-dimensional (3D) and the 1D patterns for a square cross-sectional tunnel. They performed detonations of charges ranging between 0.150 kg and 15,000 kg of trinitrotoluene (TNT) in a 5 m^2 cross-sectional tunnel. Defining the ratio size $\alpha = 100d_c/d_h$, where d_c was the charge diameter and d_h was the hydraulic diameter of the tunnel. They shown the transition zone is located at:

$$Z_{trans} = \frac{0.0509}{(\alpha/100)^{13/9}}. \tag{5}$$

However, in square cross-sectional tunnel the four Mach reflections (upper and lower in both transversal and vertical coordinates) occur at the same time producing a large pressure increase when the Mach reflections catch up the incident wave. The shape of the blast wave looks totally different in rectangular cross-sectional tunnel where transversal and vertical reflections do not occur simultaneously.

The objective of this paper is to determine the position of both the 3D-2D and the 2D-1D transition zones and to predict the overpressure occurring in these three zones. To accomplish this, the detonation of different quantities of TNT explosives inside a perfectly rigid tunnel was simulated. The following section presents the geometrical configuration, the numerical methodology and the ECF method. Moreover, scaling laws that eliminates the solution's parametric dependence on the explosive energy, the weight of the explosives and the real tunnel cross-sectional size are provided. These scaling laws transform the infinite number of solutions into a single solution that demonstrates a monotonic transition from one wave pattern to another pattern. Afterwards, the numerical results are brought in Section 3. These numerical results consisted of overpressure history for different widths and heights of the cross-section, and of different detonation mass. In Section 4, fitting power law are proposed to estimate the locations of both transition zones. Furthermore, an algorithm giving the complete map of the overpressure pattern is introduced. This algorithm is validated by comparison with previous experimental data.

2. Configurations, numerical details and ECF method

2.1. Calculation domains and non-dimensional numbers

The calculation domains are presented in Fig. 1. They consist on rectangular cross-sectional tunnel of length $L = 25$ m. The cross-sectional widths and heights ranged from 3 to 7 m and 2–5 m respectively. Especially, a square cross-sectional tunnel of 3 m^2 area was considered to verify results from Benselama et al. (2010). In order to study the effect of the width, four additional configurations with 3 m height and width ranging from 4 to 7 m are investigated. A 6 m width and 2 m height domain is considered because it yields the same hydraulic diameter as the 3 m side square section. Then, two additional configurations with 6 m width and respectively 4 and 5 m height are studied to evaluate the effect of the height. Furthermore, TNT charge ranging from 1000 to 10,000 kg are investigated.

It can be anticipated that the first reflection modifying the 3D shape of the blast wave in a 2D shape depends on the height of the