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# Numerical and experimental study of blast wave shape in tunnels

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## Abstract

When an explosion occurs in a tunnel, the study of the blast wave quickly becomes complicated, due to the multiple propagation patterns of the blast wave (Incident wave, regular and Mach reflections) and to the geometrical conditions. Considering this problem, two patterns can be revealed. Near the explosive, one can see the well known free-field pressure wave. This overpressure, during its propagation, after multiple reflections on the tunnel's walls, can behave like a one-dimensional wave.

The aim of this paper is to determine the position of this transition zone along the tunnel with reduced-scale experiment and hence to validate the dedicated law established in a previous work. Both numerical and experimental methods are presented. Previous experimental works have been done on this topic, based on a real scale [1]. In this present study, the experiments are realized in the laboratory using a 1/30<sup>th</sup> scaled model, simulating T.N.T. detonations ranging from 0.1 kg to 12 kg in a tunnel of 25 square meter cross section and 30 meters in length. The experiment on scaled models allows us to realize many inexpensive experiments; an accurate profile of the overpressure can be determined along the tunnel. The transition zone between the free-field and the one-dimensional decay law is presented using non-dimensional parameters and is also compared with the numerical simulation.

**Key words:** Blast wave – Tunnel - Scale models

## 1. Introduction

In urban areas, we can find many tunnels and covered ways, built for the road and the rail traffic (railways and undergrounds). Those geometrical configurations can be considered as tunnels of various lengths and cross sections. As hazardous materials may transit in these areas, there is a risk of accident due to the explosion of those materials. Explosions might come from solid detonating materials, gas or gas-air mixtures. The effects of an explosion are increased by the semi-confined configuration of the tunnels. Accidents or intentional acts may cause severe injuries or lethal issues.

Blast waves have been studied by many authors. For the first propagation pattern, in a free-field case, different authors have proposed fitting laws, allowing the determination of the peak of overpressure knowing the radial distance and the quantity of energy of the explosive. We can mention the works of Baker [2], Brode in 1955 [3]. More recently, the works of Sadovski (2006), Mills (1987) and Held (1983), which are presented in the work of Chang and Young [4], have proposed an expression of the incident pressure wave depending on the explosive mass and the radial distance. Brossard and al (1993) [5] have proposed a polynomial formulation of the blast wave, including the incident angle and allowing the determination of application times and of the negative pressure for incident and reflexion waves. The TM 5-1300 manual [6] is also a good help to approach the blast phenomena and their consequences on structures.

The second pattern concerns the confined or semi-confined explosions. The approach is more complex, and was investigated by using numerical tools. The numerical codes, such as auto-

dyn or the home-made CFD code used by Benselama and al. [1, 7] require very important computer resources to provide realistic simulations. Ripley and al. [8], have discussed on small-scale modelling of explosive blasts in urban scenarios. Experimental works in semi-confined configurations can also be found, such as Pennetier and al. [9], describing the pressure of a landmine acting on a vehicle.

This paper contributes to a better knowledge of the phenomena, which can be assimilated to a blast wave in a confined area. The prediction of the phenomena and of their consequences is the final objective, using a computational code. Experiments are still necessary to test the numerical codes under different configurations, especially when we have multiple reflections. The study is mainly focused on the determination of the transition zone,  $Z_{tr}$ , which corresponds to the transition between the spherical wave and the one-dimensional one. The experimental work will allow an accurate localization of  $Z_{tr}$  as many gauges have been positioned on the scaled model.

## 2. Phenomenology

In explosions, the incident waves are spherical. So, the reflections on the tunnel walls are due to oblique incident waves. Oblique waves have been studied by many authors. Kinney [10] and Baker [2] have widely studied those phenomena. As long as the blast wave has not reached the walls of the tunnel, there is no reflection. As the incident angle  $\theta$  gets larger (fig. 1), the reflected wave can't keep the flow parallel to the wall. So, incident and reflected waves are combining and a third shock wave appears. The latter is called the Mach shock reflection. This wave is moving faster than the incident one. The point where the incident, reflected and Mach waves are joining is called the triple point. As the blast wave is progressing in the tunnel, the distance between the wall and the triple point is growing. When the Mach reflections coming both from the top and the bottom join (point A, fig. 1), the pressure becomes constant in the whole cross section. This is the transition zone  $Z_{tr}$ . When this zone is reached, the celerity of the blast wave becomes quasi constant. The celerity mainly decreases because of wall friction.

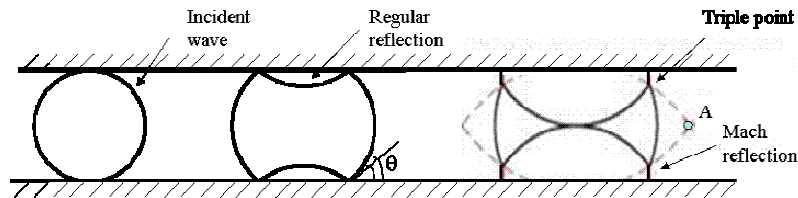


Figure 1: Different wall reflections: incident wave, Regular reflection and Mach reflection

## 3. Numerical setup

For this study, the length of the tunnel is  $L = 30$  m and its hydraulic diameter is  $d_h = 5$  m. Considering the symmetry (tunnel and explosion), we only have to consider one half of the problem, along the longitudinal axis. Fourteen gauges ( $C_1$  to  $C_{14}$ ), with a step of 1.5 meter, are placed along the tunnel (fig. 2). The gauge nearest the explosive charge is  $C_1$ , and the gauge near the opened side of the tunnel is numbered  $C_{14}$ .

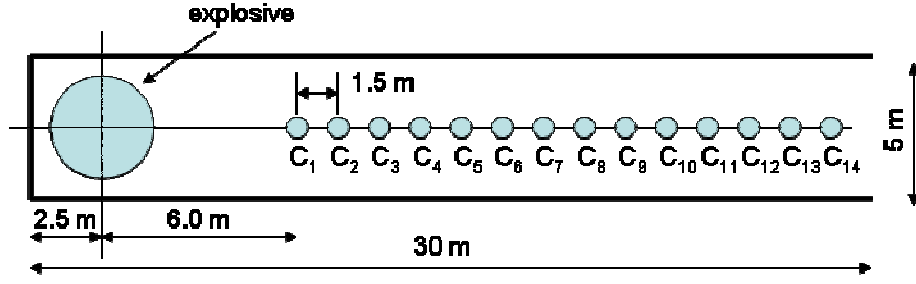


Figure 2: numerical configuration of the study

The numerical simulation has been previously discussed in [7]. In this paper, for the simulated configurations, four different masses of T.N.T. are taken into account. The explosive charge ranges between 0.5 and 11.7 kg. The T.N.T. explosive is located on the symmetry axis of the tunnel and is considered lying on the ground. Table 1 presents the four explosive charges; each explosive mass corresponds to a parameter  $\alpha$ , given by:

$$\alpha = 100 \frac{d}{d_h} \quad (1)$$

Table 1: parameters of the explosive charges at full scale

Mass (kg)	Equivalent spherical diameter d (cm)	Ratio size $\alpha$
0.535	8.7	1.73
1.593	12.4	2.49
4.266	17.3	3.46
11.691	24.2	4.84

The blast wave propagation is supposed to be governed by the unsteady Euler equations in this study. These equations are solved using home-made software [7]. The numerical method is based in an unstructured finite-volume cell-centered approach using the traditional upwind scheme and a two-stage explicit time integration technique, yielding to a second order scheme in both time and space. In order to prevent numerical oscillations, which may occur in areas of strong gradient, the minmod limiter is used. In this calculation, we have 3 million Cartesian cells.

The value of  $Z_{tr}$  can also be deduced from a fitting law [1]. This one only depends on the parameter  $\alpha$  given by equation (2). This will allow the comparison between the experiments and the numerical simulations.

$$Z_{tr} = \frac{0.0509}{(\alpha/100)^{13/9}} \quad (2)$$

#### 4. Experimental set-up

Using the Hopkinson similitude law, it is well established that for homothetic detonations, the whole history of the pressure field is identical and the application times are multiplied by the

scale ratio of the experiment. In most cases, an explosion exceeds the scale of a laboratory. The use of such a tool allows us to work on scale models.

#### 4.1. The explosive

In the laboratory, particularly for security reasons, we are using gaseous mixtures. The explosive used is composed of a stoichiometric mixture of propane and oxygen. The gaseous explosive has to be confined to keep its initial molar concentration. This confinement must be as immaterial as possible. In our experiment, the explosive is injected in a solution of sodium oleate. So, we can easily create hemispherical bubbles as it can be seen in figure 3.

The volumic energy of this mixture is  $14.16 \text{ MJ/m}^3$  at  $20^\circ\text{C}$ . According to the works of Baker [2], the specific energy of T.N.T. is  $4.69 \text{ MJ/m}^3$ . Considering the initial number of moles of the mixture, to obtain the same effects on a structure at  $20^\circ\text{C}$ ,  $2.51 \text{ kg}$  of this gaseous mixture ( $1.65 \text{ m}^3$ ) are equivalent to  $1 \text{ kg}$  of T.N.T.

#### 4.2. The detonation

A detonation is a perfectly reproducible phenomenon. A typical signal of the reflected pressure on a flat plane [5] presents a brutal rise of the signal (typically shorter than  $5 \mu\text{s}$ ), followed by a rapid decrease. In a free space, if we respectively note  $t^+$  the overpressure application time and  $t^-$  the negative one, we can notice that the length of  $t^+$  is about one third of  $t^-$  [5]. Depending on the obstacles around the detonation, the signal of pressure versus time can present strong reflections.



Figure 3: soap bubble filled of gaseous mixture

Depending on the quantity of energy igniting the explosion, we can obtain a deflagration or a detonation. In order to get a detonation, we must have more than  $20 \text{ joule}$  to initiate the proper explosion. The soap bubble, inflated with the gaseous mixture, is hemispherical. The detonation is performed using the technique of the exploded wire. A thin copper wire is welded on tungsten electrodes. A high voltage, coming from the discharge of capacitors ( $7.5 \text{ KV}$ ,  $8\mu\text{F}$ ), makes the copper wire instantaneously melt. A plasma is created, and its energy is about  $55 \text{ Joule}$ . This technique is perfectly reproducible and, keeping the same size of the bubble, we get the same field of pressure around the explosion.

### 4.3. Set-up

The experiments are realized in the laboratory using a 1/30<sup>th</sup> scaled model, simulating T.N.T. detonations ranging from 0.53 kg to 11.69 kg in a tunnel of 25 square meter cross section and 30 meters in length. The tunnel has a closed end and a free one. The scale model is realized with high-density wooden plates of 27 mm thickness, reinforced with steel profiles. The tunnel is supposed to be strong enough to withstand the blast wave.

The explosion is generated in the close-end side of the tunnel. A polycarbonate window, closing the tunnel, is fixed at the explosion side, which allows us to verify if the bubble has not burst before the explosion. A general view of the experimental set-up is presented figure 4.



Figure 4: Experimental setup

The life duration of the soap bubbles depends on its size and on the atmospheric conditions (temperature, pressure and hygrometry). Usually, we have up to 10 seconds to perform the explosion.

We have tested up to four quantities of explosives. The different configurations are summarized in table 2.

Table 2: quantities of explosive

Bubble radius (mm)	R=25	R=36	R=50	R=70
Mass of T.N.T. (g) - scale 1/30° -	0.0198	0.059	0.158	0.433
Mass of T.N.T. (kg) - full scale -	0.535	1.593	4.266	11.691

One aim of this paper is the determination of the transition zone, which corresponds to the place where the spherical wave becomes a plane one. So, the gauges are placed every 5 cm

along the longitudinal axis of the tunnel, beginning 20 cm from the explosion. Those gauges are measuring an incident pressure. 14 different positions are possible for each range of T.N.T. equivalency. As all our experiments are perfectly reproducible, we realize each explosion in two parts, using eight pressure gauges. So, two signals must be identical, which proves the repeatability of the detonations. Pressure captors are Kistler 603B, ranging from 10 kPa to 20 MPa. The raising time of those transducers (less than 5  $\mu$ s) is in accordance with our transient experiments. The captors are linked with charge amplifiers Kistler 5011.

## 5. Results

Figure 5 presents for a given explosion (radius of the bubble: 70 mm) the evolution of the incident pressure versus time, for all fourteen positions along the axis of the tunnel ( $C_1$  to  $C_{14}$ ). One can notice the initial peak of pressure, which will allow finding the transition zone  $Z_{tr}$ . Just after this peak, multiple reflections are coming and increase the initial maximum overpressure. This is due to this semi-confined explosion configuration.

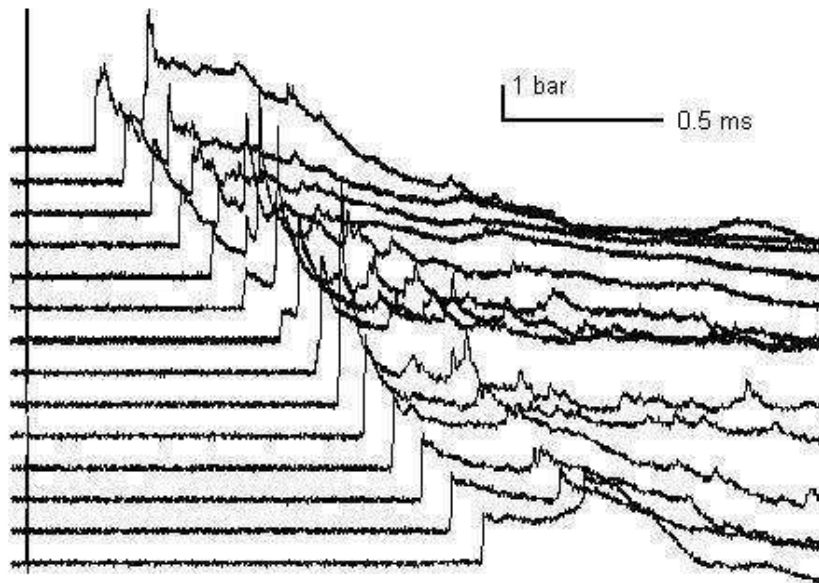


Figure 5: Experimental incident pressure versus time along the tunnel ( $C_1$  to  $C_{14}$ ) - Radius  $R = 70$  mm

The experiments have been performed three times for the same explosive charge to prove the good repeatability of the experiments. As it can be seen in figure 5, it is sometimes difficult to determine exactly the initial peak of pressure, as the reflection is nearly coming at the same time as the initial peak.

In figure 6, the spatial evolution of the incident pressure shows a first spherical propagation followed by an abrupt increase of the pressure. Then, a second propagation pattern appears, which can be considered as a planar wave. The location of the pressure jump depends typically on the quantity of explosive; this corresponds to the transition zone. For the experiments, as the pressure gauges are 5 cm spaced, an accuracy of 5 cm on the value of  $Z_{tr}$  on the scale model is obtained. This corresponds to 1.50 meters for the full scale tunnel.



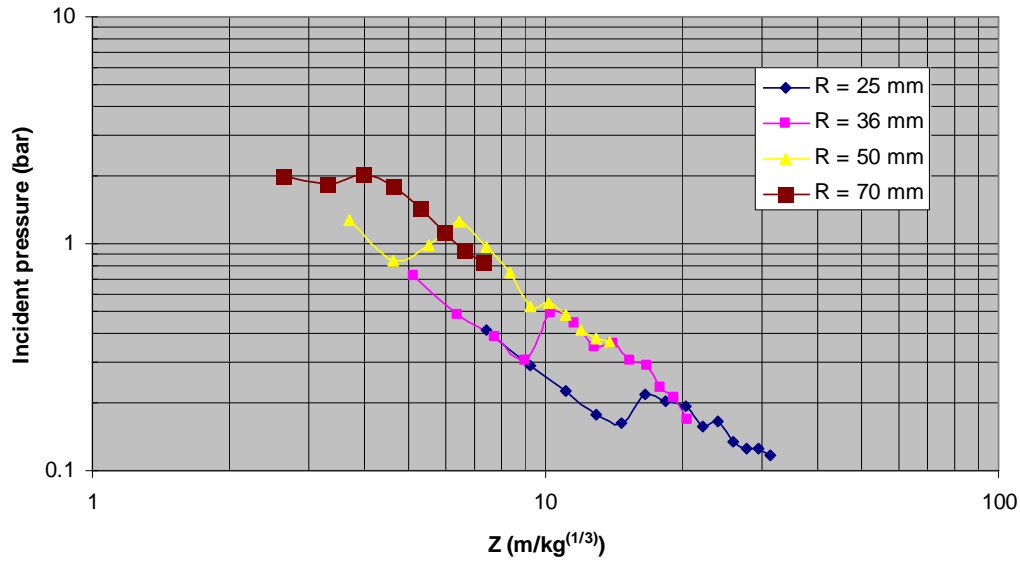


Figure 6: Incident pressure versus time along the tunnel

Figure 7 presents the iso-Mach distributions at different times given by the numerical simulations. One can see, for the first time (10 ms), the wave propagation and its interaction with the upper wall. Then, the incident wave continues to propagate spherically along the tunnel, whereas the reflected one goes towards the lower wall. A Mach reflection appears and grows with the displacement of the triple point towards the lower wall. When the latter reaches the lower wall, the Mach stem covers all the tunnel cross section. So, this wave can be considered as a planar one.

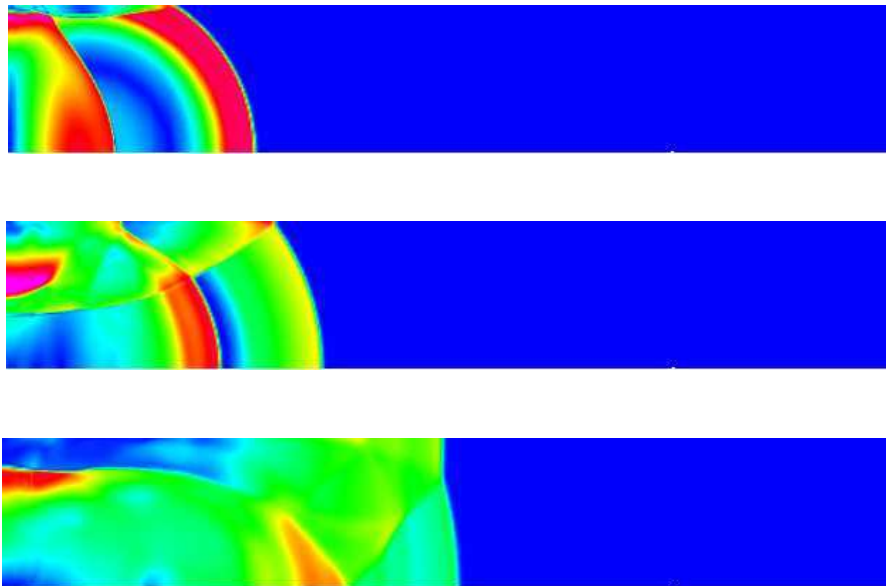


Figure 7: iso Mach at different times ( $t = 10, 20$  and  $30$  ms)  
- Full scale simulation -

The evolution of the transition zone versus the quantity of explosive ( $\alpha$ ) is presented in figure 8 where the numerical simulation, the  $Z_{\text{trans}}$  law and the experiment are compared. A



very good agreement is obtained between the three methods. It can be noticed that this transition position decreases when we use a higher quantity of explosive.

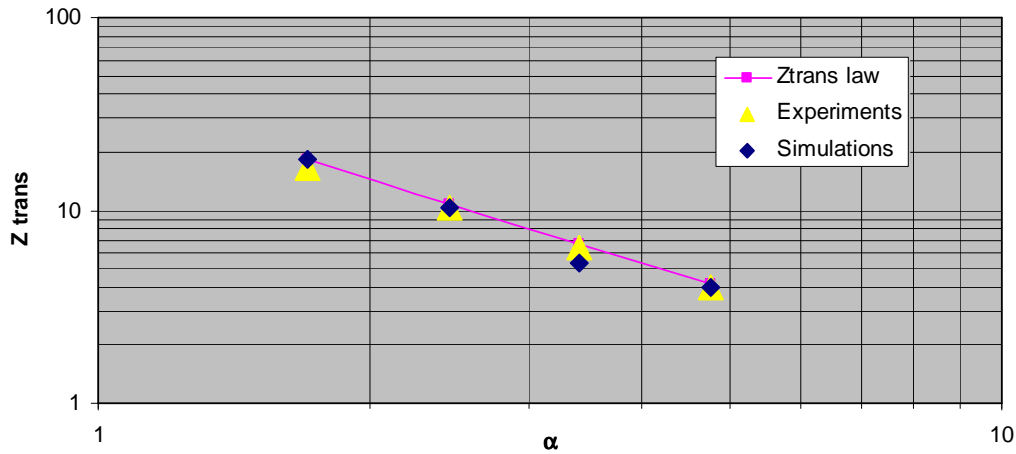


Figure 8: Experimental, numerical and  $Z_{trans}$  law zone of transition  $Z_{tr}$

## 6. Conclusion

In this paper, the experimental and numerical simulation of a blast wave in a tunnel has been presented. Near the explosive, the propagation of the blast wave is like the propagation in a free-field. Then, as there is an interaction with the walls of the tunnel, we get a driven wave which is nearly a 1D wave. We have mainly focused this study on the transition zone  $Z_{tr}$ . The experimental campaign in the laboratory, made on scaled models, has given an accurate position of the transition zone, as fourteen pressure gauges were used. Comparing the results of the numerical simulation and the corresponding fitting law, we found a very good agreement between the calculation and the real phenomena. The use of a scale model has allowed us to make numerous and inexpensive experiments. Using the Hopkinson law, the scale model can be transposed to the full scale structure. Different shapes of tunnels can be studied, and a focus on the signals of pressure can be of great interest.

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