Computational simulation of shock wave generated by the detonation of explosives for civil use

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Abstract. When conducting a research concerning the propagation of a shock wave generated by the detonation of civil use explosives, the first thing that comes to mind should be if the detonation process takes place in an obstacle-free field, or the area has obstacles such as rocks, metals structures, wood etc, obstacles that can and will influence the final results, the shock wave curve being obturated by it. On one hand, the paper presents the experimental results obtained after the detonation of a freely suspended load, placed at 0.5m above a concrete surface. On the other hand, it compares the values of explosion pressure as shock wave, measured on 4 sensors linearly disposed at the same elevation to the ground, at a distance of 2,3,4 respectively 6 meters from the explosive charge. These values are determined through computerized simulation, using ANSYS AUTODYN software, by virtually reproducing the real scenario. Following the two experiments (real and virtual), one can conclude that computerized simulation proves to be a very useful instrument in an a priori evaluation of hazardous situations/utility of peak values for shock wave, by allowing the user to develop prevention measures/optimization of the analysed processes and also in further investigations

1 Introduction

The shock wave that appears after the detonation of an explosive material can be characterized in coordinated quantity explosive (W) - distance (R) from the following measurable parameters: maximum pressure (overpressure) and dynamic pressure, incident and reflected pressure, incident and reflected pulse, the arrival time of the wave front, the speed of the wave front, etc. [1] The coordinates of the explosive quantity - distance (WR) are linked by a relation, also called the Hopkinson-Cranz scaling law:

$$R_1/R_2 = (W_1/W_2)^{1/3} \quad (1)$$

$$\text{Or equivalent } R = ZxW^{1/3} \quad (2)$$

in which:

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- **R** is the distance from the place of the explosion and to the place where the respective parameter is measured (e.g. maximum pressure).

- **W** coordinate represents the amount of TNT equivalent (Tri-Nitro-Toluene) of the explosive material, which was used in detonation.

The equivalence relation between the mass of an explosive material - M_{exp} and the reference mass TNT - M_{TNT} is based on the thermal energy ratio (E_{exp}^d and E_{TNT}^d) released by the combustion reaction when detonating explosive materials, as follows:

$$M_{TNT} = (E_{exp}^d / E_{TNT}^d) \times M_{exp} \quad (3)$$

The shock wave produced by an explosion may have a spherical geometry, if the explosion occurred in the air at a considerable distance from the surface of the soil and a hemispherical geometry, if the explosion occurred on the surface of the soil or in its immediate vicinity [2]. In case of shock waves with hemispherical geometry, a wave front reflected by the surface of the ground also appears, besides the incident wave front. Also, the reflection of the shock waves can also occur at the interface between the air and the exterior or interior rigid surfaces of some civil constructions (e.g. walls, monuments, etc.).

At a certain distance from the blast site, shock wave has the general profile shown in Figure 1.

Fig. 1. The profile of a shock wave

In which: P_{max} is the maximum value of the pressure (overpressure) that is reached in an extremely short time and then descends until it reaches the reference P_0 value of atmospheric pressure

As it can be seen in figure 1 besides the positive phase, the shock wave profile also has a negative phase in which the pressure value decreases below that of the atmospheric pressure to a minimum value, P_{min} [3]. The duration of the positive phase is noted with t_d , t_a , being the time when the shock wave front reaches that point and which also includes the duration of the detonation process. The duration of the negative phase is noted by t_n .

Between the 60s and 80s Charles Kingery and Gerald Bulmash carried out a series of experiments in which they measured the mentioned parameters, using quantities from under 1Kg and up to 400 tons of TNT. The results of the measurements were fitted with polynomial functions that became a benchmark in the evaluation of the effects produced by a shock wave in relation to the explosive mass and the distance at which the evaluation is made. In coordinates (WR), the experiments were performed for a range of variation of Z between 0.05 and 40 [4]. For the shock wave with spherical symmetry the characteristic parameters can be determined using the polynomial expression:

$$P_0 = C_0 + C_1 U + C_2 U^2 + \dots + C_n U^n \quad (4)$$

where: P is the logarithm based on parameter 10 (e.g. pressure, impulse), $C_{0,1,2,\dots,n}$ are constant and: $U = K_0 + \ln(K_1 x Z)$, where $K_{0,1}$ are constant.

Knowing the maximum values for the air pressure wave is important for the preliminary evaluation of the effects of an explosion with detonation (by energetic relation to the TNT equivalent) on the structures and on the people, the limits being known in the literature, but also by the investigations conducted by the INCD INSEMEX for elucidating the causes of industrial or domestic explosions. In these cases, computer simulations, previously calibrated on physical models, become very useful tools for assessing the damage, for approximating with a high degree of accuracy the energetic value of the explosion, going in the opposite direction and finally getting to express quantitatively the combustible substance that was involved in the investigated explosions.

2 Methods used

2.1 Experiments in open field for the air pressure wave in the INSEMEX Polygon

In order to carry out research on the propagation of the pressure wave when detonating explosive charges, an experimental assembly was performed as follows:

- a flat concrete surface in open field, without obstacles, was selected;
- 4 pressure sensors were cascaded (two KISTLER systems were used to measure the explosion pressure, so that on the bayonet type sensors cylindrical sensors were placed, both systems using IEPE sensors and LabAmp type amplifiers 5165A4) at the following distances from the explosive charge at 0.5m above the concrete surface [5]: pressure sensor sp1 at 2m; pressure sensor sp2 at 3m; pressure sensor sp3 at 4m; pressure sensor 4 at 6m; metal support for suspending the explosive charge; a mass of 280 g equivalent TNT was used as an explosive charge [6]

Fig.2. Assembly in the open field – INCD INSEMEX Polygon

2.2 Virtual simulation of the experiment

Through numerical simulations, the propagation of the shock wave with hemispherical geometry was modeled for an amount of 280 g TNT. The modeling was done in 2D axial symmetry, the actual space of simulation being a solid angle with the tip in the centre of detonation of the load considered spherical. [7]

Table 1. Distance between point of detonation and gauges

Gauges	Distance [mm]
#1	2000
#2	3000
#3	4000
#4	6000

2.2.1 Input parameters

Table 2. Variables

TNT- 0.28 KG	
Air	
Variables	Value
Density (kg/m³)	1,225
Gamma	1,40
Specific heat (KJ/gK)	0,000718
Reference temperature(K)	288,15
Density (g/cm³)	1,63
C1	374
C2	3.750
R1	4,15
R2	0,09
w	0,35
C-J detonation velocity (m/ms)	6,93
C-J Power/ volume unit (MJ/m³)	6.000
C-J Pressure (MPa)	21.000

2.2.2 Finite element discretization

- Mesh elements: quadrilateral elements with 1 mm dimension (figure 3.a)
- Detonation point located at (0,0,0) (figure 3.b)
- Location of explosion pressure measuring devices

Fig.3. Graphic elements of virtual simulation

3 Results and discussions

3.1. The results of the real tests - experiments in the INSEMEX Polygon

The results on the pressure curves for each distance and for 280 g of TNT equivalent explosive are as follows:

Fig.4. Overpressure curve for 280 g of explosive

Table 3. The maximum values for the explosion pressure recorded at sp1, sp2, sp3 and sp4 for 280 g of explosive, with the two systems of pressure sensors, as well as the velocities of the wave front are in the following table:

Sensor placement	Sp1 (mbar)	Sp2 (mbar)	Sp3 (mbar)	Sp4 (mbar)
Overpressure measured by sensors	775	624	413	207
Time elapsed from detonation source to sensors	t ₁ (ms)	t ₂ (ms)	t ₃ (ms)	t ₄ (ms)
	2,56	5,12	7,424	12,8
Wave front velocity on the distances between sensors	v ₁ (m/s)	v ₂ (m/s)	v ₃ (m/s)	v ₄ (m/s)
	781,25	585,94	538,79	468,75

3.2. Virtual simulation results

The numerical simulations modeled the shock wave propagation, the results being as follows:

Fig.5. Pressure profile of the spherical shock wave generated by 280 g TNT at distances: 2,3, 4 and 6 m from the symmetry center of the detonation

The maximum values for explosion pressure recorded at gauge # 1, # 2, # 3, # 4 for 280g TNT, transformed into mbar, as well as the wave front velocities are in the following table:

Table 4. The maximum values for the explosion pressure recorded at sp1, sp2, sp3 and sp4 for 280 g of explosive, with the two systems of pressure sensors, as well as the velocities of the wave front

Sensor placement	gauge #1 (mbar)	gauge #2 (mbar)	gauge #3 (mbar)	gauge #4 (mbar)
Overpressure measured by apparatus	762	396	265	162
Time elapsed from the detonation point to the measuring devices	t ₁ (ms)	t ₂ (ms)	t ₃ (ms)	t ₄ (ms)
	2,551	5,122	7,777	13,611
Wave front velocity over distances between measuring apparatus (gauges)	v ₁ (m/s)	v ₂ (m/s)	v ₃ (m/s)	v ₄ (m/s)
	784,004	585,708	514,33	440,819

3.3. Exemplary use of the PHANTOM high-speed camera

Visualization of the air pressure wave (observe the undistorted circular contour next to the sp2 pressure sensor) by using the BOS (background oriented Schlieren) effect, applied on fast shooting at 10,000 fps.

Fig.6. Illustration of shock wave propagation filmed with Phantom VEO high speed camera (@ 10000 fps)

4 Interpreting the results and discussions

Comparing the results of the real tests in the INSEMEX polygon with those of the computer simulation ANSYS AUTODYN shows a good correlation of them, thus validating the used models.

Fig.7. Comparison of maximum overpressure and velocities values for detonating an explosive charge of 280 g equivalent TNT - physical experiment INSEMEX polygon and computer simulation results AUTODYN ANSYS

Based on the obtained results, a preliminary evaluation of the effects of an explosion with the equivalent energy of a 280g TNT mass on the structures (table no.5) and people (table

no. 6) can be performed, in comparison with the reference limits, appreciating its degree of destruction and bodily injury. Also, the results are useful in the investigations subsequent to the explosions, being able to estimate the energetic values involved, knowing the degree of destruction / damage of the structures and the people involved in the analysed event.

Table 5. Estimated damage due to overpressure following an explosion [8]

Overpressure (mbar)	Estimated damage
2.07	Occasional breaking of large windows that are already subject to stress.
48.26	Minor damage to the structure of the houses.
.....	
68.94	The houses are rendered uninhabitable due to the partial demolition.
89.63	Slight distortion of steel frames from reinforced buildings.
137.89	Partial destruction of the walls and roofs of houses.
.....	
620.52	Demolition of loaded long trucks.
689.47	Probable complete destruction of the building. 99% deaths in the exposed population as a result of the direct effects of the explosion.

Table 6. Injury to the human body as a result of the explosion overpressure [9]

Overpressure (mbar)	Effects
350	The ear drum rupture limit
700	Limit for lung damage
1000	Up to 50% rupture of the eardrum to the exposed population
1800	1% mortality
2100	10% mortality
2600	50% mortality
3000	90% mortality
3500	99% mortality

5 Conclusions

The data presented in the paper show that computer simulations allow the user to obtain the maximum explosion pressures, for various configurations (quantities of explosive materials, distances), to be used in preliminary evaluations of dangerous situations, respectively for estimating the characteristics of the substances involved in the investigation of post-factum explosions.

For the results of the overpressure of detonating a mass of 280g TNT it is estimated that this explosion could cause lung damage for persons less than 3m away, or punctured ear drum to people caught less than 6m away, at the same time being able to estimate the deterioration of unreinforced buildings.

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