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Analysis of Parameters of Blast Waves Generated by Explosions of 75 g TNT Charges

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Abstract: The paper presents test results and the analysis of blast waves parameters generated by explosions of 75 g trinitrotoluene (TNT) charges. Pressure sensors designed for measuring the passing wave overpressure were applied for the tests. An analysis of the test results and the calculations based selected empirical formulas was performed. The results of tests and calculations specify the values of permissible distances (the so called safety areas) for 75 g TNT charges.

Keywords: shock wave, blast wave, aerial burst, explosives, TNT

Introduction

During the realisation of works with the use of high explosives (HE) special precautions need to be taken. Such measures are defined by detailed work safety regulations concerning shot-connected tasks and mine warfare etc. One of many safety conditions is the preservation of an appropriate distance from the personnel detonating HE. This distance depends on the amount of overpressure produced by the detonation of an HE charge at the given point. Literature [1-8] provides many empirical formulas that can be used for calculating the quantity of the shock wave overpressure. Formulas of that kind may also be employed for calculating the overpressure value needed in mine warfare tasks. The experimental data published in this article have enabled a derivation of the equation defining the real shock wave value for a 75 g TNT charge. On the basis of derived relation, an analysis of experimental data and values calculated with the use of selected empirical formulas has been performed.

Measurement conditions

The measuring position used for determining the value of the overpressure generated by explosive charges, was composed of the following elements:

- measuring instruments:
  - pressure sensor PCB 137A23 placed on a stiff stand at the height of 1 m above the ground surface (Figure1);
  - oscilloscope Tektronix TDS 1012*)

Figure 1. PCB 137A23 sensor installed in the measuring position.

- recording devices
  - portable PC**);
  - WaveStarTM v.2.6 Software;
- HE position
  - The first phase of measurements involved charges placed on the ground, and the second – charges placed at the height of 1 m above the ground surface (Figure 2).

*) Maximum sampling rate 1.0 Gs s^{-1}.
**) The data was transferred from the oscilloscope to the PC through a serial port.

Figure 2. Measuring position: a) HE charge on a stand; b) pressure sensor on a stand.

After a preliminary analysis of the test results, a uniform method of placing the explosive at the height of 1 m was adopted. This decision was caused by the incorrect measurement results (Figure 3). The blast wave generated by a charge placed on the ground shows no distinct changes of parameters in the farther part of wave form, as can be observed in the case of waves generated by charges placed over the ground. It may mean a summation of the shock wave and reflected wave generated by charges placed on the ground.

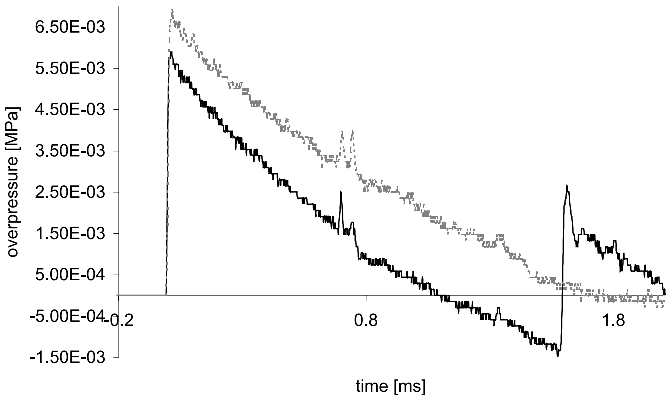

Figure 3. Measurement of the blast wave generated by a charge located at the distance of 4 m from the sensor and placed:
- on the ground – broken line,
- at the height of 1 m – solid line.

The adopted method was verified by carrying out one measurement with the charge placed at the distance of 20 m and height of 2 m (Figure 4). The purpose of this test was to find out whether an increased measurement height effects the value of the measured blast wave.

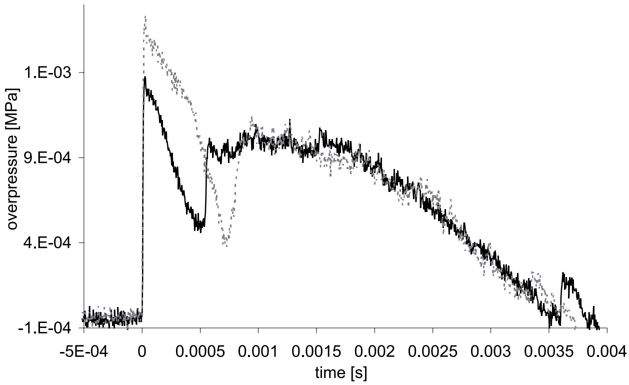

Figure 4. Measurement of the blast wave generated by a charge located at the distance of 20 m from the sensor and placed:
- at the height of 2 m – broken line,
- at the height of 1 m – solid line.

The performed tests lead to the following conclusions:

1. The pressure sensor should be placed at the same height as the tested explosive charge.
2. The immediate generation of a reflected wave and summation of waves (Figure 3) during the explosion of a charge placed directly on the ground cause an increase of the measured wave value.
3. The height of the sensor and the charge, adopted for the test purposes, equals 1 m.

Measurement error

PCB piezoelectric sensor series 137 was used during the tests. The structure of sensors allows recording the overpressure of a passing wave. Table 1 shows the characteristic of the sensor used in the tests.

Table 1. Technical parameters of the piezoelectric sensor

Parameter	Measure unit	Sensor 137A23
Measuring range	[MPa]	0-0.345
Resolution	[kPa]	0.069
Sensivity	[mV/kPa]	1.361
Maximum pressure	[MPa]	6.895
Time resolution	[μs]	≤ 4.0
Resonance frequency	[MHz]	≥ 0.5
Active element	material	quartz

The producer's calibration data and error calculation values are presented in Table 2.

Table 2. Calibration data

Input [PSI]	Output [mV]	Proportionality factor	Standard deviation	Root mean square deviation
0	0	-	0.12307	0.0606
10	936	93.6		
20	1876	93.8		
30	2818	93.933		
40	3754	93.85		
50	4691	93.82		

On the premise that 1 psi = 6894.757 Pa, the following conversion factor connected with values read from the oscilloscope in [mV] and converted to pressure has been adopted:

$$p[\text{MPa}] = \times 0.06894757 \quad (1)$$

According to the assumptions made, the unreliability of test results has been adopted as not higher than ±0.001 MPa.

Calculation for the shock wave in the air

Equation (2) describes for trinitrotoluene Sadowski empirical formulae [1] for high explosives, which define overpressure in a function of reduced distance ($\overline{R}$).

$$\Delta p[\text{atm}] = 0.95\overline{R}^{-1} + 3.9\overline{R}^{-2} + 13\overline{R}^{-3} \text{ where } 1 \leq \overline{R} \leq 10 \quad (2)$$

where

$$\overline{R}[\mathrm{m\ kg}^{-\frac{1}{3}}] = R\, q^{-\frac{1}{3}} \qquad (3)$$

q is the charge weight [kg], and R is the distance [m] from the explosion point.

Equation (2) concerns the case of an explosion on the ground surface.

In [2] average values of factors for Sadowski formulae are presented:

$$\Delta p[\mathrm{atm}] = 0.84\overline{R}^{-1} + 2.7\overline{R}^{-2} + 7.0\overline{R}^{-3} \qquad (4)$$

Sadowski formula given in [3] adopts the following form:

$$\Delta p[\mathrm{atm}] = 0.76\overline{R}^{-1} + 2.55\overline{R}^{-2} + 6.5\overline{R}^{-3} \text{ where } 1 \le \overline{R} \le 15 \qquad (5)$$

In the monograph [2] Stoner formula for pentolite (TNT/PETN 50/50) has been given:

$$\Delta p[\mathrm{atm}] = 0.863\overline{R}^{-1} + 2.951\overline{R}^{-2} + 7.823\overline{R}^{-3} \qquad (6)$$

Henrych [3, 4] has also suggested his own formulae, obtained on the basis of explosion tests for TNT.

$$\Delta p[\mathrm{atm}] = \begin{cases} 14.0717\overline{R}^{-1} + 5.5397\overline{R}^{-2} - 0.3572\overline{R}^{-3} + 0.00625\overline{R}^{-4} \text{ where } 0.05 \le \overline{R} \le 0.3 \\ 6.1938\overline{R}^{-1} - 0.3262\overline{R}^{-2} + 2.1324\overline{R}^{-3} \text{ where } 0.3 \le \overline{R} \le 1 \\ 0.662\overline{R}^{-1} + 4.05\overline{R}^{-2} + 3.288\overline{R}^{-3} \text{ where } 1 \le \overline{R} \le 10 \end{cases} \qquad (7)$$

Additionally, it is possible to estimate the blast wave scale on the basis of Brode formulae (8), [1, 3, 5, 6].

$$\Delta p = \begin{cases} 1 + 6.7\overline{R}^{-3} & \text{where } \Delta p \ge 10 \\ 0.975\overline{R}^{-1} + 1.445\overline{R}^{-2} + 5.85\overline{R}^{-3} & \text{where } 0.1 \le \Delta p \le 10 \end{cases} \qquad (8)$$

No unambiguous units in Brode formula are specified by the literature. In [1] the normal atmosphere unit [atm] is given, in [3] – metric atmosphere unit [at], while in [5] – [bar] unit. Due to the estimating character of these formula, the differences in units exert no significant influence on the final result. In this paper it has been assumed that Brode’s formulas are expressed in [atm].

Moreover, the following formula has been adopted for the military needs [7]:

$$p[\text{MPa}] = 3.2q^{\frac{2}{3}}R^{-2} \tag{9}$$

The formula (9) used in the engineer forces constitutes a special case of Wlasow formula (9a, b) [8]:

$$p[\text{atm}] = 3.2q^{\frac{2}{3}}R^{-2} \quad \text{where } R < 13q^{\frac{1}{3}} \tag{9a}$$

$$p[\text{atm}] = 2.4q^{\frac{1}{3}}R^{-2} \quad \text{where } R < 13q^{\frac{1}{3}} \tag{9b}$$

The military application has required simplifications achieved thanks to the following assumptions:

- 1 atm equals 0.1 MPa;
- regardless of the charge size, only one Wlasow formula is fulfilled – Table 3 shows the real range of this formula for standard charges.

Table 3. Range of Wlasow formula application (9a)

TNT standard charge [kg]	Conformity distance for formula (9a) [m]
0.075	5.49
0.200	7.60
0.400	9.58
1.000	13.00
5.000	22.23
8.000	26.00

The amount of the overpressure in measuring points located 2 m, 5 m, 10 m and 20 m from the HE charge has been calculated with the use of formulae (2), (6), (7), (8), (9) and the test results. Values of the reduced distance for 75 g TNT charge amount to:

$$R = 2\text{ m} \Rightarrow \overline{R} = 4.74\ [\text{m kg}^{-\frac{1}{3}}]$$
$$R = 5\text{ m} \Rightarrow \overline{R} = 11.86\ [\text{m kg}^{-\frac{1}{3}}]$$
$$R = 10\text{ m} \Rightarrow \overline{R} = 23.71\ [\text{m kg}^{-\frac{1}{3}}]$$
$$R = 20\text{ m} \Rightarrow \overline{R} = 47.43\ [\text{m kg}^{-\frac{1}{3}}]$$

Table 4. Measured and theoretical values of overpressure

Sensor at the height of	Charge at the height of	Distance from the sensor to the charge [m]	Maximum measured over-pressure [MPa]	Theoretical value according to [MPa]				
				Sadowski	Stoner*)	Henrych	Brode**)	Mlitary Manual
1 m	1 m	2	0.032	0.050	0.039	0.035	0.033	0.142
	1 m	5	0.009	0.012	0.010	0.008	0.010	0.023
	1 m	10	0.004	0.005	0.004	0.003	0.004	0.006
	1 m	20	0.001	0.002	0.002	0.002	0.002	0.001
	2 m	20	0.002	0.002	0.002	0.002	0.002	0.001

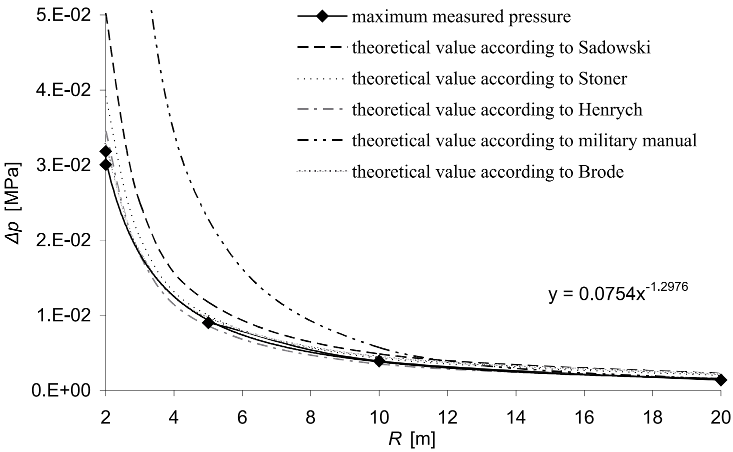

Figure 5. Amount of overpressure in the function of distance from the explosion point for the measured and selected theoretical values.

On the basis of experimental data, the trend line has been determined in the form of a power function, with a simultaneous assumption that the function relates to 75 g TNT charges only. The function is described by the equation (10), where R [m] is the distance from the explosion point.

$$p[\text{MPa}] = 0.0754\, R^{-1.2976} \tag{10}$$

*) Even though Stoner formula is intended for pentolite, the values calculated for 75 g of TNT do not exceed the spread limit for values calculated from the formulae intended exclusively for TNT

**) The difference in overpressure values according to Brode formula for various units amounts to ±0.0001Mpa

Blast wave effect on a human

Dependently on its scale, the overpressure can have various effects on the human body. Blast wave effects are shown in Table 5.

Table 5. The influence of the overpressure scale on the human body [7]

Range	Overpressure interval [MPa]	Effect on the human body
I	$\Delta p < 0.01$	Safe overpressure
II	$0.01 \le \Delta p < 0.0175$	Hearing impairment
III	$0.0175 \le \Delta p < 0.04$	Respiratory system injury
IV	$0.04 \le \Delta p < 0.3$	Severe injury (possible crushing of soft body parts)
V	$\Delta p \ge 0.3$	Death

Due to limitations of the experiment, formula (10) is fulfilled to the overpressure amount of 0.032 MPa. For the purpose of a comparative analysis, overpressure values have been extrapolated by formula (10) to the initial values. An exception has been constituted by initial blast wave conditions. These values have been calculated on the basis of assumptions described below.

The following data have been adopted for the external environment, constituted by the air: initial density $\rho_0 = 1.29$ kg m^{-3}, initial pressure $p_0 = 0.1$ MPa, polytropic exponent $k_0 = 1.4$. The point explosion theory [1], has provided a basis for selecting relations (11) and calculating initial parameters of the blast wave (BW) in the air, caused by the blast of a detonation wave generated by a standard 75 g TNT charge.

$$p_{BW} = \frac{2\rho_0 D^2}{k+1}, \qquad \rho_{BW} = \rho_0 \frac{k+1}{k-1}, \qquad u_{BW} = \frac{2D}{k+1} \tag{11}$$

For 75 g TNT charge the following values have been adopted: $\rho_{MW} = 1600$ kg m^{-3}, $D = 6680$ m s^{-1} [9]. BW initial values are: $p_{BW} = 47.969$ MPa, $\rho_{BW} = 7.74$ kg m^{-3}, $u_{BW} = 5567$ m s^{-1}.

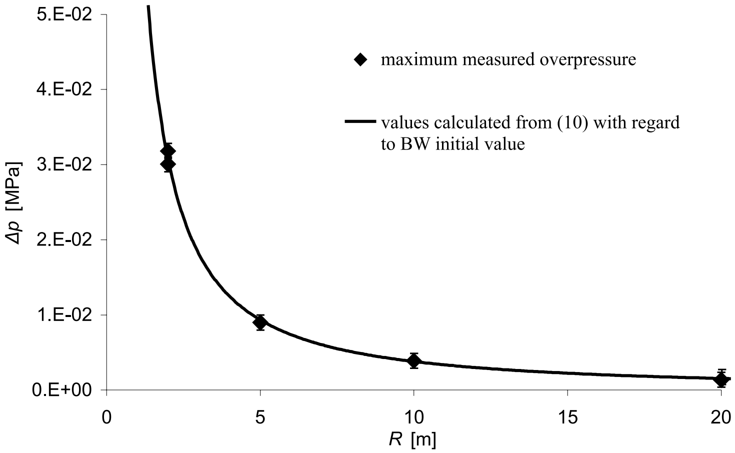

Figure 6. Overpressure amount calculated on the basis of equation (10), with regard to the BW initial value in the function of distance from the explosion point.

Equation (10), overpressure ranges given in Table 4 and BW initial values have constituted a basis for determining overpressure values in the function of distance for a standard 75 g TNT charge, commonly known as the drilling charge. Error bars at the graph presented above (Figure 6) determine the adopted unreliability as not bigger than ±0.001 MPa.

On the basis of the performed calculations, distances for particular safety zones (Table 6) have been defined (Figure 7).

Table 6. Scale of particular effect spheres for the 75 g TNT charge, calculated according to the equations discussed in this paper

Range	Distance from the charge [m], obtained					
	as the experiment result	from Sadowski formula	from Stoner formula	from Henrych formula	from Brode formula	from manual formula [7]
I	up to 4.75	up to 5.65	up to 5.00	up to 4.50	up to 4.90	up to 7.55
II	from 4.75 to 3.10	from 5.65 to 3.75	from 5.00 to 3.35	from 4.50 to 3.05	from 4.90 to 3.10	from 7.55 to 5.70
III	from 3.10 to 1.65	from 3.75 to 2.30	from 3.35 to 2.00	from 3.05 to 1.85	from 3.10 to 1.75	from 5.70 to 3.80
IV	from 1.65 to 0.35	from 2.30 to 0.85	from 2.00 to 0.75	from 1.85 to 0.65	from 1.75 to 0.65	from 3.80 to 1.40
V	up to 0.35	up to 0.85	up to 0.75	up to 0.65	up to 0.65	up to 1.40

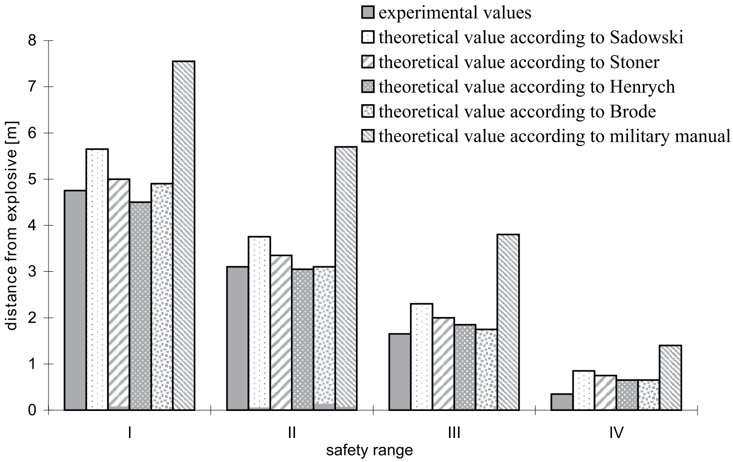

Figure 7. Graph of the experimental distances and distances calculated for particular safety zones.

Conclusions

With regard to the assumed test accuracy of ±0.001 MPa, it is to be concluded that values calculated according to the Henrych and Brode formulae are optimal equivalents of the experimental data. The compatibility range of data calculated by means of the above formulas overlaps with the adopted accuracy of the experimental overpressure value in the distance range of 2-20 m from the HE charge. At the distance shorter than 2 m from the charge the discrepancies exceed the experimental error range. The discrepancy notwithstanding, values calculated according to the Brode formula are the best equivalents of experimental data. Another potential measure error results from the oscilloscope's sampling frequency. Readout delays of about 2 μs in the wave's biggest intensity zone may cause additional differences of overpressure measurements up to 0.001 MPa. In the future, effects of this error can be eliminated through carrying out measurements for more than two charges at one test point.

Due to the selective character of the performed tests (75 g TNT charges only), the authors consider making the measurements for shorter distances and bigger TNT charges. It would enable the derivation of a formula based on experimental data and useful for the determination of the overpressure quantities of shock waves generated by various TNT charges.

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