Analysis of the field test results of ammonium nitrate: fuel oil explosives as improvised explosive device charges

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Abstract

When the over pressure of a blast wave is calculated and its effects on valuated objects are set, many approximations are used. Basic relationships, used to calculate the maximum blast overpressure, safety distances and building damage, are created for industrial accidents or for objects where explosives and munitions are stored. This method is invalid in public spaces. More than 95% of all terrorist attacks are carried out using ANFO (ammonium nitrate – fuel oil) explosives in three different variants (ammonium nitrate with oil, ammonium nitrate with oil and aluminium powder or ammonium nitrate with oil and trinitrotoluene (TNT)).The commonly used method to calculate the overpressure uses a scaled distance. The value of the scaled distance is derived from heat created by combustion. A theoretical value for the combustion heat of an industrial-produced ANFO explosion does not represent the real history of explosion or the size of overpressure. For example, the heat of combustion of Slovak-produced DAP-E is the same as TNT. From the relationship used, it emerges that the explosions have the same capacity. We have conducted more than 130 field tests of the ANFO explosive, where the history of blast wave was recorded. The results of the measurements clearly show the invalidity of this theory. The values of the calculated and measured overpressure are significantly different. It is necessary to choose a different approach for the TNT equivalent method. In the first part of this paper, we present the results of the conducted field tests. The experimental results are analysed using commonly-used methods. At the end of our paper we present a new relationship, used to calculate the maximum blast overpressure, which is based on the measured overpressure. This paper presents the results of scientific research at the Faculty of Special Engineering, University of Zilina.

Keywords: blast wave, blast pressure, ANFO explosives, critical infrastructure, blast field test.

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1 Introduction

The global threat of terrorism presents a grave security problem in the 21st century. To combat this threat in the coming decades, a constant adjustment of forces will be required; concepts as well as capacities. These changes will also affect the issues of the protection of persons and property in the civilian environment. Improvised explosive devices (IED) as a means of the asymmetric threat in the present, as well as in the future, pose a significant threat to the democratic states. IEDs are insidious and effective weapons being used by terrorists, alien militants and criminals, primarily for the purpose of crippling or killing people, destroying of country's economy or for instilling fear among the civilians. Their aim is to challenge the legitimacy of governments and their ability to give their citizens freedom and security. Where the democratic processes end, the radical solutions begins.

Objects, the security breach of which can cause extensive damage not only in terms of the protection of human life and health, but also to the economy and to performance of the state functions, are the elements from the sectors of the critical infrastructure [1]. The elements of the critical infrastructure are the second most important target, right after the human targets. Their destruction or long-term disposal translates into restrictions in traffic, the supply of drinking water, food or energies and the total collapse of citizens' services including the exchange of information. Resistance to the security tools used for the protection of an object as well as resistance to the building particles of an object both play a significant role in the protection of the critical infrastructure. If it is inadequate, the probability of a successful security breach is higher and so is the probability of the actual attack on this object [2, 3]. The possibility of a terrorist attack stems from the instability and unpredictability of developments in the security field in the world. Bombing tactics can be applied to all elements of the critical infrastructure sectors or on personal targets. The use of explosives as tools of terrorism and partisan-guerrilla warfare has a long tradition and its usage has no boundaries. Thanks to the globalization and informatization of the world, modern technologies are now available to anyone, anywhere and at any time. Given the wide range of uses of explosive devices on critical infrastructure objects, we will not focus on the tactics of the attacks, but rather on the ways that limit the effects of the explosions.

2 Explosion and blast phenomenon

In the beginning of this section, it is important to note that, in a real situation every explosion of a real booby trap/explosive device is different and there are no two identical cases. Each can take place in a different location, in different climatic conditions, it can be initiated differently or an explosive used may have different characteristics. Mathematical models simulating an explosion are currently only being used in preventing major industrial accidents or in the military field, and only in setting a safety distance of objects from the potential sites of explosion, i.e. from ammunition warehouses, combat vehicles parking, etc. and even that is without taking into account built constructions and possible reflections. In terms of risk assessment, due to a reduction in the number of weapons and the control of the movement of explosives, there is a small probability that terrorists in a developed country with standard legislation could acquire a substantial delivery of goods, such as a truckload of standard explosive type TNT, RDX, HMX or PENT. Most attacks are therefore committed using homemade explosives, which are, if possible, technologically the easiest to produce and are relatively safe when handling or transporting. Ammonium Nitrate explosives are to a large extent fulfilling these conditions.

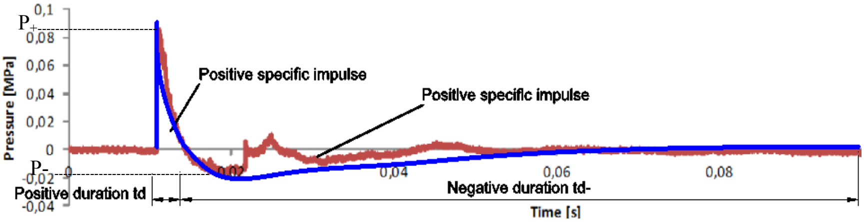

Figure 1: Real and approximated blast wave time history. P0 – ambient pressure, P+ – peak value of overpressure, P- – under pressure (creating a partial vacuum), tA – arrival time of blast wave, td – duration time of blast wave.

The real detonation of a spherical charge runs in such a way that the detonation wave extends from the centre of the charge in all directions. Its front strikes against the surrounding environment at the charge brim. From this point the blast wave extends and after a gas explosion the reflected one is distributed. The blast wave profile has two phases – a positive and negative one. Its real form is approximated with the regular shape with one peak and then it drops below the ambient pressure (Figure 1). In reality, the blast wave can occur as more than one peak; this is due to the unstable detonation (Figure 2).

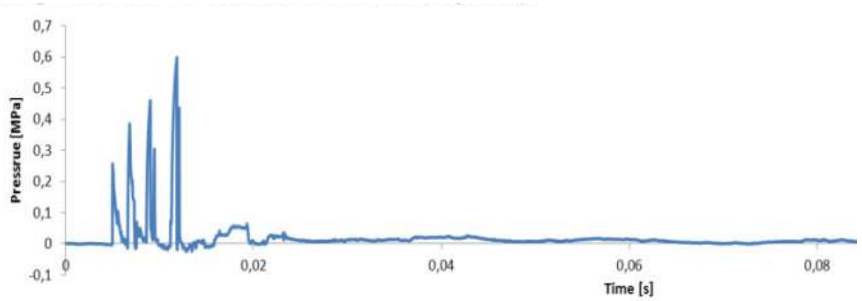

Figure 2: Real blast wave time history with more peaks of pressure.

For the fundamental parameter of critical infrastructure objects, the rating of the threat from IED is the peak value of the blast wave. The values that are necessary to the objects' damage are markedly different in current literature. However, in [4] it is stated that the value of pressure necessary for wall damage is about 83–100 kPa. But [5] says that the maximum peak pressure necessary to create wall damage is 1.8 bar, i.e. 180 kPa. The European Standard [6] prescribed that the pressure of the most resistant class windows, EXR5, is 6.3 bar, i.e. 630 kPa. This limit is much higher than the pressure value necessary for wall damage. This suggests a wall with a fixed window would not resist but the window itself would. This is illogical.

Table 1: Building damage depending on the blast wave [4].

Building damage	**Peak value of overpressure [kPa]**
Small	> 3.5
Medium	> 17
Great	> 35
Destruction	> 83

When a security project of the critical infrastructure object is designed, it is necessary to set the limit values of all used elements.

3 Prediction of blast pressure

3.1 Blast wave scaling law

Estimations of peak overpressure due to a spherical blast are based on scaled distance. The "cube root law" states that if the detonation of two charges made from same material, in the same form but with different weights, occur in the same atmosphere, then this phenomenon generates similar blast waves in the same scaled distance. The scaled distance is expressed as $Z = R/W^{1/3}$, where R is the actual effective distance from the explosion expressed in meters and W is the weight of the charge in kilograms.

3.2 Estimation of blast wave parameters

Using the scaling law the scaled variable is the weight dependent on the distance. According to the "cube root law" the variable would have to be the energy of the explosion. The reference sample of the explosion has been set as TNT. According to this assumption the weight of a single explosion has been set using the so-called TNT equivalent (K_{TNT}-p), where the basic unit Qv is heat of combustion [7]:

$$K_{TNT-P} = 0.3\,Q_v - 0.2 \tag{1}$$

Subsequently, the scaled weight is set, where W_n is the weight used in the explosion, in kilograms:

$$W = W_N\,K_{TNT-p}k_E\,k_G \tag{2}$$

where k_E – the factor of charge for leakiness, and

$$k_E = 0.2 + \frac{0.8}{1+k_B} \tag{3}$$

where k_B is the ballistic ratio (the weight of packaging to the weight of explosion) and k_G is the factor of the blast wave geometry propagation in space. For the detonation in free space, $k_G = 0.5$ and for the detonation on an earth surface, $k_G = 1$. We assume that the energy is propagated in the form of a half sphere with maximum deflection from the surface.

The parameters of the blast wave can be set according to different authors. The calculated values vary and the accuracy and reliability increase with the distance of the blast wave from the source of the explosion. But this increase is exactly the opposite of what is needed in the rating of the security.

In our opinion it is important that the reliability of the calculated results was achieved as close to the charge as possible (i. e. a “critical distance” of 5 to 10 m from the explosion source). The critical distance is set using safety distance analysis, as in the distance of a car from a building’s façade, the distance of an entrance in the protection zone from a check point, the distance of the taxi stands from an airport hall, etc. The structure of empirical relationships is very similar and only varies in the values of coefficients. Here, we present some of them.

3.2.1 Sadovskij methodology – the Soviet Union

The relationships introduced by the soviet geophysicist Sadovskij [8] determine an explosion in the air. For the explosion on the surface we must calculate using the double weight of the charge.

$$p_+ = \frac{1.07}{z^3} - 0.1 \quad pre\, z \le 1 \quad \text{[MPa]} \tag{4}$$

$$p_+ = \frac{0.076}{z} + \frac{0.255}{z^2} + \frac{0.650}{z^3} \quad pre\ 1 < z \le 15 \ \text{[MPa]} \tag{5}$$

3.2.2 MILLS methodology – the UK

In 1987 Carl Mills introduced the relationship based on older works from the Western Bloc [9]:

$$P_+ = \frac{1772}{z^3} + \frac{114}{z^2} + \frac{108}{z} + 0.19 \quad \text{[kPa]} \tag{6}$$

3.2.3 HENRYCH – Czechoslovakia

Henrych's [8] methodology originated from the scaled distance with the double weight of the charge:

$$p_{+} = \frac{0.0662}{z} + \frac{0.405}{z^2} + \frac{0.3288}{z^3}\ pre\ 1 < z \leq 10\ \ [\,\mathrm{MPa}\,] \qquad (7)$$

All the presented formulae are focused on industrially, technologically and correctly produced explosives. However, the control tests of TNT and SEMTEX 10 show that set pressures differentiate primarily in distances of up to 10 m.

4 ANFO explosives

From the terrorists' perspective it must be stated that it is easier to obtain ANFO than a few kilograms of military explosive. Although military norms also envisage the use of several tons of TNT, this notion is more unrealistic than probable. Available analyses state that in more than 95% of all acts of terrorism the combination of ANFO (Ammonium Nitrate + Fuel Oil) is used [10]. From the chemical-technological point of view it is possible to differentiate three different versions of ANFO explosives: ammonium nitrate + fuel, ammonium nitrate + fuel + powder metal (usually aluminum or magnesium) and ammonium nitrate + fuel + wooden powder – delaborated TNT. The affordability of the raw materials and the ease of manufacture allows for its production, using only simple devices. The availability of nitrate as an agricultural fertilizer is almost unlimited and so is fuel (oil, diesel, petrol). An ordinary construction concrete mixer can be used as the necessary machinery. The optimal content of diesel or oil in ANFO is about 5.5–6% and in porous AN it is about 10–11%. The mixture where the fuel content is less than the optimum decreases the energy of the explosion while simultaneously significantly increasing the content of nitrogen oxides in products of the explosion. On the contrary, a higher content of fuel leads to an increase in the content of carbon monoxide in the products of the explosion and again to a decrease in the energy of the explosion. After the analysis of our findings that we gained by comparing the results of our experiments and calculations we conclude that Sadovskij's formula is the nearest to the measured values. In the case of ANFO explosives there are some considerable variations. The TNT coefficient derived from the explosion heat is with industrial explosives or with chlorate and perchlorate pyrotechnic composition, a misleading value. This method is inadequate for the calculation of threats and for the setting of security measures. As an example it is suitable to refer to the theoretical values of industrially manufactured ANFO explosives. For our research we chose the products DAP-2, DAP-E and POLONIT of the Slovak company – Istrochem Explosives a.s. Bratislava. Their characteristics and the represented type of explosives are given in Table 2. It should be pointed out that all the explosives used were fabricated industrially, meeting the standards of the production technology. It is know that home-made explosives are not mixed well, made from low quality raw material (nitrogen content), they contain chemical impurities, possibly water and so we can supposed that their efficiency is 70–90% of standard fabricated explosives.

4.1 DAP – 2

The explosive is a mixture of ammonium nitrate, kerosene and dye. The explosive is of loose consistency, red in colour and is used for blasting on the surface as well underground without the danger of gas, vapour and dust explosions as a rock mining explosive.

4.2 DAP – E

The explosive is a mixture of ammonium nitrate, methyl esters of higher fatty acids, vegetable oil and red dye. The explosive is of loose consistency, red-grey in colour and it can be used in blasting operations on the surface as well as in the underground in an environment without the danger of gas, vapour and dust explosions as a rock mining explosive.

4.3 POLONIT – V

The explosive is a mixture of ammonium nitrate, kerosene, charcoal, ground TNT with water-resistant additives. The explosive is of loose consistency, white to yellowish in colour and it can be used in blasting works on the surface as well as in the underground in an environment without the danger of gas, vapour and dust explosions.

The industrial explosive DAP-E has the same heat of combustion value as that of TNT (see Table 2). Logically, according to the noted formulas these two explosives have the same efficiency. The experiments that were conducted show the invalidity of this theory. It is the same with Slovak explosive POLONIT. Its heat of combustion predetermines it in the same efficiency as Semtex, i.e. 130% of TNT.

The density of the explosive influences the explosive velocity and pressure. The density varies, but this fact is not taken into account in the calculations. The final explosion effect depends on the consistency of the explosive. Different explosive pressures and overpressures are obtained when the explosives are aggregate, liquid or pressed. The explosive pressure depends on the density of the explosive in its different forms and has a significant impact on the overall power of the explosives. In the case of ANFO explosives what matters is the size and the porosity of the granules. Generally ANFO with small porous granules has a higher explosive velocity and a higher sensibility to bust. The power of the explosive depends on whether we use only a standard detonator or also a buster. The buster size is important only to a certain weight. If it is greater than 20–25 g it does not influence the overpressure. When analysing the field test overpressures and calculated ones, we have to note that Sadovskij's formula was the closest to the measured values. However, it shows significant anomalies for ANFO explosives. The TNT coefficient derived from the heat of combustion is misleading for industrial explosives or chlorate and perchlorate pyrotechnic composition. This method is unsuitable for the determination of threat and subsequent measures.

5 Set of new relationships for blast wave parameters

We have compounded a set of new relationships for the determination of threat using IEDs. The formulas are base on the study of Henrych [8]. He claims that the velocity and explosive pressures are dependent on the density of the explosive. However, as we stated above the TNT coefficient is unsuitable for these types of explosives. We have replaced it with a coefficient derived from the assumption of the dependence of explosive pressure and density of explosives. From the basic rules it is apparent that the explosive pressure, explosive velocity and subsequently overpressure of the explosive with a lower density will be lower than that of the same explosive with a higher density. This theory has been verified with experiments in [7]. If the explosives have different values of explosive pressure and density they do not have the same TNT coefficient. Thus it is more realistic to determine a new coefficient k_v for the IED explosives, where P_{cj} is the explosive pressure and ρ is density:

$$k_v = 0.085\left(\frac{P_{cj}}{\rho}\right) \tag{8}$$

Table 2: Characteristics of used explosions.

Explosive	Type of represented ANFO explosive	Explosive velocity [m/s]	Heat of combustion [kJ/kg]	Density [g/cm^3]	Explosive pressure [GPa]	Factor K_{TNT}	Factor Kv
DAP – 2	AN + oil	2650	3830	0.65	2.95	0.91	0.39
DAP – E	AN + oil + Al	3100	4200	0.65	4.58	1.00	0.60
Polonit – V	AN + oil + TNT	4000	5138	0.9	6.93	1.23	0.66
TNT	Reference sample	6800	4200	1.58	18.4	1.00	0.99

When we change k_v with k_{TNT} the relationship for the scaled weight has this form:

$$W_R = W_{exp}.k_E.k_G.k_v \tag{9}$$

where W_R is a real weight of charge in kilograms and the scaled distance is:

$$Z = \frac{R}{\sqrt[3]{W_R}} \tag{10}$$

The supposed overpressure in the distance R for 0.3< Z ≤ 1 can be obtained from Henrych's formula [8]:

$$p_+ = \frac{0.61938}{z} + \frac{0.03262}{z^2} + \frac{0.2134}{z^3} \quad [\mathrm{kPa}] \tag{11}$$

The relationship for the overpressure in the distance R for ≤ 1 Z ≤ 10 has been modified to this form:

$$P_{+} = \left(\frac{0.202}{Z} + \frac{0.224}{z^2} + \frac{1.182}{z^3}\right).0.5.e^{0.035R} \tag{12}$$

For the scaled distance Z > 10 it is possible to use the relationship (12) but with e0.035R = 1. The under pressure of the negative phase is obtained:

$$p_- = \frac{0.03}{z} [\ \mathrm{kPa}\ ] \tag{13}$$

The duration of overpressure from [11] is:

$$\tau_+ = 1.7.10^{-3}\sqrt[6]{W}\sqrt{z} \quad [\mathrm{s}] \tag{14}$$

The duration of negative phase, from [11] is:

$$\tau_- = 0.0154 * \sqrt[3]{W}\ [\mathrm{s}] \tag{15}$$

6 Field tests

6.1 Sets of field test no. 1

For the verification of our theory we conducted sets of field tests, with 150 explosives weighing from 400 g to 4.5 kg in the years of 2012–2013. The field tests took place at the development and testing set of the Ministry of Defence of the Slovak Republic, called the Military Technical and Testing Institute Zahorie. The methodology of the measurement is based on [12]. The maximum overpressure was measured using blast pressure sensors, type 137A23, and 137A24 PCB Piezotroics. The explosive charge was positioned 1.6 over the ground surface, i.e. the height of a man's chest. Sensors were placed at the distances of 10, 20 and 30 meters from the source. Besides maximum overpressure, the velocity of the blast wave and the level of noise were also measured. The experimental results are compared with the results obtained according to different approaches.

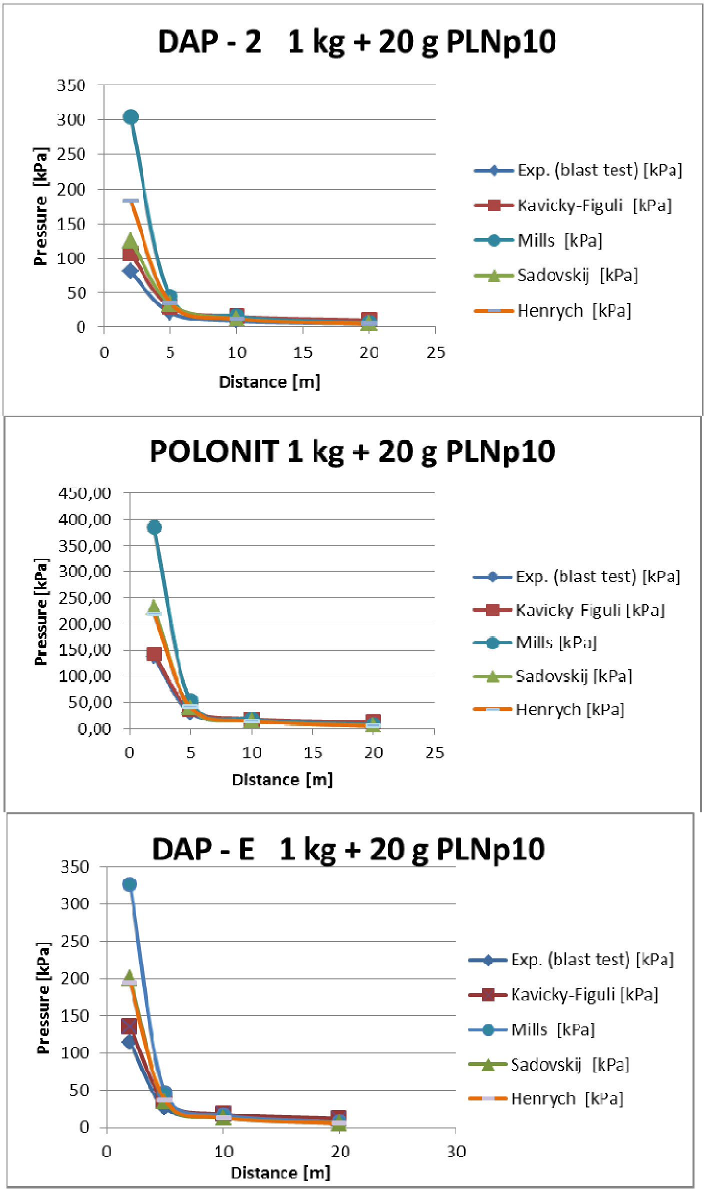

Figure 3: The overpressure dependence on the distance in field test no.°1 .

6.2 Sets of field test no. 2

We made the second round of field tests using ANFO explosives on 21st January 2014. The field tests were focused on the measurement of overpressure and its influence on steel beams. An analysis of steel beams under blast loading will be the aim of our future work. We conducted 16 measurements to verify our theory and relationships. POLONIT was used as the explosive. The weight of charges were selected: 2.3 kg (pipe bomb), 4.5 kg (bomb belt) and 9 kg (bomb vest – it was not detonated because of a high overpressure of 4.5 kg explosive which caused a damage of the construction with steel beams). The explosive was in plastic bags with the internal diameter Ø = 95 mm (2.3 kg) and Ø = 150 mm (4.5 and 9 kg). The charges of POLONIT were detonated using an electric ignition. The explosives were used together with 25 g of ignition explosive PLNp10. The sensors were placed at the height of 1.6 m at an angle of 45° from the normal line in the distances of 2 m, 5 m and 10 m from the source of the explosive. One of the sensors was orientated in parallel with the steel beams at the distance of 5.5 m opposite of the gabion wall and at the distance of 3 m from the source of the explosion (we wanted to record the reflected blast wave). The charged explosives were placed at the wooden base at the height of 10 m. The field tests took place on sandy subsoil. In Figure 3 the experimental results are compared with the results obtained from the different approaches mentioned previously.

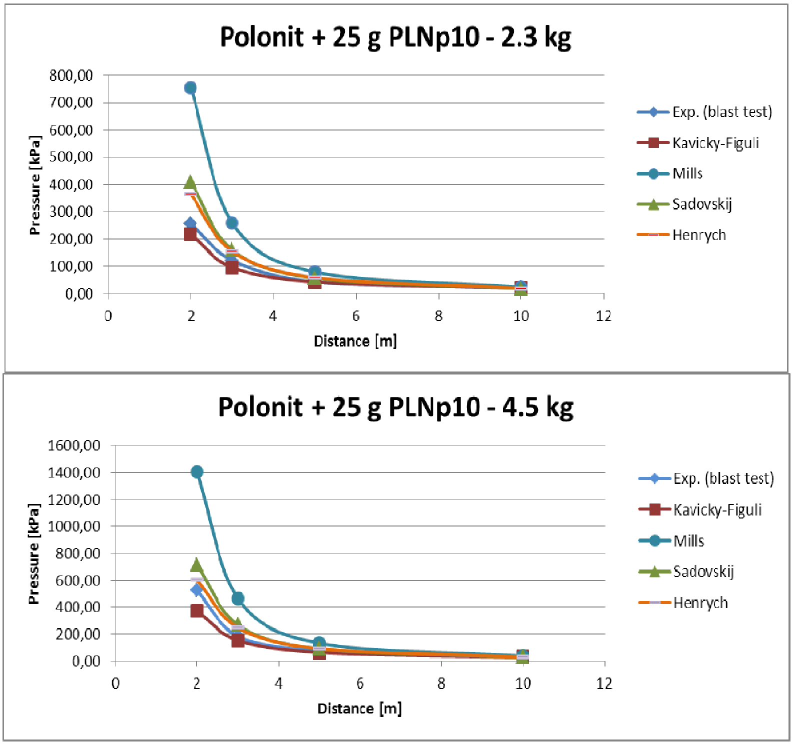

Figure 4: The overpressure dependence on the distance in field test no.°2.

7 Conclusions

ANFO explosives operate according to the explosion heat of powerful explosives. In reality, however, their power is lower and it is therefore necessary to select another method for calculating the overpressure than that used for standard explosives. The formulas that we designed border the measured values and are often even below this threshold. We nevertheless believe that real overpressure will be even lower than the value that we calculated. We support this argument with the fact that our experiments were conducted using industrially manufactured explosives and were not homemade. Homemade explosives typically contain substandard nitrate, the characteristics of which are affected by other factors such as the porosity of the basic nitrate, its thickness, the percentage of nitrogen, the presence of water, the homogeneity of fuel incorporation and other technological nuances. All these characteristics influence the course of detonation and its output values such as detonation velocity, overpressure values or fragments velocity. In terms of the quality of an explosive, the stability of detonation as well as of the power of an explosive, the power of HME is lower than the real one. It is also necessary to mention that due to the imperfect homogeneity of the mixture, part of the nitrate used does not behave as an explosive but as an INERT. In large loads of explosives, the percentage of volume that behaves as inert mass in detonation can reach up to 20% of the overall weight.

Acknowledgement

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