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Preliminary Estimation of the Explosive Mass Based on the Crater Resulting From the Surface Explosion on Asphalt*

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Abstract: In the course of court trials and for the purpose of legal proceedings, forensic engineers often produce estimations of the explosive mass based on the explosion effect. For the preliminary estimation of the explosive mass one often uses empiric formulas. This paper describes experimental surface explosions of variable mass of known explosive charge on the asphalt with the objective to make correlations between causes and consequences of an explosion. Dimensions of the resulting craters were measured and an overview of experimental tests of five equations for calculating the mass of explosive based on the dimensions of the craters is given. The asphalt surfaces were chosen since the highest number of explosions, which are the results of terrorist or some other criminal acts, occur in urban conditions where asphalt is the dominant surface. Based on the given overview it is possible to give an evaluation of equation's reliability for certain explosive masses. The paper also includes a brief review of the facts related to the position of initiation and its influence the shape and dimensions of the crater.

*** Prethodna procjena eksplozivne mase na temelju kratera – posljedice površinske eksplozije na asfaltu**

Izvornoznanstveni članak

Sažetak: U tijeku suđenja, te u svrhu sudskog postupka forenzični inženjeri često daju procjene mase korištenog eksploziva na temelju učinka eksplozije. Za preliminarnu procjenu eksplozivne mase često se koriste empirijske formule. Ovaj rad opisuje eksperimentalne površinske eksplozije na asfaltu sa promjenjivom masom eksplozivnog naboja, a sa ciljem uspostavljanja korelacije izmedju uzroka i posljedica eksplozije. Dimenzije nastalih kratera su mjerene i dan je pregled eksperimentalnih ispitivanja pet jednadžbi za izračunavanje mase eksploziva na temelju dimenzija kratera. Asfaltne površine su izabrane s obzirom da najveći broj eksplozija, koje su rezultat terorističkih ili nekih drugih kaznenih djela, javlja u urbanim uvjetima u kojima je asfalt dominantna površina. Na temelju danog pregleda je moguće dati procjenu pouzdanosti jednadžbi za određivanje mase eksploziva. Rad također obuhvaća kratak pregled činjenica koje se odnose na položaj inicijacije i njegov utjecaj na oblik i dimenzije kratera.

1. Introduction

There are a large number of planted explosions throughout the world (terrorist purposes, intimidation, intention to assassinate a person, or for the purpose of overcoming possible obstacles during an act of theft, or to cause public danger, etc.) It is therefore important to focus on the analyses showing how reliable the estimations of the mass of planted explosive are, since these analyses are produced for the court. Namely, following the explosion of some lethal device there are visible traces based on which the cause of the explosion can be determined. The traces that are typical of an explosion of a lethal device are the formation of a crater and some other damages, different in shape and size, as well as parts of the explosive device [1-4]. Establishing the exact mass of explosive used is of importance for the court because it can prove the intention of the perpetrator of the criminal act in which the explosive is used, as well as establish the manner in which the act was performed. Higher values of explosive mass are indicative of the intention of causing a larger number of casualties and greater material damage. Those estimations are done by forensic engineers. During their work for court and in general, "Engineers need to be aware of ethics as they make choices during their professional practice of engineering" [5]. The decisions of engineers that they present in the court have a great impact on life of the perpetrator and society at large.

Symbols/Oznake

m_e	- explosive charge mass, kg - masa eksplozivnog naboja a
k	- the coefficient - koeficijent
r	- radius of the crater, m - polumjer kratera
h	- depth of the crater, m - dubina kratera
n	- coefficient of the crater *(n=r/h)* - koeficijent kratera
u	- critical velocity required for the demolition of the centre, ms^{-1} - kritična brzina potrebna za rušenje u centru
r_e	- the radius of the explosive charge, m - polumjer eksplozivnog naboja
F	- correction factor - korekcijski faktor

Greek letters/Grčka slova

ρ	- soil density, kgm^{-3} - gustoća tla
ρ_e	- density of the explosive, kgm^{-3} - gustoća eksploziva

Subscripts/Indeksi

e	- which refers to explosive - koji se odnosi na eksploziv

2. Crater as the effect of an explosion to the environment

Many authors who deal with the effects of explosions, such as Ambrosini, for example, emphasize the importance of studying the effects of an explosion to the environment [6].

When an explosion takes place different experts (forensic experts and experts from other fields of expertise) will go to the crime scene in order to perform an investigation in accordance with the court order. At first it cannot be determined with certainty what kind of the explosion that was (whether it was a chemical explosion or not). The answer to that and all other questions in relation with the explosion will be given by an expert – registered court's expert who, with the authority of his knowledge, skills and experience from certain area, offers his expertise and opinion about the facts that are being determined during the procedure. He is actually an expert witness [7].

Investigation, i.e. processing of an explosion site can include the engagement of experts from many areas since it is a phenomenon calling for a multidisciplinary approach. Thus, the examination of causes of the explosion can be made by chemical experts who, based on the samples taken from the explosion site and with the use of appropriate analytical methods (explained in more details in [2,3]), can give information about the type of the explosive that was used; forensic experts – engineers - can give information about the mass of the explosive used based on the damage caused by the explosion, type of the used explosive device, the method of initiation, and, finally, about material damage; forensic pathologists can provide information about the injuries sustained by the victims of the explosion; forensic biologists i.e. experts for dactyloscopy (fingerprinting) can give information about possible DNA profile and fingerprints left by the perpetrator, and the like. Other experts may also give valuable contribution.

The main purpose of studying explosions, i.e. investigating an explosion site, is to determine three basic elements: the origin, cause and responsibility for an explosion. The origin of an explosion is usually related to the place of initiation of the explosive. The cause of an explosion is the circumstance or the activity that leads to the explosion. Basic reasons for which we investigate the cause and the origin of an explosion is to establish the responsibility for the explosion, to estimate the total financial loss and to determine the number of injuries and fatalities that may occur. Responsibility for an explosion lies within the circumstance, activity, mistake and intention, and it is connected to the human factor [3]. Many traces resulting as consequences of an explosion, which can serve the purpose of identifying the cause of an explosion, can be scattered over a large area, but those traces are also inconstant, while the damages have permanent nature. The damages that emerge from some surface explosion of condensed explosive charge may occur as a variety of different mechanical damages with the obligatory characteristic trace – the crater, which represents the centre of the explosion and the place where the explosive device was placed. In the case when the explosive charge was interred at great depth, this centre can be camouflaged – pure underground explosion, which is explained in more details in [8].

When it comes to the definition and terminology in the creation of the crater there is some confusion among the researches. This refers to the definition of the border line of the crater and natural structure, as well as to what is meant by the size of the crater [9]. The true crater is limited by the area that emerged after the cleaning of pieces of the surface that went back to the crater after having been thrown out by the explosion. In this paper, the dimensions of the crater are adopted in accordance with Cooper [10].

The crater emerges as the consequence of the brisance effect of an explosion to its immediate surroundings. Namely, the effect of the explosion to the surroundings is determined in terms of the momentum (pulse) which is given to the particles of the surroundings as the result of the blast of detonation products [11]. In case of an explosion on the soil surface or just above the soil surface a pressure wave is created that compresses the surrounding area. The explosive wave spreads through the air and through the surface – in this case that surface is asphalt [12].

Military brisant explosives, such as TNT, PETN and hexogen leave visible traces in the form of blackening in the centre of an explosion (in most of the cases that is the crater) which tells us about the presence of carbon in the products of decomposition due to the contents of organic components and their negative oxygen balance, which is not the case with tertiary explosives [13].

When an explosion occurs in contact with the soil surface, or just above or under it, a dent emerges that is usually described as crater. For a forensic expert a crater that is found on the soil surface at the explosion site represents a great potential. The size of the crater depends on the location of an explosive charge in relation to the soil, type of soil, as well as on the mass of explosive used. [4]

During the first examination of the crater, traces of an explosion can contain important information, i.e. they may indicate the characteristics of an explosive device [14]. Craters can be the source of fragments of the device and the residues of the non-reactant explosive substance.

Material traces that are secured from an explosion site are then examined in the scientific or forensic engineering laboratory [3]. A request with the basic data about an explosion and questions which must be answered is submitted to an expert i.e. to an expert institution. The request is attacked to the material traces that were retrieved from the site of the explosion, and these are accompanied by the investigation documentation. An expert gives answers to the following questions: What is the cause of the explosion? What explosive was used? What was the mass of the explosive used? How was the explosive initiated? Who planted the explosive device? etc. With the examination of the received material and the documentation, the expert determines the type of the device, method of initiation, etc., and based on the crater dimensions, type of soil and damages in the surrounding area, the expert calculates the mass of the used explosive.

From a forensic point of view, the existence of a crater at the site of an explosion is important for it offers possibilities to estimate the mass of the explosive that was used for some concrete explosion. It has so far been a widespread practice to determine the mass of used explosive based on the literature data and empiric terms for calculation, but the results obtained in this way have not always been reliable.

Some of the authors emphasize the low availability of literature about the examination of explosions at ground level and mechanisms of the emergence of a crater. [6]. The starting point is the hypothesis that the crater volume is directly proportional to the explosion energy i.e. to the weight of the explosive charge. Relevant literature offers equations for the calculation of the mass of an explosive m_e based on the dimensions of the crater in the case of the explosion at ground level.

Within the forensic practice in the Republic of Serbia the equations of the following scientists are commonly used: Boreskov, Vlasov, Pokrovskii, Kinney and Cook, which are shown as from (1) to (5) [15]. These equations are applicable for different sorts of soil.

$$m_e = 38k\, h^3\,(0{,}4 + 0{,}6n^3), \quad (1)$$

$$m_e = 2\pi\rho u\, r^3 10^{-2}, \quad (2)$$

$$m_e = 2r_e^3\rho_e 10^{-2}, \quad (3)$$

$$m_e = 3{,}2r^3\, 10^{-5}, \quad (4)$$

$$m_e = 1{,}32F(r^2h)^{0{,}877}10^{-4}. \quad (5)$$

All these equations are applicable for the calculation of TNT mass with the multiplication with correction factor for the used type of explosive.

The correlation between the dimensions of crater and mass of the used explosive is given in the computer program *Crater Sizes from Explosions and Impacts* [16] by Holsapple, which was designed for the surfaces that have lots of differences in asphalt characteristics and for the explosive charges of large mass. Because of the mentioned reasons, experimental data were not checked through this program.

3. Experimental examinations of the effects of some brisant explosives on the asphalt surface – material and method

Experiments focused on the detonation of known explosives (known chemical and physical characteristics) on the asphalt surface. The objective of the experiments is to create a correlation between the type and mass of used explosive and the damage on the surface that emerged from detonation, in order for the forensic investigation of an explosion site to become better in quality and more efficient in terms of easier and faster recognition of damages on an explosion site in cases when the ground explosion was on asphalt surface. Since the forensic practice of the Republic of Serbia indicates that most commonly used brisant explosives are TNT, PETN and amoneks1, that was the reason for which these explosives were examined in the experiment. Table 1, taken from [11, 15], lists some characteristics of these explosives.

Table 1. Characteristics of the explosives used in the experiment

Tablica 1. Karakteristike eksploziva koji se koriste u eksperimentu

No	Explosive characteristics	TNT	PETN	Amoneks1
1	Chemical formula	$C_6H_2(NO_2)_3CH_3$	$C(CH_2ONO_2)_4$	-
2	Molecular weight	227	316	-
3	Density ρ [kg/m^3]	1600	1760	1050
4	Oxygen balance [%]	-73,9	-10,1	0,24
5	Melting point [°*C*]	80,8	141,3	-
6	Heat of explosion [*kJ/kg*]	4310	5860	4248
7	Detonation velocity [*m/s*]	6900	8400	4200
8	Deflagration point [°*C*]	300	205	-
9	Explosion temperature [°*K*]	3370	4500	2450
10	Ignition temperature [°*C*]	300	210	248

Standard TNT bullets of 0,1*kg* and of 0,2*kg*, plastic explosive PETN, with the mass of 0,5*kg* and prepared smaller explosive charges of 0,1*kg* and of 0,25*kg* were taken for the samples of brisant military explosives. Amoneks1 is brisant commercial explosive (mixture of ammonium nitrate 45%, TNT-30%, Aluminum 23% and woodflour 2%). It was used in its original package of 1*kg* and in prepared cartridges of 0,1*kg*, 0,2*kg* and of 0,5*kg*. The activation of explosives with the blasting cap and the follow-up of the effects after detonation were made on the asphalt surface that was of good quality without visible damages in the form of holes, cracks, etc. Asphalt was made by compression of previously prepared mixture of gravel, mineral powder and bitumen. Asphalt obtains its physical and chemical characteristics after being pressed with a roller compression. When mixing mineral substances with bitumen, complex physical and chemical processes take place and their nature depends on the properties of created materials. The reaction between the binder and mineral material determines the properties of asphalt that change as the outside temperature changes. At the temperature below 0^oC asphalt is an elastic material while at the temperatures above 0^oC asphalt behaves like viscous-plastic material.

The asphalt that was used for the experiment had the compressive strength of $1{,}47*10^6 N/m^2$ and density $2140 kgm^{-3}$. Fine-grained asphalt surface was used, i.e. mineral grains in asphalt mixture had the coarseness up to $15*10^{-3}m$. The explosive charge was placed horizontally on the surface. Initiation of the explosive was carried out with the use of blasting cap with the DK-8 label and instantaneous electric detonator.

After the detonation damages emerged on the surface in the form of the crater that was examined in details, cleaned and measured (length, width and depth) with conventional strain gauge (error of measurements is 0,001m). Volumes of true craters were measured on the site. The crater volume was calculated as that of a cone with ellipse base ($V=abh\pi/12$, where a and b are ellipse's axes). The results of the experiments and values of the volume of the true crater are shown in Table 2.

Table 2. Results of experimental explosions: dimensions and volumes of crater after the explosion along with calculated dimensions of used explosive charge

Tablica 2. Rezultati eksperimentalnih eksplozija: dimenzije i obujmi kratera nakon eksplozije zajedno s izračunatim dimenzijama korištenog eksplozivnog naboja

No.	Explosive	Mass *[kg]*	Form and dimensions [*m*] of explosive charge	Crater dimension [*m*] and volume V*[$10^{-4}m^3$]*	Explosive mass by Boreskov *[kg]*	Explosive mass by Vlasov *[kg]*	Explosive mass by Pokrovskii *[kg]*	Explosive mass by Kinney *[kg]*	Explosive mass by Cook *[kg]*
1	Amoneks1	0,1	Cylindrical charge Ø0,028x0,155	0,2x0,08x0,02 V=0,84	0,041	0,036	0,017	0,019	0,060
2	Amoneks1	0,2	Double cylindrical charge 2(Ø0,028x0,155) placed horizontally on each other	0,2x0,11x0,02 V=1,15	0,061	0,044	0,025	0,026	0,060
3	Amoneks1	0,5	Cylindrical charge Ø0,50x0,180	0,28x0,2x0,05 V=7,33	0,214	0,180	0,086	0,092	0,125
4	TNT	0,1	Cylindrical charge Ø0,033x0,108	0,14x0,13x0,02 V=0,95	0,025	0,021	0,010	0,012	0,035
5	TNT	0,2	Charge in cuboids shape 0,1x0,05x0,025	0,26x0,2x0,045 V=6,12	0,111	0,107	0,045	0,048	0,175
6	TNT	0,4	Double charge in cuboids shape	0,25x0,21x0,055 V=7,56	0,117	0,107	0,045	0,048	0,175
7	PETN	0,1	Cylindrical charge Ø0,020x0,140	0,21x0,20x0,035 V=*3,85*	0,051	0,045	0,021	0,024	0,075
8	PETN	0,25	Charge in cuboids shape 0,08x0,035x0,025	0,40x0,30x0,07 V=*22*	0,335	0,240	0,115	0,122	0,390
9	PETN	0,5	Charge in cuboids shape 0,15x0,06x0,04	0,38x0,38x0,09 V=*34*	0,375	0,307	0,147	0,156	0,560

4. Results and discussion

After experimental detonations of TNT, PETN and amoneks1, damages in the forms of craters have emerged on the asphalt surface. The existence of the crater on the site of an explosion is the proof that the cause of the explosion was the explosive charge. The importance of the crater is great since based on its dimensions we can estimate the mass of explosive used.

The experimental explosions were used to determine that the dimensions of craters primarily depend of the explosive mass used for the explosion, which confirmed the starting hypothesis. In this case the size of the crater depends, besides the mass of the used explosive, on the type of explosive, i.e. the damage to the surface was the most extensive when PETN was used, and this was followed by TNT and finally amoneks1, the quantities of the said explosives having been exactly the same.

The shape of the explosive charge has a big influence on the shape of the crater base – elongated charges make elongated craters. The way in which the explosive charge was placed i.e. the size of the contact area also had the influence on the shape and dimensions of the crater, which means that if the explosive is placed horizontally the crater will be wider and shallower and vice versa. Horizontally placed charges will result in elliptic craters and vertically placed charges will result in circular craters. It can be noticed that the contact area between the explosive charge and the asphalt surface has the influence on the shape of the crater base. Namely, for the same value of the contact area approximately the same values of the crater bases will be obtained, while the larger masses of explosive will result in craters of larger volume.

The place of explosive initiation also had the influence on the shape and dimension of the crater. So, for example, if the horizontally placed charge was initiated on one side, the crater will be a bit deeper on that side than on the other side. This is especially important from the forensic point of view since in that is the part of the crater where one has to search for the residue of the initiation material.

Deviations of true values of the mass of explosives with which the experiments were performed in relation with the values of mass that resulted from calculations are shown in diagrams in Figures 1, 2 and 3 in the continuation of the text, in the following order: PETN, TNT and amoneks1.

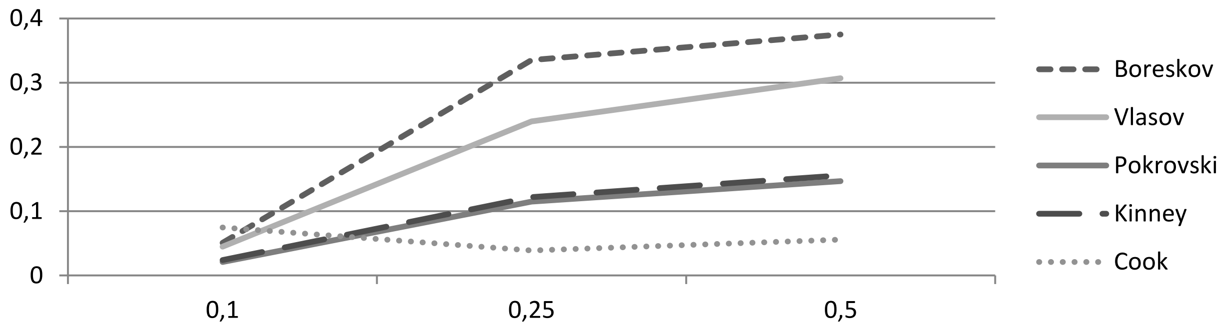

Figure 1. Diagram of dependence of calculated explosive mass values from the mass of explosive charges that were used in the experiments for PETN explosive

Slika 1. Dijagram ovisnosti izračunatih vrijednosti masa eksploziva od masa eksplozivnih naboja korištenih u eksperimentima za eksploziv PETN

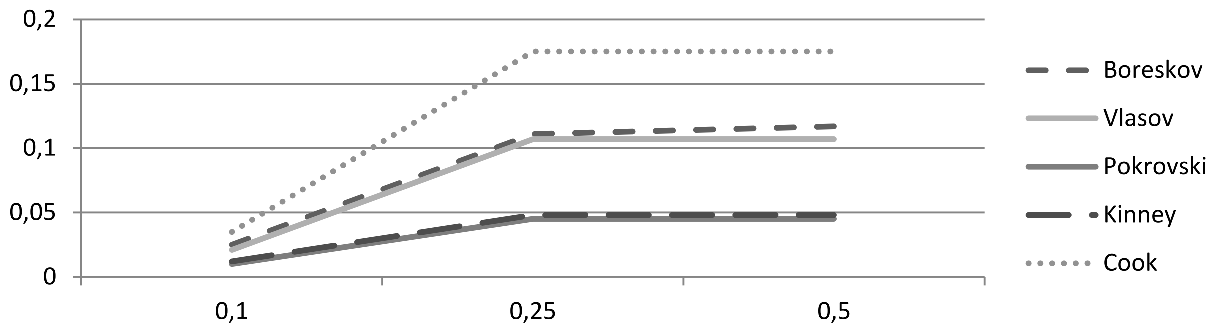

Figure 2. Diagram of dependence of calculated explosive mass values from the mass of explosive charges that were used in the experiments for TNT explosive

Slika2. Dijagram ovisnosti izračunatih vrijednosti masa eksploziva od masa eksplozivnih naboja korištenih u eksperimentima za eksploziv TNT

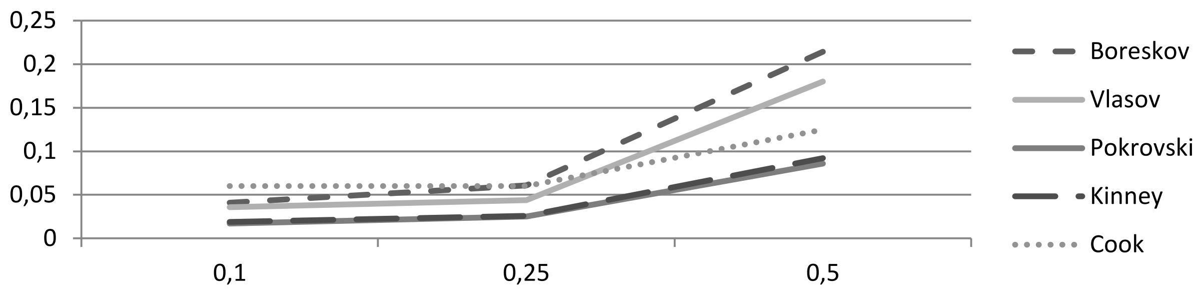

Figure 3. Diagram of dependence of calculated explosive mass values from the mass of explosive charges that were used in the experiments for amoneks1 explosive

Slika 3. Dijagram ovisnosti izračunatih vrijednosti masa eksploziva od masa eksplozivnih naboja korištenih u eksperimentima za eksploziv

From these diagrams one can read which of the offered equations give the most reliable results in accordance with the values of the mass of explosives and based on the overlapping of initial experimental and calculated values of the mass of explosives (overlapping of curved with straight line y=x).
When it comes to the mass of PETN of 0,1*kg* the most reliable equations are given by Vlasov (2) and Cook (5), for the mass of 0,25*kg* the most reliable equation is given by Vlasov (2), while for the mass of 0,5*kg* the most reliable equation if given by Cook (5).

For TNT explosive mass of 0,1*kg* large deviations were notice in all equations, as well as for the mass of 0,4*kg*, but for the mass of 0,2*kg* the best results were obtained from the equation given by Cook (5).
For 0,1*kg* and 0,2*kg* of the commercial explosive amonex1 large deviations were noticed in all equations. The exact mass of the used explosive can be calculated with the use of the equation given by Cook (5) and then the obtained value is multiplied by the factor 1,7 i.e. 3,4. For the mass of used explosive of 0,5*kg* all the equations shown deviations, but the most reliable value can be calculated if, after the use of the equation, the obtained value of mass is multiplied by the factor 2,3.

5. Conclusion

Theoretical considerations and experimental studies have shown that the level of damage to the surface in the form of a crater is in the functional dependence of: mass, type and geometry of the explosive charge and the place of explosive's initiation. Based on the above listed experimental data it can be concluded that the shape and size of the base of a crater largely depend on the shape and size of the contact area between the explosive charge and the surface, with which the initial hypothesis is confirmed.
The obtained experimental results indicate the dependence of emerged effects of the explosion (craters) and starting values (type of explosive, mass, shape, way of placement and way in which the charge was initiated), so these can be used for the estimation of the explosive charge mass that caused the explosion. The estimation of the mass of explosive – cause of explosion could be made with the use of comparison method – comparison of parameters in the concrete case with the parameters of experimentally performed explosions.
The crater dimensions are also highly influenced by the size of the contact area of the explosive charge and the surface.
If during the investigation of an explosion site one finds a crater with the diameter of approximately 0,2*m*, and if by means of chemical analytical methods one determines that the used brisant explosive was PETN, the most reliable equations for the estimation of the mass of explosive used are the equations given by Vlasov (2) and Cook (5). For the crater diameter of approximately 0,35*m*, the most reliable equation is given by Vlasov (2), whereas for the crater diameter of approximately 0,4*m* the most reliable equation is given by Cook (5).
If during the investigation of an explosion site one finds a crater with the diameter of approximately 0,13*m*, and if based on chemical analytical methods one determines that the used brisant explosive was TNT, it was shown that all the equations have resulted with large deviations. However, the mass of used explosive can be calculated with the use of the equation given by Boreskov (1) and multiplication of the calculated value of mass with the factor 4. In case when the crater that was found has the diameter of approximately 0,25*m* the most reliable results are obtained with the equation given by Cook (5) and the value of volume of the crater should be taken into account.
In the case when the commercial explosive amoneks1 was used to cause an explosion (confirmed by some chemical analytical methods) and if the crater with the diameter of approximately 0,2*m* was found, than the value of the volume of crater should be taken into consideration. The exact mass of the used explosive can be calculated with the use of the equation given by Cook (5) and when the calculated value is multiplied by the factor 1,7 or 3,4 respectively, if the volume is larger than expected.

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