COMPARATION OF EFFECTS GENERATED BY SHOCK WAVES OF SELECTED EXPLOSIVES

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Research article

Abstract: Article deals with assessment of exactly acquired values of shock wave effects generated in the course of explosion of an explosive device and with comparation of the current options for determination of magnitude of their effect by the means of mathematic models using experimentally measured values.

Keywords: Shock wave, sensor, explosive, explosion, mathematical models.

Introduction

Current world situation constantly provides types of explosives that may be applied into improvised explosive systems. Effective defence against those explosives necessitates deeper knowledge of their factual destructive effects. Currently existing mathematic models allow us to predict, to certain degree, their destructiveness. Since these models were based on knowledge of effects of the most utilized explosive - trinitrotoluene (TNT) - it appeared to us that it is reasonable to verify applicability of these mathematic models for determination of assumed effect of new types of explosives.

Because of this, we focused on assessment of accuracy and determination of tolerance of existing mathematic models describing the course and effect of shock waves of different explosives within our scientific research activities. Cooperation with Military Technical and Testing Institute Záhorie was used for acquirement of exact results and realization of the experiment. Seven types of explosives were used in the course of the experiment. Its goal was to determine the effect of shock waves of used explosives and to determine their effect on their environment. Construction of devices containing explosives was designed in a way to simulate improvised explosive devices as credibly as possible. Acquired experimental results were subsequently compared to results of mathematical models.

Materials and methods

In testing were used the following materials and methods.

Materials

To obtain practical results of measurements have been used commercially available pressure sensors and commercially produced explosives. Types of sensors and explosives are listed in other parts of the article.

Applied mathematical methods

Effects of studied explosives were modelled on the basis of mathematic relations described by the renowned authors M. A. Sadovskij, J. Henrich and D. Makovička.

a) *M. A. Sadovskij* (Makovička and Makovička, 2009)

Mathematical relations which this Russian geophysicist derived are intended for explosion in the air. The variant of explosion on the ground surface is proposed by substituting twice the value of actual mass of explosive for the mass of charge C_W (equivalent mass of charge [kg TNT]):

$$p_+ = \frac{1,07}{z^3} - 0,1 \qquad \text{[MPa] (1)}$$

for $z \leq 1$

$$p_+ = \frac{0,076}{z} + \frac{0,255}{z^2} + \frac{0,650}{z^3} \qquad \text{[MPa] (2)}$$

for $1 < z \leq 15$

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b) *J. Henrych* (Makovička and Makovička, 2009; Henrych, 1973)

Author deduced assumption of doubled actual mass of charge C_W for explosion on the ground surface as follows:

$$p_+ = \frac{1,40717}{z} + \frac{0,55397}{z^2} - \frac{0,03572}{z^3} + \frac{0,000625}{z^4} \quad \text{[MPa]} \quad (3)$$

for $0,05 < z \le 0,3$

$$p_+ = \frac{0,61938}{z} + \frac{0,03262}{z^2} + \frac{0,2134}{z^3} \quad \text{[MPa]} \quad (4)$$

for $0,30 < z \le 1$

$$p_+ = \frac{0,0662}{z} + \frac{0,405}{z^2} + \frac{0,3288}{z^3} \quad \text{[kPa]} \quad (5)$$

for $1,00 < z \le 10$

c) *D. Makovička* (Makovička and Makovička, 2009; Korenev, 1981; Makovička 1998; Makovička and Janovský, 2008)

An assumption was accepted according to author's claim, that in the case of explosion on ground level we substitute twice the value of actual mass of the explosive for the mass of charge C_W. Author states that the formulas were verified by means of experiments using small charges of Semtex near the loaded construction. (1, 4, 5):

$$p_+ = \frac{1,07}{z^3} - 0,1 \quad \text{[kPa]} \quad (6)$$

for $z \le 1$

$$p_+ = \frac{0,0932}{z} + \frac{0,383}{z^2} + \frac{1,275}{z^3} \quad \text{[kPa]} \quad (7)$$

for $1 < z \le 15$

$$p_- = \frac{0,035}{z} \quad \text{[kPa]} \quad (8)$$

$$\tau_+ = 1,6.10^{-3} \cdot \sqrt[6]{C_w} \cdot \sqrt{z} \quad \text{[s]} \quad (9)$$

$$\tau_- = 1,6.10^{-2} \cdot \sqrt[3]{C_w} \quad \text{[s]} \quad (10)$$

where

z reduced gradual distance from the explosion epicentre [m/kg$^{1/3}$],

p_+ overpressure on the front of the wave [kPa],

p_- underpressure of negative phase of the shock wave [kPa],

τ_+ time duration of overpressure phase of the shock wave [s],

τ_- time duration of underpressure (negative) phase of the shock wave [s].

Components and setup of the measuring system

Shock wave was measured according to ITOP 4-2-822 (Electronic measurement Airblast overpressure and impulse noise). ITOP 4-22822 (International Test Operations Procedure) is an international standard providing test procedure of the electronic measurement of air pressure and high impulse noise.

Measuring system components

For measuring the shock wave is used measuring chain, which includes the following elements:

- Pressure sensor (Pressure transducer),
- Single-channel signal conditioner,
- 4 slot pci expansion system connecting a laptop via Express Card/34 slot containing Dual channel Digitizer,
- PCI Express Card/34 mm, to connect the laptop and the expansion system,
- Laptop equipped with suitable software used to evaluate the measured analog signals,
- Stands for placing pressure sensors,
- Security features of pressure sensors,
- Equipment for electrical power supply system,
- Necessary cabling.

Measuring system setup

Measuring chain consists of a set consisting of PC + dig. PCI board 9820 + program DL 9820, sensing part of the chain was formed by sensors 4 x 137 and PCB 23 (345 kPa).Standard ITOP 4-2-822 (Electronic Measurement of Airblast Overpressure and Impulse Noise) was used as basis for measurement of the shock wave. Measurement was carried out with use of different types of explosives. Construction was placed in such way, that its manifestations would not be influenced by the surrounding environment and the effects could be measured (see Fig. 1).

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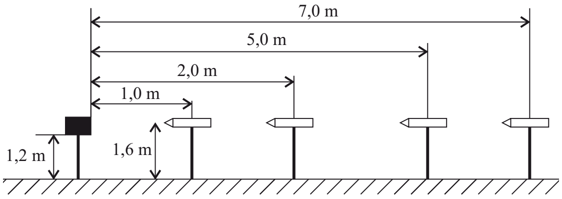

Fig. 1 Placement of sensors of the measurement system for measuring with regard to set environmental situation

Theory of omnidirectional spreading of shock wave into surroundings was applied for the placement of sensors. Sensor setup was supposed to simulate covert placement of improvised explosive system in exterior environment (for this case it was simulation of improvised explosive system placed in trash basket at the edge of sidewalk). Individual sensors represent positions of persons and solid obstacles positioned in particular distances that arise from terrain characteristics.

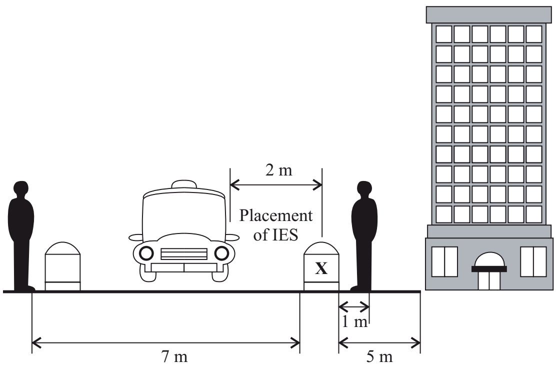

Fig. 2 Sample of sensor distances depending on spatial layout of terrain

Used explosives

Selection of explosives was subject to operative knowledge of the most frequently used explosives in improvised explosive devices. Following explosives which are most frequently used for this purpose were identified:

- TNT (trinitrotoluene) - one of the most frequently used military explosives. It is mostly used for preparation of military explosives in combination with other explosives. Its utilization is very wide because of its characteristics.
- Ammonium nitrate - is one of the most used substances used for preparation of improvised explosive devices because of its low costs, easy accessibility and relatively fast production process.
- DAP - 2 - industrial explosive used for surface and underground blasting operations.
- DAP- E - industrial explosive used as rock mining explosive.
- EcoDanubit - explosive of plastic consistence used for both surface and underground blasting operations.
- Ostravit - mining explosive of semi-plastic consistence used for blasting operations both on surface and underground in environment without danger of dust explosion.
- PlNp - 10 - military plastic explosive (known also as Semtex 10) intended for special types of blasting operations. For its characteristics it is utilized mostly for destructive operations under water and it is used also as priming charge of explosives.

Comparation of experimentally acquired results

The comparation of results is based on direct comparing of values acquired by measurement and values acquired by calculation by the means of individual mathematical models. Individual characteristics are subsequently expressed by means of graphical representation for possible visual comparation.

a) EcoDanubit / 400 g

Tab. 1 Comparation of values acquired by measurement and calculation for EcoDanubit / 400 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij $1 < z < 15$ [kPa]	Henrych $1{,}00 < z < 10{,}0$ [kPa]	Makovička $z > 1$ [kPa]
1	195,1	490	428	850
2	61,15	101	102	160
5	14,5	20	20	27
7	9,3	12	12	16

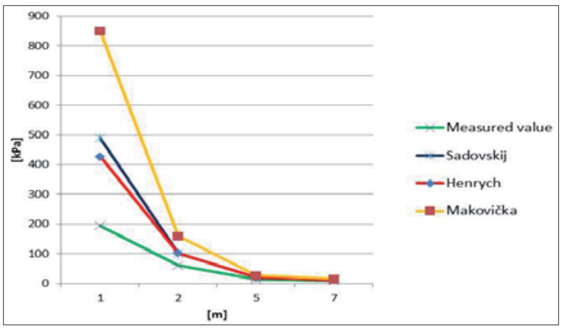

Fig. 3 Graph of actual and calculated course of explosion for EcoDanubit 400 g

b) EcoDanubit / 1000 g

Tab. 2 Comparation of values acquired by measurement and calculation for EcoDanubit / 1000 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	434,4	1072	907	1072
2	135,6	196	187	324
5	26,5	32	34	47
7	19,3	19	20	26

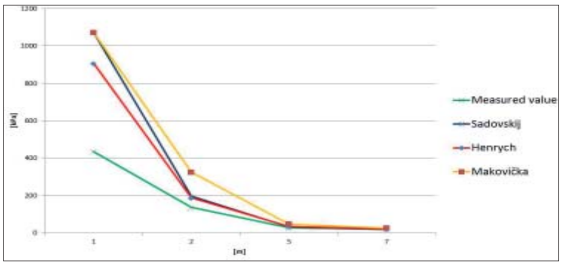

Fig. 4 Graph of actual and calculated course of explosion for EcoDanubit / 1000 g

c) Ostravit / 400 g

Tab. 3 Comparation of values acquired by measurement and calculation for Ostravit / 400 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	195,1	490	428	850
2	61,15	101	102	160
5	14,5	20	20	27
7	9,3	12	12	16

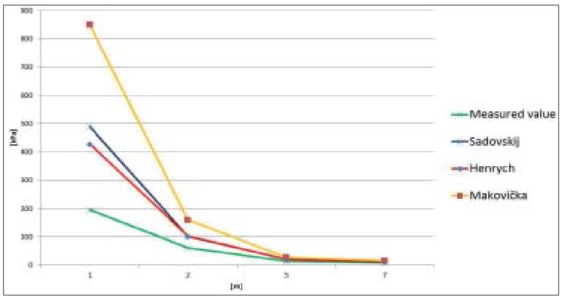

Fig. 5 Graph of actual and calculated course of explosion for Ostravit / 400 g

d) Ostravit / 1000 g

Tab. 4 Comparation of values acquired by measurement and calculation for / 1000 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	234,1	539	467	941
2	66,8	110	110	175
5	15,1	21	22	29
7	8,9	13	13	17

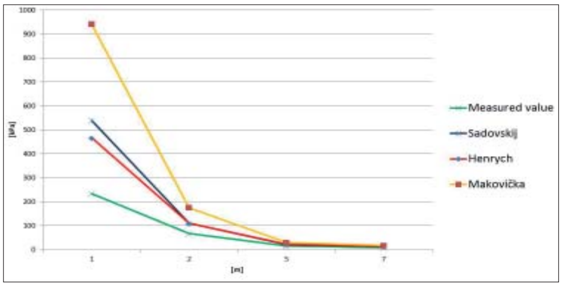

Fig. 6 Graph of actual and calculated course of explosion for Ostravit / 1000 g

e) DAP - 2 / 400 g

Tab. 5 Comparation of values acquired by measurement and calculation for DAP - 2 / 400 g

Distance [m]	Measured value [kPa]	Measured value[1] [kPa]	Calculation		
			Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	91,85	213	422	347	727
2	31,9	53,2	89	90	140
5	7,6	x[1]	18	19	25
7	4,85	x[2]	11	11	15

Legend:

[1] Added priming charge of PlNp - 10 with mass of 5 g.

x[1, 2] Value not assessed because of appearance of measurement anomaly.

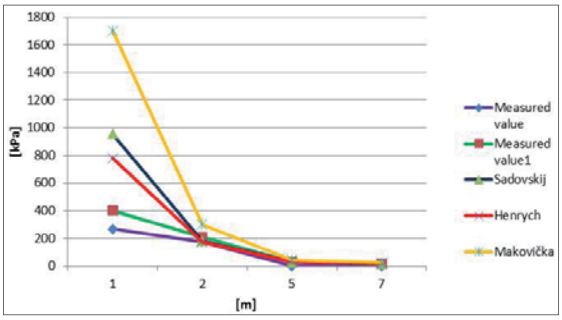

Fig. 7 Graph of actual and calculated course of explosion for DAP - 2 / 400 g

f) DAP - 2 / 1000 g

Tab. 6 Comparation of values acquired by measurement and calculation for DAP -2 / 1000 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	361,1	906	745	1613
2	119	171	165	281
5	19,25	29	30	42
7	11,15	17	18	24

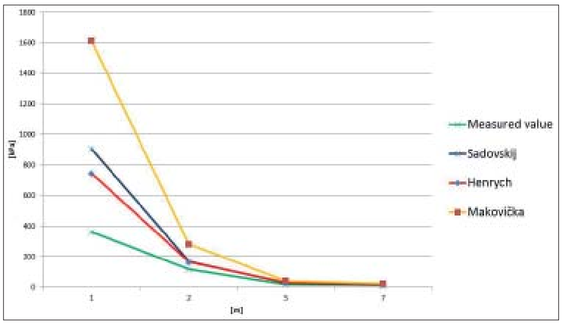

Fig. 8 Graph of actual and calculated course of explosion for DAP - 2 / 1000 g

g) DAP - E / 400 g

Tab. 7 Comparation of values acquired by measurement and calculation for DAP - E / 400 g

Distance [m]	Measured value [kPa]	Measured value[1] [kPa]	Calculation		
			Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	285,15	314,8	454	400	787
2	68,5	71,4	96	96	150
5	14,25	14,7	20	20	26
7	8,7	8,6	12	12	16

Legend:

[1] Added priming charge of PlNp - 10 with mass of 5 g.

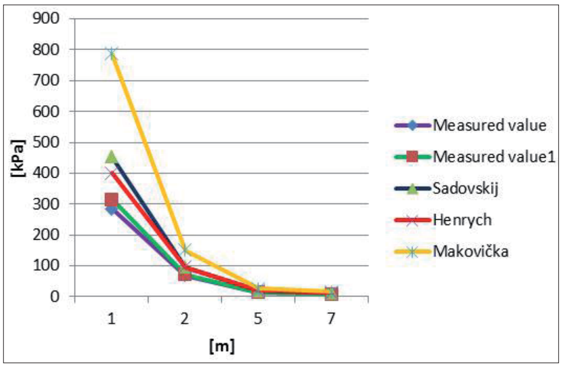

Fig. 9 Graph of actual and calculated course of explosion for DAE - E / 400 g.

h) DAP - E / 1000 g

Tab. 8 Comparation of values acquired by measurement and calculation for DAP - E / 1000 g

Distance [m]	Measured value [kPa]	Measured value[1] [kPa]	Calculation		
			Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	269	402,4	956	782	1705
2	176,2	210,3	183	175	302
5	x[1]	29,3	31	32	44
7	x[2]	16,4	18	19	25

Legend:

[1] Added priming charge of PlNp - 10 with mass of 5 g.

x[1, 2] Value not assessed because of appearance of measurement anomaly.

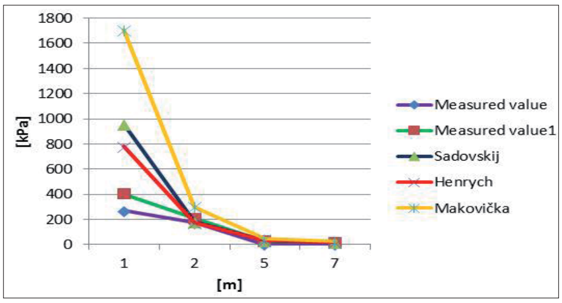

Fig. 10 Graph of actual and calculated course of explosion for DAE - E / 1000 g

i) TNT / 400 g

Tab. 9 Comparation of values acquired by measurement and calculation for TNT / 400 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	215,85	454	400	787
2	75,4	95	96	150
5	19,65	19	20	26
7	14	12	12	16

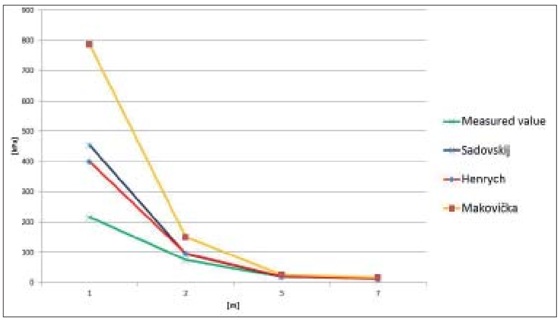

Fig. 11 Graph of actual and calculated course of explosion for TNT / 400 g

j) TNT / 1000 g

Tab. 10 Comparation of values acquired by measurement and calculation for TNT / 1000 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	x^1	956	782	1705
2	x^2	183	175	302
5	48,35	31	32	44
7	34,95	18	19	25

Legend:

$x^{1,2}$ Value not assessed because of appearance of measurement anomaly.

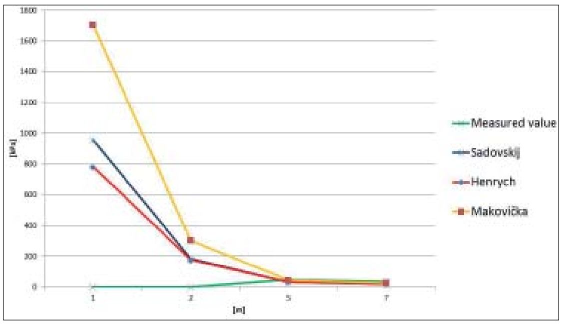

Fig. 12 Graph of actual and calculated course of explosion for TNT / 1000 g

k) PlNp - 10 / 400 g

Tab. 11 Comparation of values acquired by measurement and calculation for PlNp - 10 / 400 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	376,1	426	377	735
2	103,85	90	91	142
5	18	18	19	25
7	14,2	11	11	15

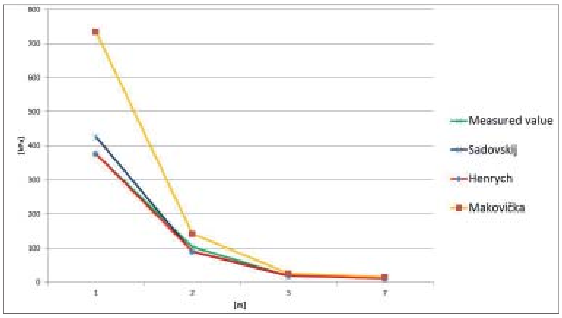

Fig. 13 Graph of actual and calculated course of explosion for PlNp - 10 / 400 g

l) PlNp - 10 / 1000 g

Tab. 12 Comparation of values acquired by measurement and calculation for PlNp - 10 / 400 g

Distance [m]	Measured value [kPa]	Calculation		
		Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička z > 1 [kPa]
1	449,6	916	752	1630
2	336,3	172	166	283
5	39,15	29	31	42
7	28,6	17	18	24

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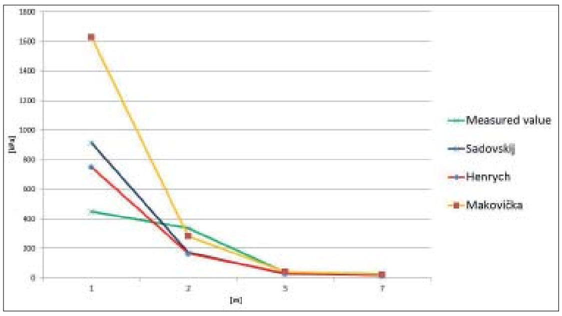

Fig. 14 Graph of actual and calculated course of explosion for PlNp - 10 / 1000 g

Results

By means of comparation of measured and calculated values we were able to conclude that there are relatively large differences between values acquired by mathematical calculations and by measurement. Results of measurements show lower values. The origin of differences between individual results may be subject to factors that are active in the place and time of experiments. Some of these influencing factors may be climatic conditions in time of measurement such as pressure and humidity of the air, climatic temperature, wind force, as well as the method of sensor placement, method of placement and arrangement of explosives, or age period of individual tested samples.

Experimentally measured values are usually lower than values acquired by calculations according to particular authors. Measured values were most frequently approaching the values acquired to Sadovskij's and Henrych's principles. Results of PlNp- 10 (Semtex 10) explosive tests are closest to values acquired by the means of mathematical model according to Makovička. Measured values initiated us to modify the calculation model in such way, that the values calculated would eliminate the determined differences. It was necessary to design the calculation coefficient in such way that:

- acquired values would exhibit lower differences while compared to measured values and
- rule, which refers to necessity of acquirement of higher values than the limiting values induced by the explosion of specific improvised explosive system, would be valid.

It is necessary to accept this rule because of practical utilization in the field, since if it is necessary to set safe boundary or influence of effects that are induced by the shock wave, it is necessary to consider slightly higher values than the actual ones. If we were to accept only the exact actual values, a situation of inaccurate or insufficient determination of required protection level, because explosive used in improvised explosive system may, because of its modification, cause higher effect as the one assumed by us.

Therefore, calculation model according to Sadovskij was selected as a basic starting point (considering the exhibited values were the closest) for the modification of calculation model. During the creation of the original model the author considered placement of explosion in area and above the ground surface. Comparation of values measured and values calculated according to the original calculation model shows significant differences exhibited in measurements in distances of 1 m and 2 m. In other cases (distances of 5 m and 7 m) the differences are not notable and thus we recommend continuing the use of the model for these distances. For distances of 1 - 2 m we proceeded to the modification of the coefficient.

Original coefficient with modification of measurement distances:

$$p_{+} = \frac{0,076}{z} + \frac{0,255}{z^{2}} + \frac{0,650}{z^{3}}$$

for $5 < z \leq 15$

After proposed modification of coefficient for measurement distances of 1 m and 2 m the mathematical relation is as follows:

$$p_{+} = \frac{0,0445}{z} + \frac{0,254}{z^{2}} + \frac{0,490}{z^{3}} \tag{11}$$

for $1 < z \leq 5$

Proposed modification of coefficients is not appropriate for use with the PlNp - 10 explosive. Measured values are higher than the ones acquired by calculation, especially in the distance of 2 m. Therefore we propose the utilization of original coefficient according to Makovička, taking into account the differences between measured and calculated values in distance of 1 m. Results of comparation of values acquired by measurement, by means of original mathematical models and modified mathematical model in distance of 2 m from the explosion epicentre are stated in Tab. 13 and Fig. 15.

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Tab. 13 Comparation of values acquired by measurement, by means of original mathematical models and modified mathematical model in distance of 2 m from explosion epicentre

Name of explosive	Measured value	Measured value + priming	Modification of coefficient	Sadovskij 1 < z < 15 [kPa]	Henrych 1,00 < z < 10,0 [kPa]	Makovička [kPa] z > 1
EcoDanubit 400 g	61,15	-	99	101	102	160
EcoDanubit 1000 g	135,6	-	189	196	187	324
Ostravit 400 g	24,6	-	58	60	62	91
Ostravit 1000 g	66,8	-	107	110	110	175
DAP - 2 400 g	31,9	53,2	87	89	90	140
DAP - 2 1000 g	119	-	165	171	165	281
DAP - E 400 g	68,5	71,4	93	96	96	150
DAP - E 1000 g	176,2	210,3	176,5	183	175	302
TNT 400 g	75,4	-	93	95	96	150
TNT 1000 g	x[1]	-	177	183	175	302

Legend:

x[1] Value not assessed because of appearance of measurement anomaly.

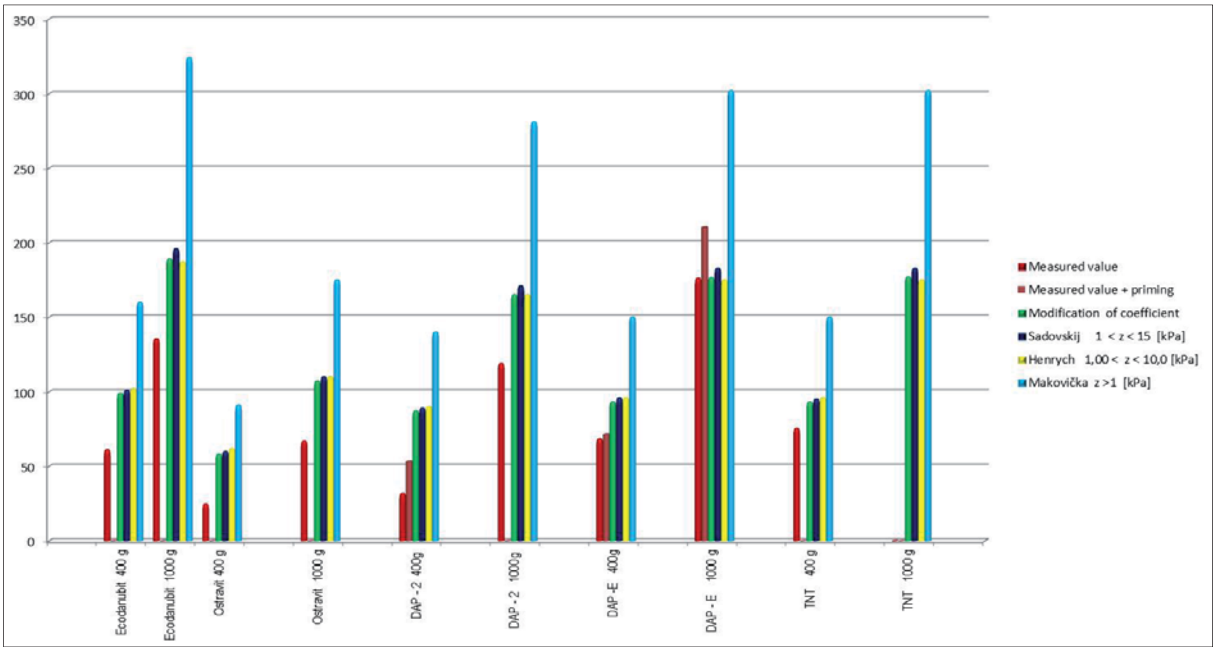

Fig. 15 Graph depicting values acquired by measuring, by means of original mathematical models and modified mathematic model, in distance of 2 m from the explosion epicentre

Conclusion

The modification of coefficient allowed us to eliminate the differences to some extent and to approach the values acquired by measuring. The modification and determination of coefficient for calculation model should respect all values in assessed distances. They should not exhibit lower values than the values acquired by measuring. It was possible to observe higher values of overpressure while using the explosives DAP - 2 a DAP - E and priming charges. As we verified by experiment, improvised explosive system is able to react even without this priming charge. When taking into account improvised explosive systems with higher mass, it is possible to assume the use of priming, which will also lower the probability of failure.

In the course of the experiment, individually placed sensors simulated the ordinary environmental conditions. The individual sensors represented possible objects that were affected by the shock wave effects. Measured results allow us to determine scope of injuries of persons in particular distances from the explosive. Value of 200 kPa is considered to be the limit of threat to human life. This limit (in distances of 1 m and 2 m) is reached and, in some cases, surpassed by nearly all tested samples with mass from 1 kg. If the construction of improvised explosive system was modified by adding items of daily use (such as bolts, nails, steel balls, etc.), the level of possible damage to the human organism and also the effect on environment could be significantly raised, even multiplied.

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