# AN ANALYSIS OF AN EXPLOSIVE SHOCK WAVE IMPACT ONTO MILITARY VEHICLES OF CONTEMPORARY WARFARE

**Piotr Saska**

*Gen. Tadeusz Kościuszko Military Academy of Land Forces*
*Division of the Military Engineering*
*Czajkowskiego Street 109, 51 - 150 Wrocław, Poland*
*tel.: +48 71 7658155*
*e-mail: piotrsaska@wp.pl*

**Edyta Krzystała**

*Silesian University of Technology*
*Department of Mechanical Engineering*
*Konarskiego Street 18 A, 44 -100 Gliwice, Poland*
*Tel.: +48 32 2372847, fax: +48 32 2371309*
*e-mail: Edyta.Krzystala@polsl.pl*

**Arkadiusz Mężyk**

*Silesian University of Technology*
*Department of Mechanical Engineering*
*Konarskiego Street 18 A, 44 -100 Gliwice, Poland*
*Tel.: +48 32 2372847, fax: +48 32 2371309*
*e-mail: Arkadiusz.Mezyk@polsl.pl*

***Abstract***

*Landmines and improvised explosive devices (IED) are the basic weapon used by the rebels against the Coalition forces in Afghanistan and Iraq. It is estimated that about 50% of the casualties (wounded and killed) among the soldiers from the US and other countries participating in both conflicts are caused by explosive charge. Introduction of vehicles providing proper protection of the crew against an explosive shock wave generated by a detonation of mines and improvised explosive devices into the arsenal has become one of the priorities of modernization of armed forceps. The parameters critical to the emerging of a hazard for the surrounding includes the overpressure impulse and the shock wave overpressure. The problem of defining the parameters of an explosive shock wave generated after detonation of charges of various mass, shape and physical-chemical properties is a subject of studies at much scientific institution. The gained quantitative data are not, however, published in public reports, thus a need of performing one's own experimental and numeric research arise. The goal of these studies is to find solutions increasing soldier's safety at the battlefield. The paper presents an analysis of impact of a shock wave onto structures of military vehicle. Furthermore, methods of experimental definition of explosion shock wave parameters were presented and conclusions for the needs of further experimental-numerical studies were formulated.*

***Keywords:*** *shock wave, military vehicle, landmine and IED protection, experimental researches,*

## 1. Introduction

Use of explosive devices as a basic weapon against an enemy with technological advantage is a distinctive feature of the so-called asymmetrical warfare of the beginning of $21^{st}$ century. Wars in Iraq and Afghanistan are the most known conflicts of this type. NATO armies participating in warfare in both countries, despite their technological domination in terms of equipment and weaponry, suffer relatively high losses due to explosions of landmines and improvised explosive devices (IED). The tactics employed by the terrorist groups, focusing on irregular, guerrilla-type actions, targeting mainly moving vehicles and their crews made the introduction of vehicles, that provide their personnel protection from the explosive shock wave generated by landmines and improvised explosive devices a primary goal for the countries militarily involved in Iraq and Afghanistan. The influence of a shock wave onto structures of military vehicles is a subject of research at numerous scientific centres. In recent years, this research has been intensified due to constantly increasing number of casualties suffered by NATO armies.

## 2. An analysis of explosion impact onto vehicles and their crews

Terrorist groups combating the coalition forces in Iraq and Afghanistan take actions only on their own terms, in favourable conditions, often by surprise. The tactics employed by the terrorist groups, focusing on irregular, guerrilla-type actions, targeting mainly moving vehicles and their crews made the introduction of vehicles, that provide their personnel protection from the explosive shock wave generated by landmines and improvised explosive devices a primary goal for the countries militarily involved in Iraq and Afghanistan. During a few years of warfare in Iraq and Afghanistan, the number of attacks with the use of landmines and improvised explosive devices against the coalition forces has been increasing fast. As a result, many coalition soldiers have been killed or wounded (fig. 1).

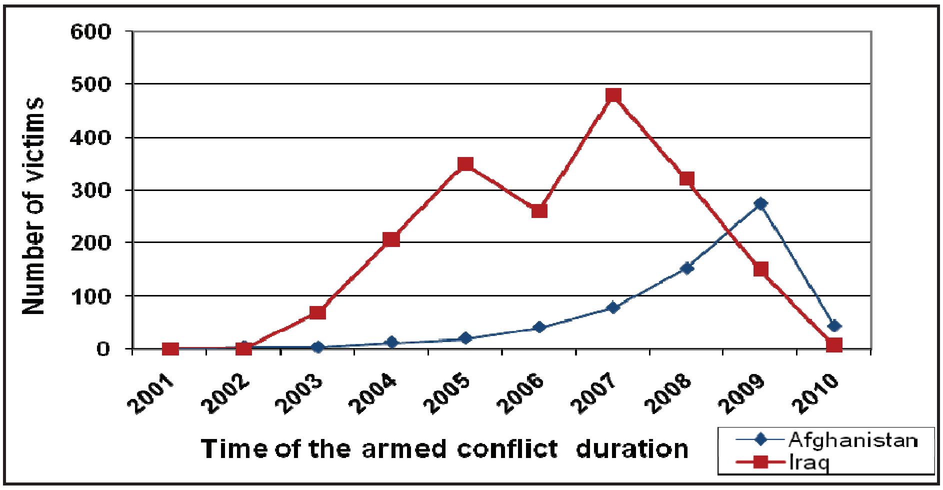



*Fig. 1. Number of the coalition forces' soldiers killed in Iraq and Afghanistan due to explosions of IEDs and other explosive charges between 2001-2010 (based on [9], [11], [26])*

Structures of military vehicles used in the area of combat are exposed to the risk of shock wave generated by explosions of landmines and improvised explosive devices under the wheels, under the frame and from the sides of the vehicle. Such hazards forced definition of specific requirements in terms of the ballistic protection, for armoured vehicles used by armed forces (Fig. 2). These requirements are defined by the STANAG 4569 standardization agreement [20].

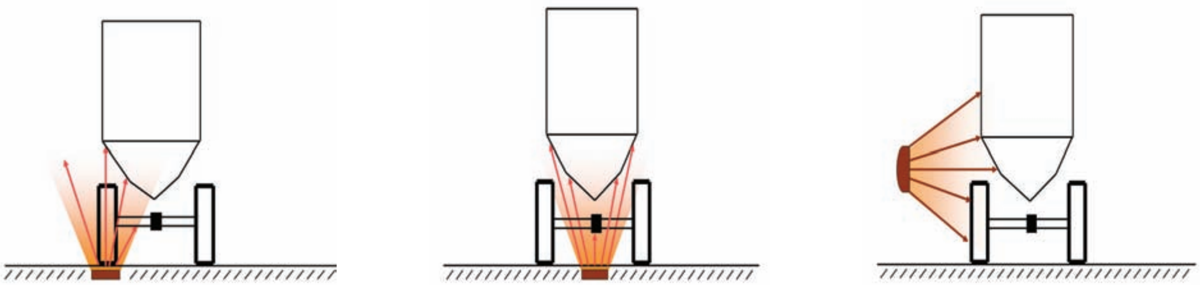


*Fig. 2. Requirements of mine resistance and shrapnel resistance according to the STANAG 4569 standardization agreement*

The military demand for vehicles resistant to explosive charges led to the creation of Mine Resistant Ambush Protected (MRAP) program in the USA in the beginning of 2007. As its result, the US forces and armies of other countries have received a relatively numerous line of vehicles, divided into three groups (categories):

- Group I – Light vehicles on a wheel chassis, 4x4 (RG-31, Cougar 4x4, MaxxPro RG-31 Cougar, MaxxPro), resistant to explosions of a 7kg charge below the frame and 14kg charge below the wheel (Fig. 3a);
- Group II – Vehicles on a wheel chassis, 6x6 (RG-33, Mastiff), resistant to explosions of a 14kg charge below the frame and 21kg charge below the wheel (Fig. 3b);
- Group III – Heavy vehicles on a wheel chassis, 6x6 (Buffalo), used by specialized engineer patrols, resistant to explosions of a 21kg charge below the frame and 21kg charge below the wheel (Fig. 3c) [5], [15].

a) b) c)

*Fig. 3. MRAP vehicle examples: a) MaxxPro, b) RG - 33L, c) Buffalo [ 27, 28, 29]*

Introduction of the mine resistant vehicles into the equipment of armies combating in Afghanistan and Iraq has significantly decreased the number of casualties among the soldiers taking part in action (Fig. 4).

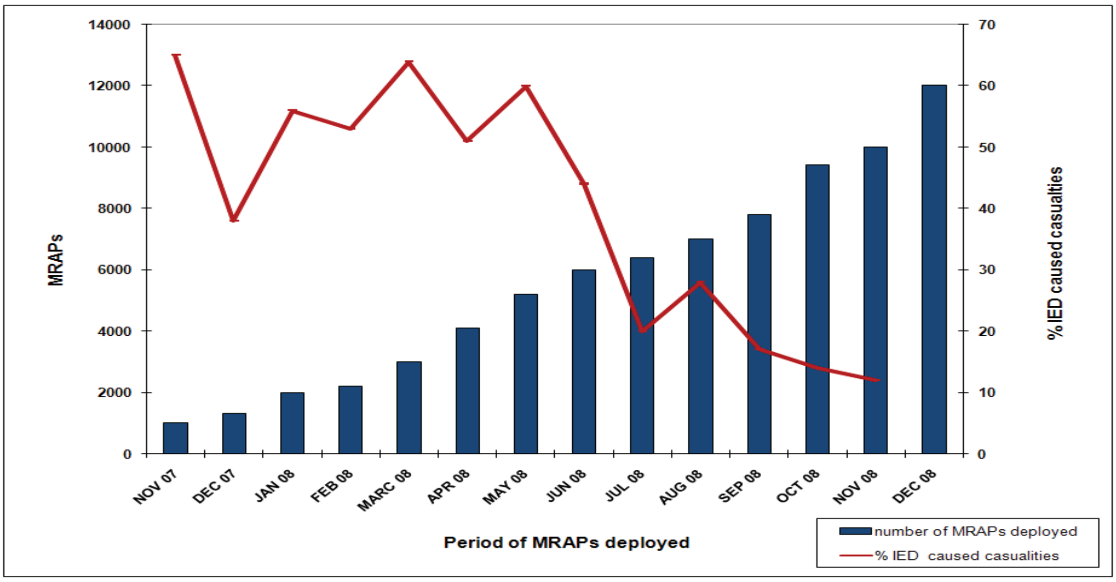



*Fig. 4. Influence of introduction of mine resistant vehicles on the decrease of casualties among the soldiers (basing on [16])*

The most numerous MRAPs are those of category I. The leading model, RG-31 is manufactured by the South African company - Land Systems OMC and Couguars manufactured by the Force Protection [5]. On 17$^{th}$ November 2008 these vehicles were deployed as a part of the

Polish Military Contingent Afghanistan [15]. From the moment of their deployment the Cougars have taken over most of the tasks formerly performed by HMMWV. During the period from November 2008 until April 2009, they have been attacked thrice by means of improvised explosive device. The explosion of a charge of an estimated mass between 5 and 8kg under the front axle was the most dangerous one. The explosion caused breaking off the mudguards with the air filter, and pneumatic system and ABS were damaged. Despite a relatively minor damage, it was impossible to continue the travel, but it was possible to tow the vehicle. The second incident involved an explosion of an IED probably composed of several mortar shells and an antipersonnel mine – the total of ca 2kg of explosive. The explosion pierced the right front tire. Another incident, with explosion of several kilograms of explosives under the vehicle did not cause any damage [15]. In all three cases no soldiers were killed, that proves to be the greatest advantage of the Cougar construction, able to protect the crew against explosions of much heavier charges.

## 3. Characteristics of shock wave parameters

Parameters of a detonation shock wave are the primary characteristics of an explosive material. The shock waves are the *leitmotif* of the hydrodynamic detonation wave theory. They are the main descriptive source for all phenomena accompanying explosions and their impact onto the surroundings [25]. A shock wave is generated as a result of a process of a detonation of an explosive charge. During this process, a zone of heated gaseous products is created around the source of explosion, and their pressure significantly (from several dozen to several hundred times) exceeds the values of surrounding pressure prior to the detonation. The gases, moving with ultrasonic speed, propagate along the direction from the explosion centre, in a form of a wave of high temperature, density and pressure [17]. The gaseous products depressurize behind the wave front and their pressure drops smoothly, resulting in the drop of the gas speed [17]. The model sequence of the pressure value changes is shown at Fig. 4.

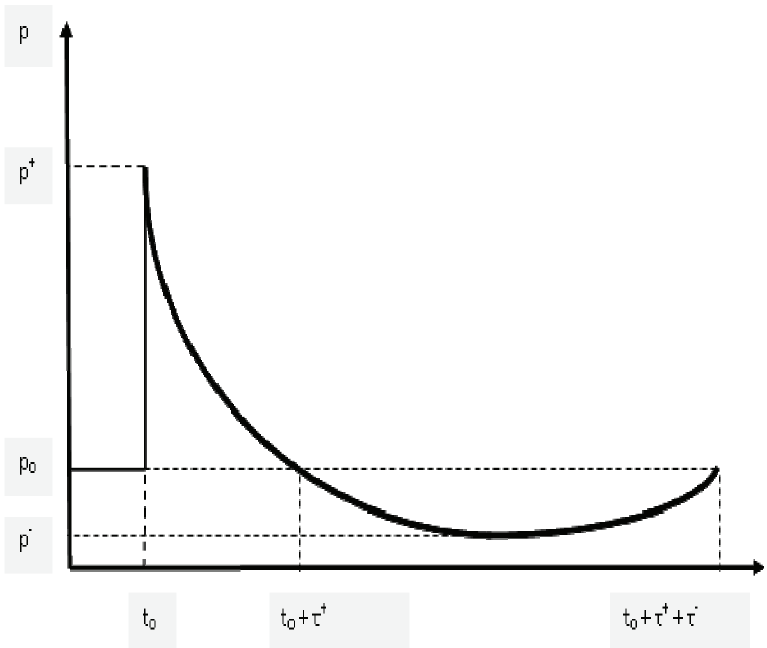



*Fig. 5 The sequence of pressure value change in time [19]*

The primary parameters of an explosive shock wave, defining its mechanical impact, include:

- maximum overpressure at the shock wave front $\Delta p^+ = p^+ - p_0$;
- maximum negative pressure of the shock wave $\Delta p^- = p_0 - p^-$;
- duration of the positive impulse phase $\tau^+$;
- duration of the negative impulse phase $\tau^-$ [14,];

Additionally the characteristics of a shock wave are supplemented by the definition of the positive and negative pressure impulse, being integrals of overpressure and negative pressure after time [6]:

$$I^{+} = \int_{t_0}^{t_0+\tau^{+}} [p(t) - p_0]dt\,, \tag{1}$$

$$I^{-} = \int_{t_0+\tau^{+}}^{t_0+\tau^{+}+\tau^{-}} [p_0 - p(t)]dt\,. \tag{2}$$

Parameters of a shock wave influencing emergence of hazards to the surroundings include the overpressure impulse and the shock wave overpressure. Loading of a real system with a shock wave causes a change in distribution of stresses in its structure, resulting in deviations from the balance or generating system deformation. Due to a complex composition of real systems and analysis of dynamics of stress changes in a structure is generally unobtainable. It is, however, possible to define the maximum allowed deflection from the balance in relation to the value of applied load and time of its application [14].

While considering the destructive impact of a shock wave against a given structure three action zones must be distinguished:

- close explosion zone ($\lambda < 1$),
- mid explosion zone ($1 \leq \lambda \leq 10$),
- far explosion zone ($\lambda > 10$) [6, 14].

According to the Sachs' law, the functions of a nondimensinal distance of $\lambda$ are the nondimensinal pressure $p_s$ and the shock wave impulse $I_s$, defined as:

$$\lambda = \frac{r \cdot p_0^{1/3}}{E^{1/3}}\,, \tag{3}$$

$$p_s = \frac{\Delta p^{+}}{p_0}\,, \tag{4}$$

$$I_s = \frac{I^{+} \cdot c_0}{E^{1/3} \cdot p_0^{2/3}}\,, \tag{5}$$

where:
$r$ – is a distance from the explosion centre,
$E$ – is the explosion energy, MW,
$p_0$ – is the initial pressure of the medium,
$c_0$ – is the speed of sound.

Many studies introduce the notion of relative distances, called also the reduced distance $\overline{R}$, allowing comparison of pressures for different masses of explosive charges and various distances [17], [19]:

$$\overline{R} = \frac{r}{m^{1/3}}\,, \tag{6}$$

where:
$r$ – is the distance from the explosion centre [m],
$m$ – is the mass of the explosive charge [kg].

The Sachs' law does not apply to the close explosion zone, where the distances are close to the size of the charge ($\lambda < 1$), the movement of the shockwave is influenced by the shape of the charge and the location of the initiating point [17]. For the mid and far explosion zones numerous empirical and asymptotic formulas exist, enabling calculation of the overpressure at the explosive wave front. In the papers [8] and [21] Broda's equations were used for calculation of the maximum overpressure generated in the air after detonation of TNT:

$$\Delta p^{+} = 1.38\overline{R}^{-1} + 0.543\overline{R}^{-2} - 0.0035\overline{R}^{-3} \text{ for } 0.05 \le \overline{R} \le 0.3 \text{ m/kg}^{0.33},$$

$$\Delta p^{+} = 0.607\overline{R}^{-1} + 0.032\overline{R}^{-2} + 0.209\overline{R}^{-3} \text{ for } 0.3 \le \overline{R} \le 1.0 \text{ m/kg}^{0.33},$$

$$\Delta p^{+} = 0.065\overline{R}^{-1} + 0.397\overline{R}^{-2} + 0.322\overline{R}^{-3} \text{ for } 1.0 \le \overline{R} \le 10.0 \text{ m/kg}^{0.33}, \tag{7}$$

where:

$\Delta p^{+}$ - is the maximum overpressure in [MPa],

$\overline{R}$ - is the reduced distance in [m/kg$^{0.33}$].

In case the explosive charge is set on a firm ground (soil, concrete), the TNT mass assumed for the calculation is doubled in relation to the real mass [21]. Other empirical formulas for calculation of a shock wave have been proposed by Henrych [6], [8]:

$$\Delta p^{+} = 14.071\overline{R}^{-1} + 5.5397\overline{R}^{-2} - 0.03572\overline{R}^{-3} + 0.00625\overline{R}^{-4} \text{ for } 0.05 \le \overline{R} \le 0.3 \text{ m/kg}^{0.33},$$

$$\Delta p^{+} = 6.1938\overline{R}^{-1} - 0.3262\overline{R}^{-2} + 2.1324\overline{R}^{-3} \text{ for } 0.3 \le \overline{R} \le 1.0 \text{ m/kg}^{0.33},$$

$$\Delta p^{+} = 0.662\overline{R}^{-1} + 4.05\overline{R}^{-2} + 3.88\overline{R}^{-3} \text{ for } 1.0 \le \overline{R} \le 10.0 \text{ m/kg}^{0.33}, \tag{8}$$

The value of a shock wave of TNT detonated on a ground surface can be also defined basing on Sadowski's formulas [17]:

$$\Delta p^{+} = 0.95\overline{R}^{-1} + 3.9\overline{R}^{-2} + 13\overline{R}^{-3} \text{ for } 1.0 \le \overline{R} \le 10.0 \text{ m/kg}^{0,33}. \tag{9}$$

Similar methods are used to define the overpressure impulse - the second value characterizing the shock wave and influencing emergence of hazards for real system. For TNT detonated in the air the impulse value can be calculated basing on Sadowski's (10) and Henrych's (11) formulas [17]:

$$\frac{I^{+}}{m^{1/3}} = 350\overline{R}^{-1} \text{ for } \overline{R} > 0.5,$$

$$\frac{I^{+}}{m^{1/3}} = 150\overline{R}^{-1} \text{ for } \overline{R} < 0.25, \tag{10}$$

$$\frac{I^{+}}{m^{1/3}} = 660 - 11150\overline{R}^{-1} + 6290\overline{R}^{-2} - 1004\overline{R}^{-3} \text{ for } \overline{R} \in [0.4;\, 0.75],$$

$$\frac{I^{+}}{m^{1/3}} = -322 + 2110\overline{R}^{-1} - 2160\overline{R}^{-2} + 801\overline{R}^{-3} \text{ for } \overline{R} \in [0.75;\, 3], \tag{11}$$

where:

$I^{+}$ - overpressure impulse in [Pa·s],

*m* – mass of the explosive charge in [kg],
$\overline{R}$ - reduced distance in [m/kg$^{0.33}$].

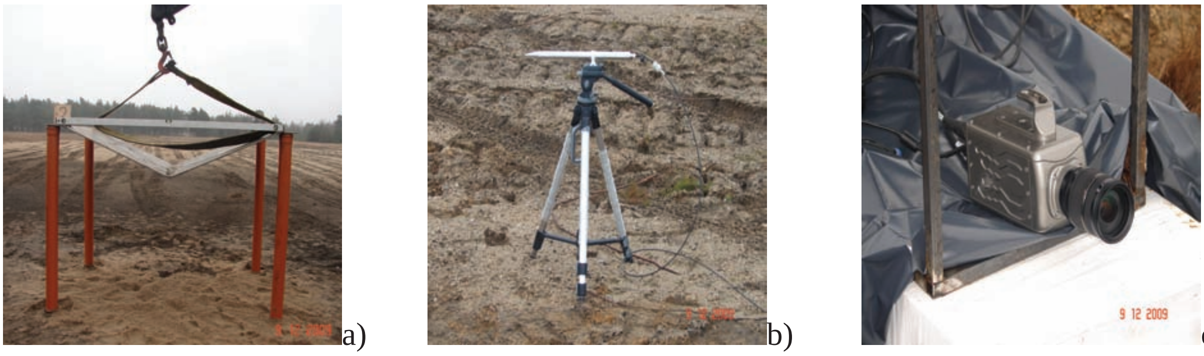
## 4. Methods of experimental definition of parameters of an explosive shock wave

### 4.1 Methods utilizing pressure, acceleration and displacement sensors

Pressure sensors are relatively frequently used during range tests, focusing on measuring of parameters of a shock wave generated during detonation of various types of explosive. Linked with sufficiently fast recorders they allow to define the change of the medium pressure in time, resulting from the passage of a wave in a chosen point of space [18]. Pressure sensors can be divided into two groups:

- incident wave pressure sensors, measuring the pressure of an undisturbed wave freely passing the sensor,
- reflected pressure sensors, usually mounted into a flat surface onto which the wave ram effect takes place [18].

Acceleration sensors are another group of measuring devices used for measurements of shock wave. They work basing on a principle of the phenomenon of communicating the pressure impulse by the shock wave onto the loaded object's surface. This method is effective during the measurement of the reflected wave impulse [12], [24]. Displacement sensors are used for definition of characteristics of a reflected shock wave. Their use allows to measure a deflection of a structure loaded by a shock wave. Results of this measurement equally depend on the wave itself, and on the properties of the loaded structure. This method was described in the paper [7]. Figures 5a), 5b), 5c) present a scheme of a measurement station for initial range tests.




a) b) c)

*Fig. 6. Experimental measurements of the characteristics of an explosive shock wave: a) tested deflector, b) pressure sensor, c) ultra-fast optical camera*

### 4.2 Optical methods

Optical methods are relatively frequently used for definition of shock wave characteristic. These methods allow precise measurements from a safe distance, which is especially important in case of detonation of high-mass explosive charge. In this method ultra-fast optical cameras (Fig. 5c) are used. They allow to measure the displacement and the deformation of an object loaded with a shock wave in many points at the same time. Additionally speed and linear and angular acceleration can be measured basing on the analysis of visual information. The use of high-speed cameras is discussed in the paper [9].

In some scientific centres (such as the Polish Military University of Technology, WAT) the method of laser roentgenography is used for the studies of explosion phenomena and propagation of shock weep. This method enables a series of photos of an object loaded with a shock wave. The potential to use this method at a close distance to the performed explosive charge test, without a risk of blurring due to the pollution and non-transparency of the environment, is its advantage. The use of the impulse roentgenography was presented in the papers [22], [23].

### 4.3 Use of a ballistic pendulum

Definition of pressure impulse and kinetic energy transferred as a result of charge explosion is the basic function of a ballistic pendulum during the studies of shock wave characteristic. The energy released as a result of a detonation of an explosive material causes deflection of the pendulum with an attached plate. The plate is loaded with shock wave and it is attached to the pendulum arm in a way transforming the energy of the wave first into kinetic energy of the pendulum, and subsequently into potential energy. Maximum deflection angle of the pendulum arm is the basic measured parameter [4].

Ballistic pendulums appear in two variants:

- vertical pendulum – shock wave propagates in horizontal direction, causing deflection of the pendulum arms upwards, along an arc.
- horizontal pendulum – shock wave propagates in vertical direction, loading a plate placed horizontally at a defined height above the ground [3, 4].

## 5. Summary

The problem of impact of a shock wave onto military vehicles is a complex one. Its solution requires knowledge of numerous issues from the field of shock wave theory and its influence on real object. Experimental studies and range tests allowing identification of wave parameters and verification of theoretical assumptions are the most important issues in case of an analysis of a shock wave impact onto special vehicle. Gaining knowledge about the loads of structures of special vehicles used in contemporary warfare becomes a key issue for further development of protection of vehicles against landmines and improvised explosive devices.

Basing on range studies of the characteristics of a shock wave, with measurements of pressure and deflection of the plate loaded by the explosion further experimental researches are planned. Experimental study results will be used as initial data for further numerical studies.

While commencing further experimental studies one must consider the following conclusions:

1. Characteristics of explosive shock wave depend not only on the shape of the explosive charge but also on its distance and placement (on the ground surface, underground, ground type – sandy, clayey),
2. In case the wave rebounds on an obstacle it creates a ram effect and pressure value can multiply (pressure value depends on the angle of incidence onto the loaded structure),
3. Values of pressure reflected from a plate with a surface parallel to the explosive charge are reflected by numerical solutions gained for a spherical charge.

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### References:

[1] Barnat, W., Niezgoda, T., *Analiza wpływu kształtu struktur ochronnych na ich energochłonność*, Journal of KONES Powertrain and Transport, 14/2007.

[2] Borkowski, W., Rybak, P., Hryciów, Z., *Badania struktur ochronnych wozów bojowych obciążonych wybuchem*, Journal of KONES Powertrain and Transport, 14/2007.

[3] Fišerová, D., *Numerical analyses of buried mine explosions with emphasis on effect of soil properties on loading*,Cranfield 2006.

[4] Enstock, L. K., Smith, P. D., *Measurement of impulse from the close-in explosion of doped charges using a pendulum*, International Journal of Impact Engineering, pp. 487–494.

[5] Garstka J., *Czy MRAP-y zastąpią LOSP-y*, Bellona, 1/2009, pp. 162.

[6] Gelfand, B., Silnikov M., *Blast effect caused by explosions*, London 2004.

[7] Guruprasad, S., Mukherjee, A., *Layered sacrificial claddings under blast loading Part II experimental studies*, International Journal of Impact Engineering; 24/2000, pp. 975-984.

[8] Henrych, J., *The dynamics of explosion and its use*, Prague 1979.

[9] Livingston, I. S., Messera, H. L., O'Hanlon, M., *Reconstruction & Security in Post-9/11 Afghanistan,* [online]. [access: 20.03.2010]. http://www.brookings.edu/~/media/ Files/Programs/FP/afghanistan %20index/index.pdf

[10] Iluk, A., *Porównanie dwóch koncepcji pojazdu minoodpornego opartego na komercyjnym podwoziu*, V Konferencja Odporność Udarowa Konstrukcji 2009

[11] *Iraq Index, Tracking Variables of Reconstruction & Security in Post-Saddam Iraq,* [online]. [access: 20.03.2010]. Accessible on the Internet: http://www.brookings.edu/saban/ ~/media/Files/ Centers/Saban/Iraq%20Index/index.pdf

[12] Jacinto, A. C., Ambrosini, R. D. Danesi, R. F., *Experimental and computational analysis of plates under air blast loading*, "International Journal of Impact Engineering 25/2001 pp. 927-947.

[13] Kolenda, J., *Stanowiska do badania energochłonności osłon*, Zeszyty Naukowe Akademii Marynarki Wojennej, nr 2/2009, pp. 33.

[14] Kuczaj, A. K., *Modelling of detonation products scattering from a cylindrical explosive charge*, [online]. [access: 20.03.2010]. Accessible on the Internet: http://www.kuczaj.pl /pages/msc/akuczaj_MastersThesis.pdf

[15] Kupidura, P., *Charakterystyka pojazdów MRAP Cougar oraz wnioski z ich eksploatacji w WP*, Problemy Techniki Uzbrojenia 2/2009 pp. 21.

[16] Lamb, Ch. J., Schmidt, M. J., Fitzsimmons, G. B., *MRAPs, Irregular Warfare, and Pentagon Reform,* New York 2009.

[17] Machowicz, M., *Oddziaływanie powietrznej fali uderzeniowej na otoczenie* Górnictwo i geoinżynieria, 3/2005, pp. 18.

[18] Rosenkiewicz D., *Określenie dynamiki wybuchu środków pirotechnicznych*, praca naukowo-badawcza, Wrocław 2005.

[19] Smith, P. D., Hetherington, J. G., *Blast and ballistic Loading of Structures*, Oxford 2003.

[20] Szudrowicz, M., *Skuteczność opancerzenia pojazdów*, Biuletyn WITU, 94/2005, pp. 80.

[21] Trzciński, W. A., Paszula, J., Trąbiński, R., *Badanie charakterystyk fali podmuchowej generowanej detonacją cylindrycznego ładunku kruszącego materiału wybuchowego,* Biuletyn WAT, 2/2003, pp. 46.

[22] Trzciński, W. A., Trębiński, R., Cudziło, S., *Investigation of the behavior of steel and laminates fabric plates under blast wave load. Part I – Experimental approach,* "Biuletyn WAT, 2-3/2005, pp. 6.

[23] Trzciński, W. A., Trąbiński, R., Cudziło, S., Badanie reakcji osłon balistycznych na obciążenie falą podmuchową i odłamkami. Część II. Analiza wyników badań, "Biuletyn WAT, 5-6/2005, pp. 39.

[24] Trzciński, W. A., Rekrucki, R., Janiszewski *J., Badanie reakcji płyt laminatowych i stalowych na falę podmuchową*, Biuletyn WAT 2/2003, pp. 97.

[25] Włodarczyk, E., *Podstawy detonacji cz. 1*, Warszawa 1995, pp. 35.

[26] [online]. [access: 20.03.2010]. Accessible on the Internet: http://icasualties.org/OEF/ index.aspx

[27] [online] [access: 20.03.2010]. Accessible on the Internet http://www.defenseindustrydaily.com/images/LAND_MRAP_MaxxPro_CAT-I_Camp_Liberty_Iraq_lg.jpg
[28] online] [access: 20.03.2010]. Accessible on the Internet http://www.globalsecurity.org/military/systems/ground/images/mrap_071111_sod_hi_mnfi.jpg
[29] online] [access: 20.03.2010]. Accessible on the Internet http://www.globalsecurity.org/military/systems/ground/images/mrap-iii_070827-f-9136o-206.jpg