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STUDY AND EXPERIMENTAL RESEARCH ON BALLISTIC PROTECTION SCREEN

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Abstract: Improvised Explosive Devices are presently a common threat to both civilians and military personnel. One of the best methods to mitigate the blast wave and propelled fragments is by using various protective panels such as water screens.
The purpose of this paper is to evaluate the thickness of the water layer necessary to provide a good level of protection against fragments resulted from an explosion either deliberate or accidental. Therefore, were done experiments and performed numerical simulations which had conduced to the fact that we can assure ballistical protection against explosive devices effects using a water screen having the thickness at least 150 mm.
Key words: water screen, Gurney method, quantitative experimental evaluation, lethal energy, numerical modelling.

1. INTRODUCTION

The increasing threat of Improvised Explosive Devices (IED) is a stimulus for researchers to seek methods that will offer protection against the blast waves and fragments resulted from explosion.
Water-filled structures are capable of providing a high level of protection to people and property against IED witch are presently a common threat to both civilians and military personnel.
Tests have demonstrated that water can reduce the blast pressures associated with an explosive event by as much as 95%. The velocity of fragments produced by an explosion and passing through a water layer is also dramatically reduced by 100%.
To model the non-linear impact and penetration phenomena involving large strains and deformations, plasticity, fracture and flow are used engineering simulation software.
ANSYS AUTODYN software is a versatile explicit analysis tool for modelling the nonlinear dynamics of solids, fluids, gases and their interactions, including shock waves, explosive devices, fragmentation and ballistic penetration [1].
D.J. Milner in [5] presents both laboratory experiments and numerical simulations using AUTODYN-2D in order to study how the velocity changes in a water layer. Thus, the tests show that for a 1 mm diameter stainless steel 420 projectile impacting into a 5 mm deep water layer, the projectile velocity is reduced from 5.49 km/s at entry to 1.72 km/s.
On the other hand, the numerical simulations show that, for a 1 mm diameter stainless steel 420 projectile into a 5 mm deep water layer at 5 km/s, the projectile slowed to 1.2 km/s by the time it reached the basement. The results are in good agreement with the laboratory data.
In the first part of this paper it was presented the experimental research on water screens used as protective panels against propelled fragments from detonation of explosive configuration.
In the second part, using the AUTODYN hydrocode with Euler and Lagrange solvers, it was performed 2D numerical simulations of impact and penetration of a fragment on water layer by different thicknesses.
The initial velocity of the fragment it was predicted using the Gurney method.

2. EXPERIMENTAL RESEARCH

IEDs can rely on natural fragmentation, such as pipe bombs with metal casing, or preformed fragments, such as nail bombs (ball bearings, nail heads, broken razors, darts and bits of metal), to kill or injure people near the device.
The purpose of the experimental research was to evaluate the water layer thickness in order to mitigate the initial kinetic energy of the fragments resulted from the detonation of the explosive charge below the lethal energy.
Therefore, two tests were realised using water screens of different thicknesses. The thickness of the water layer is set up to: 100 mm, 150 mm, 200 mm and, respectively, 250 mm.
The residual energy resulted from the passing of fragment through the water screen was evaluated depending on balls effect on the fir tree wood witness screen having the thickness equal to 20mm.
According with AASTP-1, „Manual of NATO Safety Principles for the Storage of Military Ammunition and Explosives” the fragment energy to pass through a fir tree wood witness screen having 20mm thickness is evaluated to E_{cr} = 79J.

Table 1. Characteristics of experimental configurations

No. test	Type of configuration	Explosive			Fragment		
		Type	Mass [g]	Dimensions [mm]	Shape	Mass [g]	Dimensions [mm]
1.	cylindrical	HITEX	200	D = 50 H = 65.5	spherical	1.05	D = 6.35
2.							

2.1 Equipment, devices and materials

For the experimental study were used the following equipment, devices and materials:

a) to realise experimental explosive configuration:

- cylindrical explosive charge: HITEX (plastic explosive based on hexogen - RDX)
  - density: 1.55 – 1.58 g/cm^3;
  - detonation velocity: 7860 m/s;
  - critical diameter: 2 mm
- preformed metal fragments: steel balls
  - density: 7.83 g/cm^3;
  - total number: 240.

The experimental explosive configuration (figure 1) was initiated by an electrical detonator.

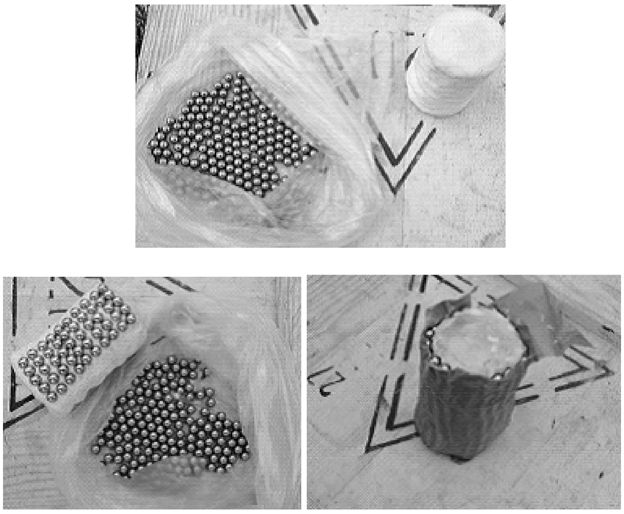


Fig. 1. Cylindrical explosive configuration

b) to build the protective screen: water, wood fibre panels and polyethylene bags.

The detonation of explosive charge and the propulsion of balls were recorded using Mega Speed Camera which is designed for industrial and scientific research applications. Terefore, after the “FIRE” command, immediately started the recording at 2500fps. After each test, a digital camera Nikon D80 was used to take pictures.

Also, in experiments it was used witness screens built from ammunition boxes. The ammunition boxes, initially designed for safe transport and storage of ammunition, are made of fir tree wood having the thickness of each side equal to 20mm.

The arrangement of the protective screens and explosive configuration in the first experiment is shown in figure 2.

Fig. 2. Arrangement of water screens and explosive configuration on the first experiment

2.2 Results

Figures 3 and 4 show the propulsion effects on the fir tree wood witness panel situated behind the water screen with 10cm and, respectively, 15cm thickness.

Fig. 3. Propulsion effects behind water screen with 10cm thickness

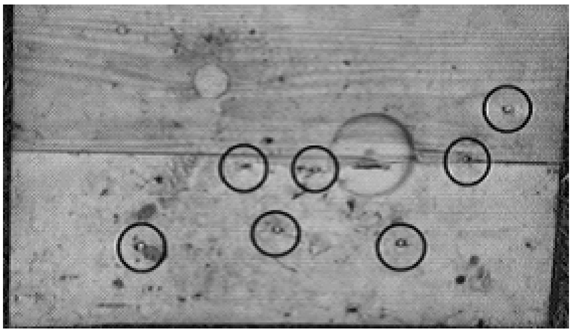


Fig.4. Propulsion effects behind water screen with 15 cm thickness

After the tests were done, the results were analysed for each water screen used to mitigate the propulsion velocity. The table 2 is presenting the quantitative experimental evaluation of the residual kinetic energy depending on the thickness of the water layer.

Table 2. Quantitative evaluation of experimental results

No. test	Mass of HITEX [g]	Characteristics of fragment	Thickness of water screen [cm]	Quantitative experimental evaluation of residual kinetic energy [J]
1.	200	steel ball with 1.05 g and D = 6.35 mm	10	≅ 79
			10 + 5	< 79
2.			2 x 10	<< 79
			2 x 10 + 5	≅ 0

3. THEORETICAL EVALUATION OF PROPULSION VELOCITY

The fragments that are resulting from the break-up of explosive casing in the event of detonation are called primary fragments. Secondary fragments are those that come from other sources – wall or glass break-up, pieces of equipment, etc.

The most important primary fragment characteristics are initial fragment velocity, fragment mass distribution and fragment shape.

R.M. Gurney, in the 1940s, obtained an algebraic relationships for metal velocity when an explosive in contact with it is detonated. The Gurney method assumes that all the explosive chemical energy is converted into the kinetic energy of the fragments and expansion of the explosive products.

The Gurney equation shows that the initial velocity V of fragments is related to the explosive type and the relative mass of metal case to explosive charge mass [2, 4]:

$$V = \sqrt{\frac{2E}{\mu + \frac{n}{n+2}}} \quad (1)$$

The term $\sqrt{2E}$ is called the Gurney constant or the Gurney velocity for a given explosive, and is expressed in units of velocity [m/s].

The coefficient μ is given by $\mu = M/C$, where M is the mass of the accelerated shell or sheet of material (usually metal) and C is the mass of the explosive charge.

The coefficient "n" is equal to "1" for tamped sandwich configuration, "2" for cylindrical configuration and "3" for spherical configuration.

To predict the initial velocity of the fragments resulted from the explosion of an IED, it was used the Gurney method.

In this case, IED contains an explosive cylindrical charge and preformed metal fragments (balls) around the circumference of the charge (figure 5).

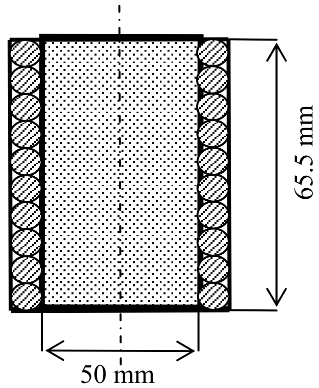


Fig. 5. Characteristics of explosive configuration

The charge (C) with 50mm diameter and 65.5mm height has the mass equal to 200 g of HITEX.

The balls are made of steel (ρ = 7.83g/cm^3) and the diameter of a ball is 6.35 mm, thus the ball's mass is equal to 1.05g. Considering the properties specified above, it results that the mass of the preformed fragments (M) is equal to 252g.

Gurney velocity can be evaluated with P.W. Cooper relation, (Carlucci, D.E., Jacobson, S.S., 2008):

$$\sqrt{2E} = 0.338 \cdot D \quad (2)$$

where D is the detonation velocity.

Knowing that detonation velocity of HITEX explosive is 7860 m/s, from the equation (2) results that the Gurney velocity $\sqrt{2E}$ is equal to 2656.68 m/s.

Thus, using the calculated Gurney velocity for HITEX charge and the coefficient $n = 2$ (for cylindrical configuration), from the equation (1) results that the initial velocity (V) of the balls is equal to 2002.54 m/s.

The initial kinetic energy of the balls is calculated using the relation below:

$$E_C = \frac{m_{ball} \cdot V_P^2}{2} \quad (3)$$

and it is obtained E_C= 2.105kJ.

4. NUMERICAL MODELLING

The numerical model is based on the two-dimensional formulation with axial symmetry. To create the model are used the following materials data from the AUTODYN library: AIR, STEEL 4340 and WATER. AIR is modeled as an ideal gas and, consequently, its equation of state is defined by the ideal-gas gamma-law relation as [3]:

$$P = (\gamma - 1)\frac{\rho}{\rho_0}E \qquad (4)$$

where P is the pressure, γ the constant-pressure to constant-volume specific heats ratio (γ = 1.4 for a diatomic gas like air), ρ_0 (ρ_0 = 1.225 kg/m^3) is the initial air density, and ρ is the current density. For eq. (4) to yield the standard atmosphere pressure of 101.3 kPa, the initial internal energy density is set to 253.4 kJ/m^3 which corresponds to the air mass specific heat of 717.6 J/kgK and a reference temperature of 288.2K.
For inert solid materials like STEEL 4340, a linear type of equation of state is typically used which assumed a Hooke's law type relationship between the pressure P and the volume change μ [3]:

$$P = K\mu \qquad (5)$$

where K is the bulk modulus of the material and $\mu = (\rho - \rho_0)/\rho_0$.
Within the AUTODYN material database, the initial material density ρ_0, the bulk modulus K, the specific heat Cp and the reference temperature T_{ref} are defined for various grades of steel.
Also, separate equations of state are used for WATER depending on whether water is subjected to expansion or compression. When water is subjected to expansion, a two-phase equation of state proposed by Morgan [3] is used while in compression a polynomial type of equation of state is used.
When water is subjected to compression, the following polynomial EOS is used [3]:

$$P = a_1\mu + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu)\rho_0 E \qquad (6)$$

where $\mu = \rho/\rho_0 - 1$ is the compression, ρ_0 the initial density and the coefficients a_1, a_2, a_3, b_0 and b_1 are defined in the AUTODYN material library.
The Air part is modeled with an Euler multi-material solver. To eliminate the numerical solution difficulties arising from highly distorted Lagrange cells, the erosion model was specified for each material data. Note that the erosion is not a physical effect or material property, it is a mechanism to combat mesh distortion.
The Air part has the physical dimensions of 520 mm length and 200 mm height and consists of 8,500 rectangular cells with grade zoning in J-direction checked (value "1.0" entered for the fixed element size) and with lower J selected (figure 6).

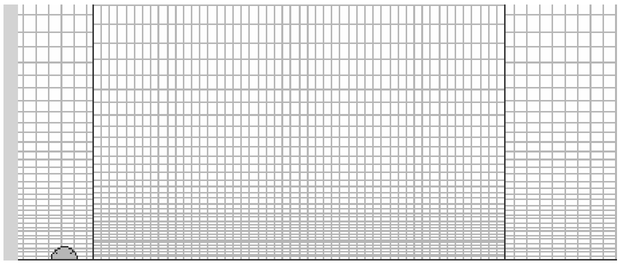


Fig. 6. Part of the rectangular mesh with lower grade zoning in J-direction

To create an initial condition for the fragment, it was set the X-velocity to 2002.54 m/s (the initial velocity predicted using Gurney equation).
Also, to initialize the air to a pressure of 1 atm is necessary to create another initial condition and to set the internal energy to 253.4 kJ/m^3.
The Fragment and the Water parts are modelled with a Lagrange processor.
Thus, it was defined a ball with 6.35 mm diameter, obtaining the Fragment part with 200 elements. Also, the Fragment part was filled with STEEL 4340 material data and was applied initial condition (X-velocity = 2002.54 m/s).
The numerical model with 100 mm thickness of the water layer is presented in Fig. 7.

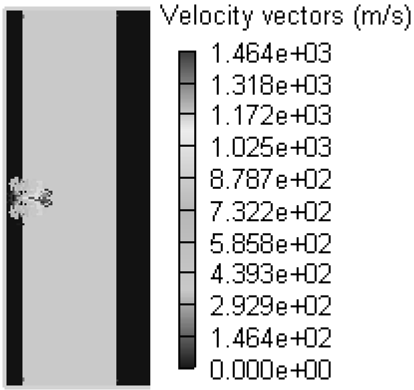
Fig. 7. Model setup for ball impact and penetration on water layer

In the same way, there are modelled the other three numerical models with different thicknesses of the water layer. In every model the steel ball was placed very close to the water layer.
The water layer thickness is set up between 100 mm and 250 mm. In this way, there are created four numerical models with the water layer thicknesses of 100 mm, 150 mm, 200 mm and, respectively, 250 mm.
To complete the numerical model, it is necessary to set up the Euler-Lagrange interactions and set the solution and output controls.

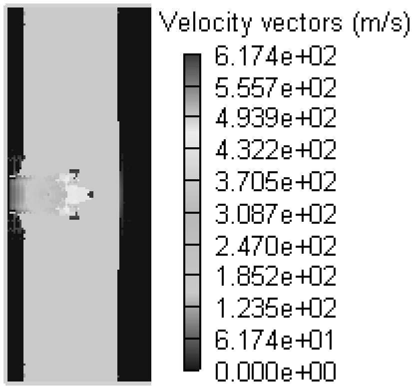
5. COMPUTATIONAL ANALYSIS

To evaluate the influence of water layer thickness on the fragment velocity, it is necessary to numerically simulate all the four models and compare the results. Because the models are based on the two-dimensional formulation with axial symmetry, it was possible to use the mirror option and to check in plane y = 0.

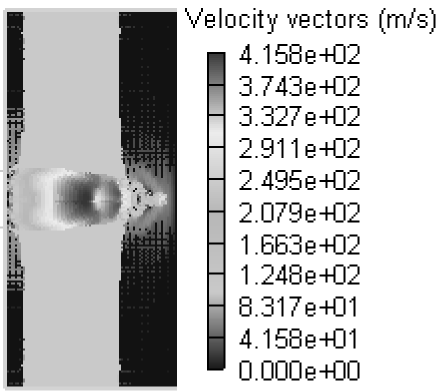
In this way, figure 8 is showing the results of the simulation for the entire model, with the thickness of water layer equal to 100 mm.



a) t = 1.5e-02 ms



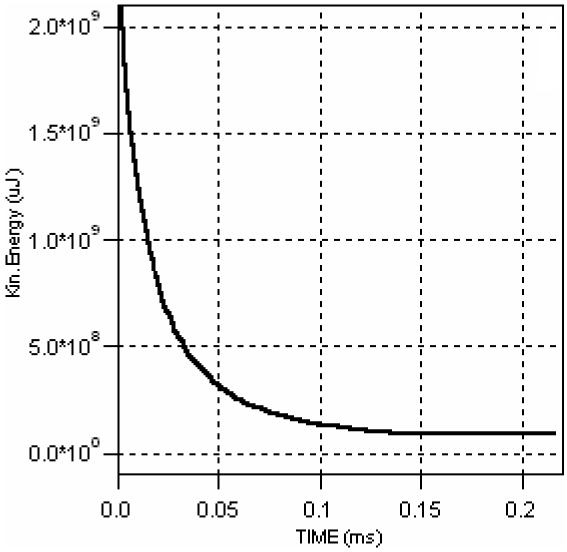
b) t = 7.5e-02 ms



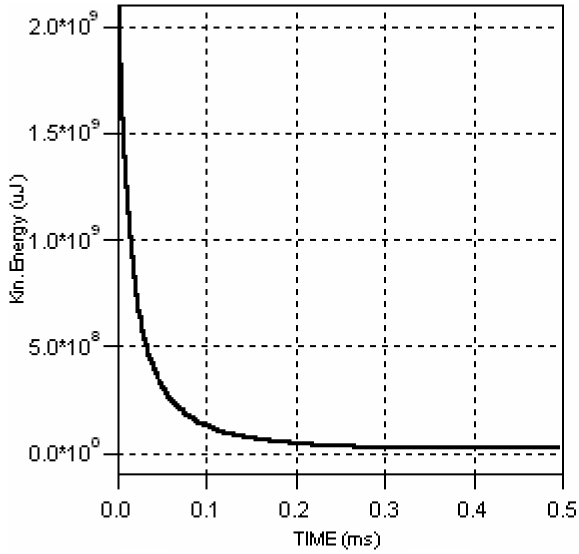
c) t = 2.1e-01 ms

Fig. 8. Ball penetration on water layer with 100 mm thickness

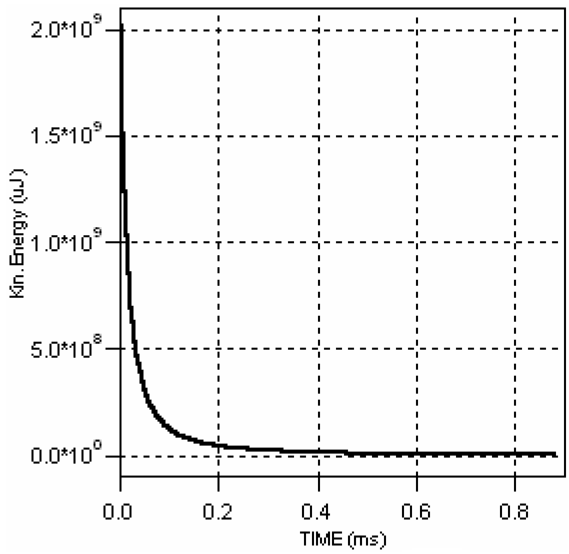
In figure 9 and figure 10 are presented the results of the numerical simulation for the models with the water layer thickness having the following values: 100mm, 150mm, 200mm and, respectively, 250mm.



a) 100 mm water layer thickness



b) 150 mm water layer thickness



c) 200 mm water layer thickness

Fig. 9. Variation of the kinetic energy with time depending on water layer thickness

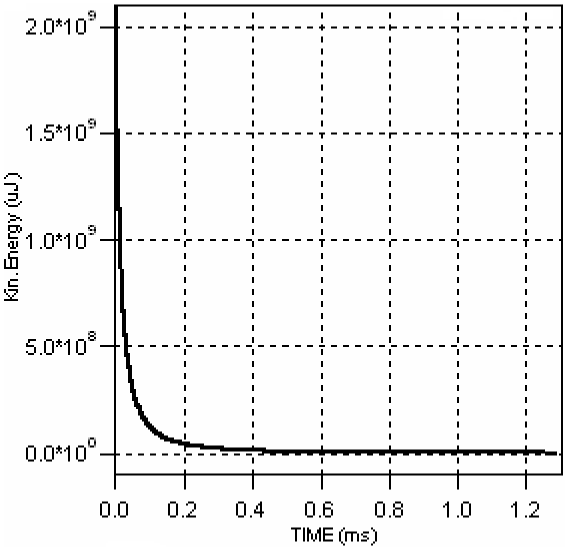


Fig. 10. Variation of the kinetic energy with time for water layer with 250 mm thickness

In order to analyze the simulation's results it was selected (350, 0) as a reference point for all the numerical models. At this distance the residual velocity and kinetic energy are presented in Table 3.

Table 3. Residual velocity and kinetic energy

Water layer thickness	Ball velocity [m/s]	Ball kinetic energy [J]
100 mm	414.09	89.44
150 mm	198.57	20.56
200 mm	91.36	4.35
250 mm	40.19	0.84

As a general rule, the vulnerability of some targets to damage caused by fragments resulted from explosion depends on the kinetic energy.

The research on the explosive devices effects, including fragments, had determined that the minimum lethal kinetic energy of a fragment is equal to 79J. This is critical energy (depending exactly where it hits) to unprotected personnel.

Therefore, the table 3 shows that the residual kinetic energy for the model with 100mm water layer thickness is greater than the lethal energy, while for at least 150mm water layer thickness the residual energy is significantly reduced.

Thus, using the AUTODYN it was evaluated the thickness of water screen which can provide ballistic protection against propelled fragments from detonation of explosive configuration. For the water layer having the thickness at least 150mm, the kinetic energy of fragments, initially equal to 2,105J, was mitigated below the lethal energy (79J).

6. CONCLUSIONS

To mitigate the IED's fragmentation effect, we must attenuate the kinetic energy of the propelled fragments from detonation of explosive charge.

The experimental research demonstrates that water screens are capable of providing a good level of protection against explosive devices effects.

The quantitative evaluation of experimental results shows that, for 6.35 mm diameter steel ball passing through a water screen having the thickness at least 150 mm, the residual kinetic energy is reduced below the lethal energy. Using the Euler multi-material and Lagrange solvers, it was possible to investigate numerically the water mitigation effect on the fragments velocity. The numerical results show that water is capable of reducing the initial velocity of a steel ball into different thicknesses of water layer. Depending on the thickness of the water layer, the residual velocity and kinetic energy are reduced below lethal level for 150 mm water layer thickness.

Therefore, the numerical results are in good agreement with the quantitative evaluation of experimental results. Thus, the water screens can provide the ballistic protection for people and goods against fragments resulted from explosion, which would cause bodily injury, death and property damage. The thickness of the water layer, which is a very important parameter, can be evaluated using the AUTODYN hydrocode. For further research on the subject analysed in this paper, is necessary to focus on the influence of the fragment's mass and shape. Also, water can be replaced with other ballistic material or composite sandwich structure panel fabricated by different thicknesses material, in order to compare the results.

7. REFERENCES

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