Water mitigation effects on the detonations in confined chamber and tunnel system

H.Z. Zhao[a,*], K.Y. Lam[b] and O.Y. Chong[c]
[a]*Department of Mechanics, Huazhong University of Science and Technology, Wuhan, 430074, China*
[b]*Institute of High Performance Computing, 89B Science Park Drive #02-11/12, The Rutherford, Singapore 118261*
[c]*Lands and Estates Organisation, Defence Technology Towers, AFPN 0007, 1 Depot Road, #12-05, Singapore 109679*

Received 15 May 2000
Revised 26 August 2001

The water mitigation effects on the detonations of explosive in a confined cube chamber are studied by use of a numerical code. Significant mitigation effects on shock pressure at various loading densities, various water/explosive mass ratios and various air gaps are obtained. Reduction of final static pressure is also obtained because water absorbs the energy released from the detonations through being compressed and vaporized. On the basis of this study, the detonations in a tunnel system with vent are further simulated. The numerical results are compared with the experimental data, and the water mitigation effects on shock pressure are verified.

1. Introduction

The blast effects of an accidental detonation of explosive materials at an ammunition storage site is normally very intense and extensive. They may cause serious damage to the structures in the near proximity of the ammunition. For this reason, military safety regulations require that large areas of land be designated as safety hazard zones around ammunition storage sites. One concept that has recently been investigated as a means of reducing these hazard areas is the use of water to mitigate the blast effects of accidental detonations [1–3].

Detonation of a high explosive produces high pressure shock waves which travel outward in all directions from the explosion at extremely high velocity. Immediately upon the wave's arrival, the pressure rises very quickly to a peak value and then decays to the ambient pressure. The level of this peak pressure is one of the measures on the destructive ability of the blast to structures. Another important index to evaluate the destructive ability of a detonation is final static pressure. It is caused by the expanding of high-temperature gases from the explosive by-products in a confined space. In turn, the expanding of the explosive gases depends on the initial density and released energy of the explosive.

Shin et al. [4] numerically examined the features of a free-field detonation process from a series of one-dimensional simulations by using a finite element program MSC/DYTRAN. The computational simulation included modeling the formation and propagation of water/air-shock waves. Chong et al. [5] also conducted numerical calculations on a simple tunnel model, and verified their results from comparisons with experimental data. In the current study, the water mitigation effects on shock pressure and final static pressure of the detonations in a confined cube chamber are first investigated. The aim of the investigation on this simple model is to describe some details of the shield effects of water on the blast waves and determine the optimal parameters for the best mitigation effect. It is also expected to provide some useful information for researches on more complicated models. On basis of the numerical results obtained from the simple model, we further conduct the investigation on a complicated model, that is a detonation in a tunnel system. This study on a tunnel system may provide more applicable information to the application of water mitigation concept in an underground magazine design. The peak shock pressure obtained from the simulation is compared with experimental data.

2. Equations of state

The equations of state are required in the numerical simulations. Air can be modeled as an ideal gas which uses a gamma law equation as following:

*Corresponding author. E-mail: llyzys@public.wh.hb.cn.

Shock and Vibration 8 (2001) 349–355
ISSN 1070-9622 / $8.00

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E, \quad (1)$$

where $\gamma = 1.4$, ρ is air density, ρ_0 is the initial density and E is the internal energy per unit volume.

The explosive is modeled with the standard Jones-Wilkins-Lee (JWL) equation. The equation may be written as

$$\rho = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}, \quad (2)$$

where A, B, ω, R_1 and R_2 are constant coefficients determined by rigorously comparing values calculated using the equation with experimental C–J conditions and expansion behavior. $V = v/v_0$ is the specific volume of detonation products/volume of undetonated explosive, and E is explosive internal energy. It can be noted that at large expansion ratio ($V \to \infty$) the first and second terms on the right hand side of the equation becomes negligible and hence the explosive can be assumed as ideal gas. All the coefficients and physical parameters in this equation for various explosive materials can be obtained from the handbook by Dobratz [6].

The polynomial equation of state for water has the form of

$$p = a_1\mu + a_2\mu^2 + a_2\mu^3 + (b_0 + b_1\mu + b_2\mu^2)\rho_0 E \quad (3)$$

when $\mu > 0$ (in compression), where $\mu = \frac{\rho}{\rho_0} - 1$. When $\mu < 0$ (in tension) the equation is given by

$$p = a_1\mu + (b_0 + b_1\mu)\rho_0 E. \quad (4)$$

The coefficients $a_1 - a_3$, $b_0 - b_2$ are determined from experimental data. In the experiment high explosives have been used to shock water to high pressure. Shock compression is accompanied by an increase in temperature and water vaporization.

3. Water mitigation effects in a confined cube chamber

The detonations of PETN explosive in a confined cube chamber are first simulated numerically. A three-dimensional multimaterial Eulerian code MSC/DYTRAN is applied to model the current problem including the detonation event, water-shock and blast waves propagation. The multimaterial Eulerian processor in this code allows three different materials (explosive, air and water) to be treated in this problem.

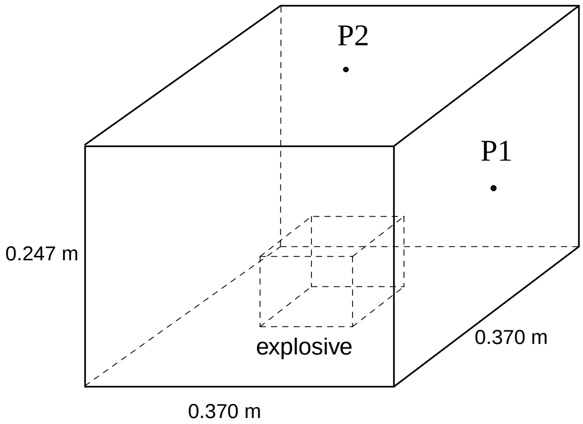

Fig. 1. Explosive in a confined cube chamber.

Dimensions of this chamber are shown in Fig. 1. Explosive is modeled as a cube with similar shape as the chamber, and it is assumed to be placed at the center of the chamber floor. For water mitigation cases, a uniformly thick layer of water is placed around the explosive. The explosive may be directly in contact with the water (no air gap) or be separated from the water by an air gap. The peak pressure and gas pressure in the cases with water jacket are compared with no-water case at different loading densities (equivalent TNT mass of explosive divided by the chamber volume, kg/m^3), different water/explosive mass ratios (water mass divided by the equivalent TNT mass of explosive) and different air gaps.

3.1. *Water mitigation effects on shock pressure and final static pressure*

Figures 2 and 3 show the pressure signatures at point P1 (center point at the chamber side as shown in Fig. 1) and point P2 (center point at the chamber top) for the loading density of 1.03 kg/m^3. The water/explosive ratio is taken as 3.07. The peak shock pressure is reduced from 100 bar to about 30 bar at P1 and from 137 bar to about 45 bar at P2 by putting water around the explosive. The arrival time of the shock peak is also delayed significantly. As the shock terminally dies away, the pressure in the chamber will settle to a constant level, that is final static pressure.

Table 1 lists the peak values of the shock pressures at points P1, P2 and final static pressure at loading densities of 1.03, 4.75 and 9.80 kg/m^3. The water/explosive mass ratio is 3.07 in all the water cases. It is shown that

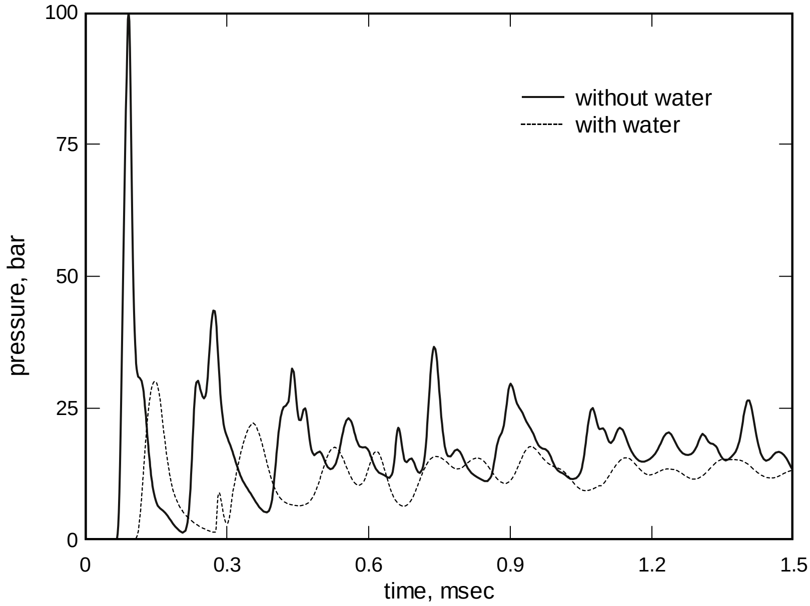

Fig. 2. Numerical Simulation of pressure signatures at pressure point P1 in the cube chamber.

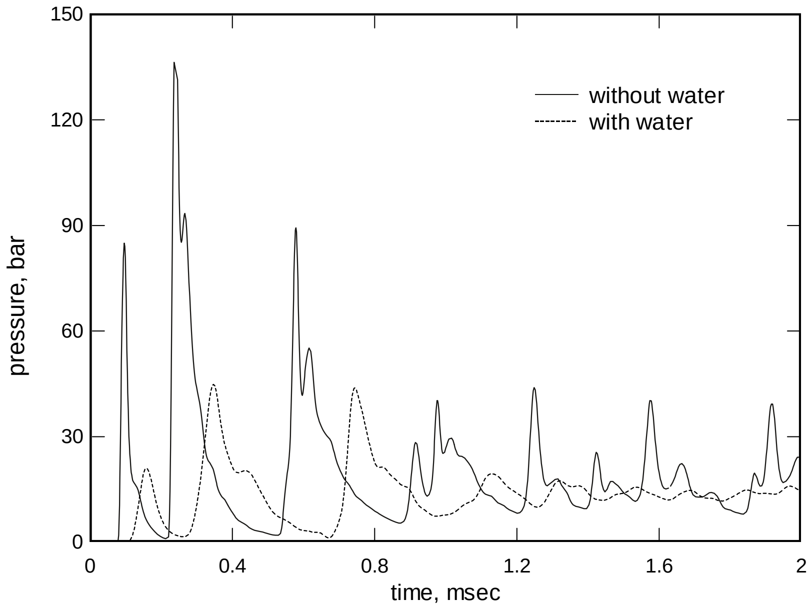

Fig. 3. Numerical simulation of pressure signatures at pressure point P2 in the cube chamber.

both the shock pressure and static pressure are reduced by the water jacket. The reduction of the peak shock pressure ranges 11% to 70 % and the final static pressure is reduced by 26% for the loading density of 1.03 kg/m^3 to 34% for the loading density of 9.80 kg/m^3.

Final static pressure is determined by the thermodynamic equilibrium of the constituent of explosive and water in a confined chamber. Water can reduce the static pressure because it absorbs the released energy from the explosive gases through being compressed and heated. Water vaporization also absorbs energy, since the enthalpy of steam is much higher than that of water, which means significant energy transfer from explosive gas to steam is required while water is vaporized to

Table 1
The peak shock pressure and final static pressure in the cube chamber at different loading densities. The water/explosive ratio is 3.07 for all the water cases

Loading density	Peak shock pressure at P1 (bar)		Peak shock pressure at P2 (bar)		Final static pressure (bar)	
(kg/m^3)	No water	Water	No water	Water	No water	Water
1.03	100	30	137	45	19	14
4.75	187	119	397	352	71	48
9.80	301	191	641	544	145	95

Table 2
The peak shock pressure and final static pressure in the cube chamber at different water/explosive ratios for a loading density of 9.80 kg/m^3

Water/explosive	0.00	1.11	2.03	3.07	6.09
Peak shock pressure at P1 (bar)	301	225	160	191	590
Peak shock pressure at P2 (bar)	641	354	346	544	6175
Final static pressure (bar)	145	110	100	95	95

Table 3
The peak shock pressure and final static pressure in the cube chamber at different air gaps for a loading density of 9.80 kg/m^3 and water/explosive ratio of 3.07

Air gap (cm)	0.00	1.68/1.12	3.36/2.24
Peak shock pressure at P1 (bar)	191	226	205
Peak shock pressure at P2 (bar)	544	617	670
Final static pressure (bar)	95	110	124

steam. In the current study, the vaporization is taken into account through using equations of state (3) and (4). The coefficients in the Eqs (3) and (4) were determined by fitting experimental data. In the experiment, shock compression was accompanied by an increase in temperature and water vaporization. However, it was also noted that the experimental data were measured in shock stage in which the vaporization might not be sufficient. It therefore can be expected that the shock pressure has been well calculated by using the equations with these coefficients but the reductions of static pressure are most possibly underestimated, because the final static status has been reached after a long-term compressing and heating process, in which more water (in limiting case all water) may have been vaporized.

3.2. *Water mitigation effects at various water/explosive ratio*

The water mitigation effects depend on the relative amount of water to the explosive, that is, the ratio of water mass to equivalent TNT mass of the explosive. Table 2 lists the peak shock pressure at P1 and P2, and the final static pressure for different water/explosive ratio. The loading density is taken as 9.80 kg/m^3. At the ratio of 2.03 we yield the best mitigation effect on the shock pressure. The reductions of peak values at this ratio are 47% and 46% at pressure points P1 and P2 respectively comparing to the no-water case (water/explosive ratio is 0.0). More water diminishes mitigation effect; at the largest water/explosive ratio (6.09) the peak pressures at both pressure points even exhibit a substantial increase. The reason for this to happen may be explained as that as water amount is increased the water shield becomes thicker, in consequence, its outer edge is closer to the chamber wall, and as a result, water-gas mixture may hit the wall at the observation points in the explosion process. The kinetic energy of the mixture is then transferred to potential energy and this raises peak pressure.

Static pressure continually decays with increase in the amount of water until the maximum reduction of 34% is obtained at the ratio of 3.07. Further increase of water amount will not produce more changes on the final static pressure, because the energy transfer from explosive gases to large amount of water is not as sufficient as does to small amount of water.

3.3. *Relation between water mitigation effects and air gap*

The peak shock pressure and final static pressure at different air gap are listed in the Table 3. The loading density and water/explosive ratio are fixed at 9.80 kg/m^3 and 3.07 respectively. At the side of the explosive the air gaps are a little larger (1.68 and 3.36 cm, as listed in Table 3) than those at the top (1.12 and 2.24 cm). Generally, the effect of air gap on the mitigation is negative; it slightly weakens the mitigation effects of the water jacket on the shock pressure, because air gap obstructed the energy transfer from explosive gas to water in a short-term shock stage. In a long-term

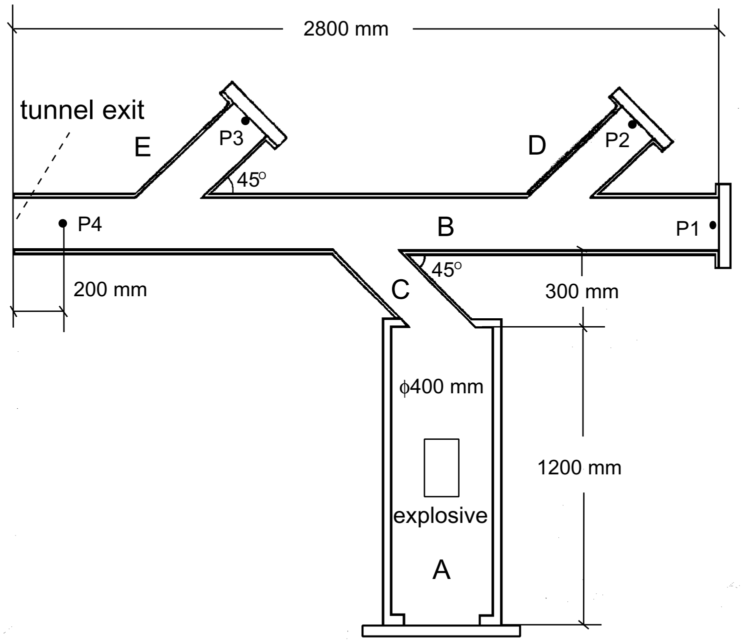

Fig. 4. Layout of the tunnel model and the locations of the pressure points.

Table 4
Peak shock pressure for 750 g TNT detonation in the chamber system. The water/explosive ratio in the water case is 2.5

Pressure points		Peak shock pressure (bar)			
		P1	P2	P3	P4
Numerical results	No water	76	46	55	47
	Water	46	30	36	31
	Reduction %	39	35	35	34
Experimental results	No water	67	43	50	41
	Water	42	28	33	26
	Reduction %	37	35	34	37

process, its influence on the final static pressure is not very evident.

4. Water mitigation on the shock pressure in a model tunnel system

Figure 4 shows the layout of a small scale tunnel system. The system consists of a detonation chamber (Part A in the figure), an exit tunnel with vent at one side (Part B) and three branch tunnels (Parts C, D and E). The cross sections of all the tunnels are semicircular, and the tunnels are made of steel pipes. The detonation chamber has an inside diameter of 0.4 m and a length of 1.2 m and the exit chamber is 2.8 m at length and 0.25 m at inside diameter. The three branch tunnels have the same geometry with 0.196 m of diameter and 0.424 m of length. 650 g PETN (equivalent to 750 g TNT) is placed at the center of detonation chamber floor, as shown in the figure. This charge of explosive corresponds to a loading density of 5.0 kg/m$^{1/3}$ in the detonation chamber. For water mitigation case, 2.5 times of water as the explosive is used. Four pressure points (P1 to P4) locate at the tunnel floor as indicated in Fig. 4.

The blast pressure of detonation was measured at pressure points P1 to P4 in a test conducted by the Lands and Estates Organisation of Singapore in 1998. In the test, the water was pre-packed in plastic bags and secured using rubber bands. The water bags were placed closely around the explosive. The pressure gauges were installed on the tunnel floor at the locations of P1 to P4. The peak values of shock pressure measured in the cases with and without water are listed in Table 4.

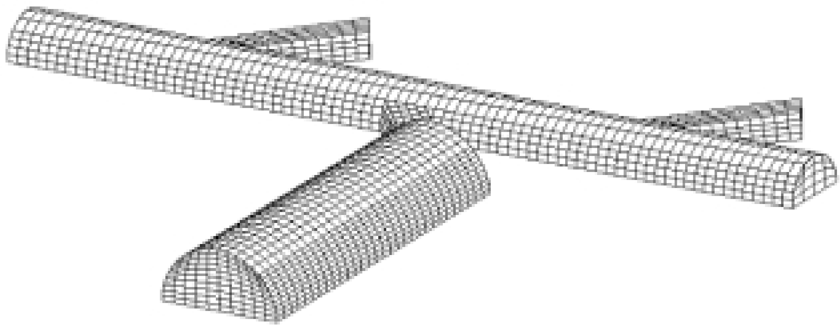

Fig. 5. Computational mesh for the tunnel model.

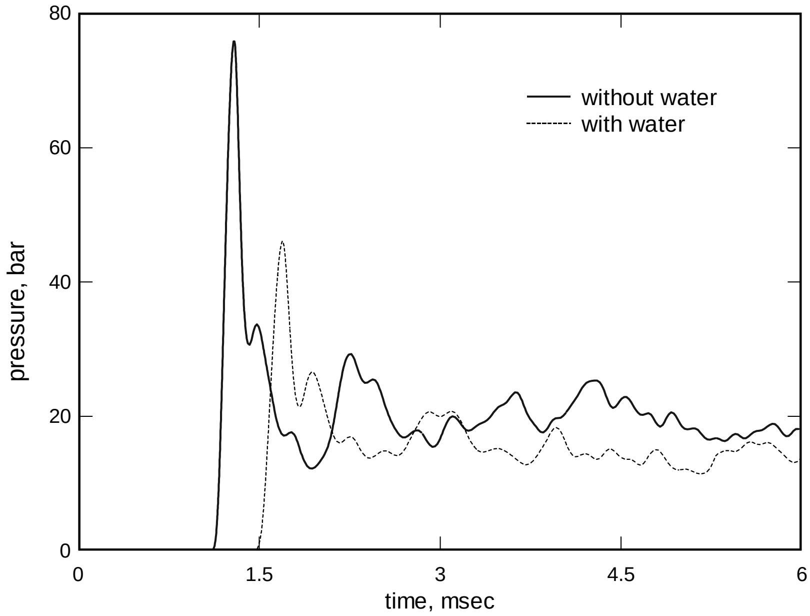

Fig. 6. Numerical simulation of pressure signatures at pressure point P1 in the tunnel system.

In the numerical simulations, on the other hand, the water is modeled as uniformly thick layers at 5 sides (surround and top) of the explosive. All the steel pipe wall conditions are simplified as rigid, and the condition at chamber exit is implemented as an outflow with specified pressure. A pre-processor MSC/PATRAN is used in the simulation to generate computational mesh for the explosive and fluid medium. The mesh includes 4760 non-rectangular hexahedron elements as shown in Fig. 5, and the element model is further converted to the MSC/DYTRAN input data using a translator.

The numerical calculations are performed for the cases with and without water. Figures 6 and 7 show the pressure signatures at the pressure points P1 and P2 respectively. At P2 a reflected shock from the closed end of the tunnel (the end near to Point P1) forms another peak. The reflected shock is even stronger than the direct shock and hence results in the maximum peak pressure at this pressure point. The pressure signatures also show that water jacket significantly reduces the peak pressure and delays peak arrival. The peak values of shock pressure are tabulated and compared with the experimental data in Table 4. The reduction of peak pressure ranges 34% to 39%, which shows a good agreement with the experimental results of 34–37%. However, it is also noted that the computed pressure are some (within 16%) higher than the experimental data. These differences are generally acceptable since the accuracy of the experiment would not be perfect and in addition, the approximations in the numerical method also contribute to the differences.

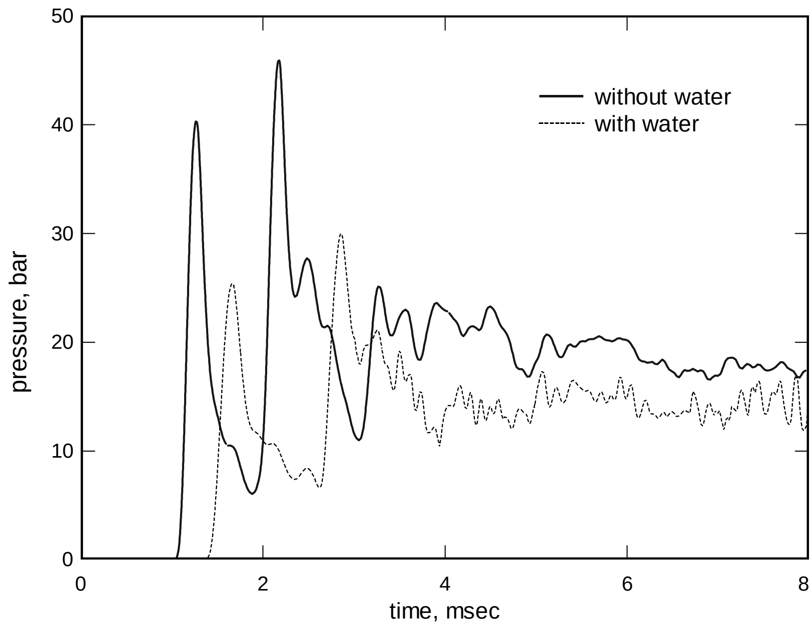

Fig. 7. Numerical simulation of pressure signatures at pressure point P2 in the tunnel system.

Table 5
Peak shock pressure for 375 g TNT detonation in the tunnel system. The water/explosive ratio in the water case is 2.5

Pressure points		Peak shock pressure (bar)			
		P1	P2	P3	P4
Numerical results	No water	45	25	31	27
	Water	28	16	19	17
	Reduction %	38	36	39	37

Table 5 lists the results for the detonation of 375 g TNT (loading density of 2.5 kg/m$^{1/3}$). The water/explosive mass ratio is still fixed at 2.5. The water jacket reduces peak shock pressure by 36–39%. These results exhibit good consistency with those for high loading density. Experimental data at this loading density are not available and hence, no comparison is made.

5. Conclusions

1) Water mitigation effects on shock pressure and final static pressure are verified in both of confined cube chamber and tunnel system. At the water/explosive ratio of 2 to 2.5, the peak shock pressure is reduced by 34% (in tunnel system) to 47% (in cube chamber). The best effect of water mitigation on the final static pressure (about 34% reduction) is obtained at a water/explosive ratio of about 3.0 in the cube chamber.
2) Air gap between explosive and water slightly weakens the mitigation effects on both of the shock pressure and final static pressure.

References

[1] S. Eriksson, Water in explosive storage, FortF/F Report C 104, Stockholm, 1974.

[2] W.A. Keenan and P.C. Wager, Mitigation of confined explosion effects by placing water in proximity of explosives, The 25th DoD Explosives Safety Seminar, Anaheim, California, 1992.

[3] B. Vretblad and S. Eriksson, Blast mitigation in confined spaces by energy absorbing materials, The 26th DoD Explosives Safety Seminar, Miami, Florida, 1994.

[4] Y.S. Shin, M. Lee, K.Y. Lam and K.S.Yeo, Modeling mitigation effects of watershield on shock waves, *J. of Shock and Vibration* **5** (1998), 225–234.

[5] W.K. Chong, K.Y. Lam, K.S. Yeo, G.R. Liu and O.Y. Chong, A comparison of simulation's results with experiment on water mitigation of an explosion, *J. of Shock and Vibration* **6** (1999), 73–80.

[6] B.M. Dobratz, Explosive Handbook, UCRL-52997, Lawrence Livermore National Laboratory, Livemore, CA, 1981.