A comparison of simulation's results with experiment on water mitigation of an explosion

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This paper presents a comparison of simulation's results with the experimental data from a series of small-scale tests conducted by Joachim and Lunderman of the United States Army Engineer Waterways Experiment Station. The purpose of the experiments was to evaluate the effect of water as a mean of reducing airblast pressure from accidental explosions in underground magazines. In the present study, a series of three-dimensional numerical calculations were conducted using a Multimaterial Eulerian Finite Element Code. Results from the numerical simulations show good comparison with the experimental data for the case with and without water. Our simulation ascertains the mitigation effects of water in reducing the maximum peak pressure and impulse density due to an explosion.

1. Introduction

The use of water as a mean of reducing the maximum peak pressure and impulse density due to an explosion has been of great interest to many researchers. Many experiments had been conducted to investigate the mitigation effects of water, such as Eriksson [2], Keenan and Wager [4], Vretblad and Eriksson [8]. In

these experiments, it was demonstrated that the maximum peak pressure and impulse density could be reduced significantly when water was stored close to the high explosive. This is due to the significant amount of energy loss from the shock to breaking up the water into small minute droplets, which in turn, enhances the process of phase change from liquid to gas state. The process of phase change extracts the heat energy from the system, reducing the temperature of the gas products and hence, leading to lower maximum peak pressure and impulse density.

However, there is a lacking in the area of numerical calculation to investigate the water mitigation concept. The use of numerical tools is important as it provides an effective way for cost savings for studying this complicated shock event due to explosion and also expedites the process for design purpose. Therefore, it is of interest for us to carry out numerical simulations to verify the effects of water mitigation on an explosion. The present study performs the numerical calculations using the Multimaterial Eulerian Finite Element Code, MSC-DYTRAN and compares the simulation's results with the experimental data from United States Army Engineer Waterways Experiment Station [3].

2. Numerical modeling

The Multimaterial Eulerian Finite Element code, MSC-DYTRAN Version 3.0 [5] was used to model the current problem including the explosion event, water-shock and blast waves propagation, and reflection from the rigid boundaries. The Multimaterial Eulerian processor in this code allows up to nine different Eulerian materials to be present in a given problem and is suitable for this problem.

The small-scale model used in the experiments from [3], consisted of a detonation chamber and an exit tunnel, shown in Fig. 1. The detonation chamber was

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Fig. 1. Layout of the tunnel model and the locations of the pressure points.

Table 1
Locations of the pressure points

Pressure points	X (m)	Y (m)	Z (m)
AB-3	1.35	0.254	0.00
AB-4	1.99	0.00	0.073
AB-5	2.61	0.073	0.00
AB-7	3.30	0.00	0.073
AB-8	4.30	0.00	0.073
AB-9	5.30	0.00	0.073
AB-11	5.61	0.073	0.00

made of a 0.508 m (inside diameter) steel pipe and rings of steel plate (0.076 m thick) and had an outer diameter of 0.813 m. The detonation chamber was 1.8 m long with a volume of 0.365 m³. The exit tunnel was made of heavy-walled steel pipe with an inside diameter of 0.146 m and had a total length of 4 m. In our numerical modeling, the boundaries are assumed to be rigid and this reduces the computational domain, thus increasing the speed of computation. Pressure points are located on the wall, shown in Fig. 1 and their locations are tabulated in Table 1.

Explosive charges for the numerical calculations were made of Composition C-4, as in the experiment and were modeled as cylindrical charges with equal height and diameter. Three charge masses are used, 0.45, 0.91 and 1.36 kg, giving explosive loading densities of 1.67, 3.33 and 5.00 kg/m³ (TNT equivalent). The charges were placed at the center of the chamber as shown in Fig. 1 and detonation was initiated at the one end of the cylindrical charge, closest to the exit tunnel. In the experiments, condoms were used as water container and these were placed surrounding the charge for direct contact with the explosive source. This placement of water was simplified in the present study. The water was also modeled in cylindrical shape with equal height and diameter as the charge and the explosive was fully immersed in the water as shown in Fig. 2. We believed that this way of modeling the water was sufficient to represent the explosion event in the experiment. The condoms used in the experiment for containing the water would not have caused any significant effects on the shock wave generated and hence, the water was assumed directly in contact with the explosive in our modeling.

Fig. 2. Plan and side views of the explosive and water configurations.

Table 2
Summary of numerical calculations performed

No.	Parameter	Mass of explosive (kg)	Water to explosive mass ratio	TNT equivalent loading density (kg/m ³)
1	No water	0.45	0.0	1.7
2	No water	0.91	0.0	3.3
3	No water	1.36	0.0	5.0
4	Water jacket	0.45	2.6	1.7
5	Water jacket	0.91	2.6	3.3
6	Water jacket	1.36	2.6	5.0
7	Water jacket	1.36	0.7	5.0
8	Water jacket	1.36	1.3	5.0
9	Water jacket	1.36	2.0	5.0
10	Water jacket	1.36	3.3	5.0

Ten numerical simulations were performed, as shown in Table 2. The baseline are the three tests without water, at the three loading densities of 1.67, 3.33 and 5.00 kg/m³. A series of five calculations are performed at loading density of 5.00 kg/m³, varying the water-explosive ratio from 0.7 to 3.3. Three more calculations are carried out with a water-explosive ratio of 2.6; one at each of the three loading densities of 1.67, 3.33 and 5.00 kg/m³.

In the present study, three-dimensional calculations were performed with hexahedron elements. An outflow boundary condition is implemented at the tunnel exit. Material modeling of the explosive and water uses the equation of state model to characterize the behavior of the detonation product and water subjected to high loading.

Development of the detonation product gases is modeled with the standard Jones–Wilkins–Lee (JWL) equation of state (EOS) [1]. The equation of pressure

P is given as

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

where A, B, ω, R_1, R_2 are constants, V is the specific volume of detonation products over the specific volume of undetonated explosive and E is the internal energy per unit volume. The density of Composition C-4 is 1601 kg/m³. The values used for JWL Composition C-4 were obtained from the handbook by Dobratz [1]. Air is modeled as an ideal gas which uses a gamma law equation of state:

$$P = (\gamma - 1) \frac{\rho}{\rho_0} E, \quad (2)$$

where $\gamma = 1.4$ is the ratio of specific heats. The initial density of air ρ_0 is 1 kg/m^3 . The initial internal energy E is 2.5 bar in order to satisfy standard atmosphere pressure.

Water is modeled as a compressible fluid with a Mie–Grüneisen equation of state [8] which uses cubic shock velocity-particle velocity to define pressure for compressed and expanded materials as, in compression ($\mu > 0$)

$$P = \rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right] \times \left[1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{1 + \mu} - S_3 \frac{\mu^3}{(1 + \mu)^2} \right]^{-2} + (\gamma_0 + a\mu)E, \quad (3)$$

in tension ($\mu < 0$)

$$P = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu)E, \quad (4)$$

where $\mu = \eta - 1 = (\rho - \rho_0)/\rho_0$. γ_0 is the Grüneisen gamma, a is the first order volume correction to γ_0 , ρ_0 is the density of water, E is the specific internal energy, C_0 is the sound speed at undisturbed state and S_1 , S_2 and S_3 are constants.

The above equation of state for water can be expressed in polynomial form [7] as, in compression ($\mu > 0$)

$$P = a_1 \mu + a_2 \mu^2 + a_3 \mu^3 + (b_0 + b_1 \mu + b_2 \mu^2) \rho_0 E, \quad (5)$$

in tension ($\mu < 0$)

$$P = a_1 \mu + (b_0 + b_1 \mu) \rho_0 E, \quad (6)$$

where $a_1, a_2, a_3, b_0, b_1, b_2$ are constants for the water. Constants for these equations were determined based on the Mie–Grüneisen EOS [8]. Hence, the above equation of state for water can be used over the range for which the Mie–Grüneisen EOS is valid. This covers the pressure range from 0 to 40 GPa and temperature range from 20°C to 2777°C . The above polynomial form of equation of state for water [7] is implemented in the present analysis.

3. Results and discussions

The Multimaterial Eulerian Finite Element code MSC-DYTRAN version 3.0 [6] was applied to model the current problem including the explosion event, water-shock and blast waves propagation and reflection at the water–air interface. This code is supported by the MacNeal–Schwendler Corporation [5]. Multimaterial Eulerian processor in this code allows up to nine different Eulerian materials to be present in a given problem.

4. Numerical calculation comparison with experimental data

4.1. Explosive without water

Experimental data was collected and calculations were performed for explosive detonated in the air tunnel for the three loading densities of 1.67, 3.33 and 5.00 kg/m^3 as shown in Figs 3–5. These data provide the baseline for comparison against the case with water (Section 4.2).

Figure 3 shows the comparison between experiment and computation for 0.45 kg (loading density of 1.67 kg/m^3) C-4 charge detonation in air tunnel. The triangles denote experimental data and the circles are computed results from our simulation. This notation applies throughout the figures unless stated otherwise. The figure shows peak pressure plotted against distance of pressure point from the rear of chamber in log scale. We can see that the simulation's results are in

Fig. 3. Comparison between experiment and computation for 0.45 kg C4 charge detonation in air.

Fig. 4. Comparison between experiment and computation for 0.91 kg C4 charge detonation in air.

Fig. 5. Comparison between experiment and computation for 1.36 kg C4 charge detonation in air.

good agreement, within 15% difference with the experimental data.

Comparison between experiment and computation for 0.91 kg (loading density of 3.33 kg/m^3) C-4 charge detonation in air tunnel is shown in Fig. 4. Similar conclusion as above can be seen in this figure. The comparison is good between the experiment and the simulation.

Figure 5 shows the comparison for 1.36 kg (loading density of 5.0 kg/m^3) C-4 charge detonation in air tunnel. Similarly, the simulation's results are in good agreement with the experiment.

In general, DYTRAN's simulations are in good agreement with the experiments for explosions in the air tunnel (without water).

Fig. 6. Comparison between experiment and computation for 0.45 kg C4 charge detonation with water ($R = 2.6$).

4.2. Explosive fully immersed in water

In this section, numerical calculations were performed for explosive fully immersed with water for the three loading densities. Water-explosive ratio of 2.6 was used for the numerical calculations for loading densities of 1.67 and 3.33 kg/m^3 . As for the loading density of 5.0 kg/m^3 , water-explosive ratio used were 0.7 , 1.3 , 2.0 , 2.6 and 3.3 .

Figure 6 shows the peak pressure versus distance from rear of chamber for 0.45 kg C-4 charge detonation with water-explosive ratio of 2.6. There are four points which show good comparison, within 20% difference between our simulation and the experiment.

Figure 7 shows the comparison between experiment and computation for 0.91 kg C-4 charge detonation with water-explosive ratio of 2.6. For this case, pressure location AB-4 did not have peak pressure values in the experiment. Most of our calculated peak pressure values are consistently higher than the experimental data. There was only one point which was in good agreement (within 20% difference) with the experiment for this case.

Figures 8–12 show the comparison between experiment and computation for 1.36 kg (loading density of 5.0 kg/m^3) C-4 charge detonation with water-explosive ratio varying from 0.7 to 3.3 , respectively. In these figures, most of the peak pressure calculations are within 20% difference with the experiments for the case of explosive with water and are consistently higher than the experimental data.

From Fig. 3 to 12, it can be seen that a straight curve with negative gradient could be fitted along the numer-

Fig. 7. Comparison between experiment and computation for 0.91 kg C4 charge detonation with water ($R = 2.6$).

Fig. 9. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ($R = 1.3$).

Fig. 8. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ($R = 2.6$).

Fig. 10. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ($R = 2.0$).

ical results. From these figures, there exists a relation between peak pressure and distance from the source of explosion and this can be written as

$$P = CD^m, \quad (7)$$

where P is the peak pressure, D is the distance from the explosive, m is a constant with negative value which is the gradient of the fitted straight curve and C is a constant obtained from the intercept of the fitted curve with the y -axis. The variables m and C are dependent on the type and weight of the explosive. This simple relation applies to the present tunnel model and needs to be verified with further experiments.

Figures 13 and 14 show the percentage peak pressure reduction versus water-explosive ratio for location AB-7 and AB-9 of 1.36 kg C-4 charge detonation. The percentage peak pressure reduction is defined as follows

$$\text{Percentage peak pressure reduction (\%)} = 1 - [P_{\text{with water}}/P_{\text{without water}}] \times 100, \quad (8)$$

where $P_{\text{with water}}$ and $P_{\text{without water}}$ are the peak pressure from the explosion with and without water-jacket, respectively. The percentage peak pressure reductions obtained from our simulation are in general lower than the experimental data. Figure 13 shows that the numerical calculations are within 30% difference with the ex-

Fig. 11. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ($R = 2.6$).

Fig. 12. Comparison between experiment and computation for 1.36 kg C4 charge detonation with water ($R = 3.3$).

perimental data. There is an experimental value which is much lower than the calculated value.

In Fig. 14, most of the calculations are within 30% difference with the experimental data. However, there is one experimental value which shows very significant percentage peak pressure reduction of more than 50% as compared to the calculated values of about 30%. These differences are acceptable since the consistency and accuracy of the experiment would not be perfect and in addition, the approximations in the numerical method and the material modeling also contribute to the differences. In general, as the ratio of water to explosive charge weight is increased, the percentage reduction of the peak pressure also increases. However, this increase of water-explosive ratio is limited by the

Fig. 13. Percent peak pressure reduction versus water-explosive ratio for location AB-7.

Fig. 14. Percent peak pressure reduction versus water-explosive ratio for location AB-9.

volume of the chamber. Hence, there is an upper limit for the water-explosive ratio which can be used for effective mitigation of an explosion.

Finally, plots of pressure and impulse versus time from the computation are shown in Fig. 15 for 1.36 kg C4 charge detonation with and without water (water-explosive weight ratio = 2.6). Pressure and impulse time-history curves from the experiment [3] were not available and hence, no comparison is made. It is clearly seen from this figure that there is significant peak pressure reduction when water is used and shock arrival time is also delayed.

Fig. 15. Pressure and impulse versus time of computation for 1.36 kg C4 charge detonation with water-explosive ratio of 2.6 for location AB-11.

5. Conclusion

The present study demonstrates that the numerical simulations are in good agreement with the experiments for explosion with and without water. These results from our simulations and the experimental findings, demonstrate the potential and effectiveness of water in reducing peak pressures from an explosion. Results also show that significant pressure reduction can be achieved with increase in the water-explosive ratio.

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