EXPERIMENTAL ANALYSIS OF BLAST MITIGATION ASSOCIATED WITH WATER SHEETS

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Abstract. An explosion yielding a blast wave can cause catastrophic damage to a building and its personnel. This threat defines an immediate importance for understanding blast mitigation techniques via readily available materials. An unconfined mass of water in the form of a free flowing sheet has been experimentally tested and analyzed as a readily available mitigant. A single water sheet, with an approximate sheet thickness of 3 mm, was experimentally tested with an explosively driven shock tube at three different standoff distances. At the strongest shock strength considered, the water sheet decreased the peak overpressure of the blast wave by 80% and the impulse by 60%. Additionally, the peak overpressure transmitted through the water sheet was roughly constant regardless of standoff distance and explosive strength.

Keywords: Water blast mitigation, water sheet, explosively driven shock tube, protective water barrier.
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INTRODUCTION

Since 1968, bombing has accounted for nearly half of international terrorist attacks [1]. To counter these threats, defensive mechanisms, such as blast mitigants, need to be deployed quickly and effectively to protect structures and individuals from explosively driven shock waves. In this work, protection by a free flowing water sheet is considered.

Blast mitigation using water has been studied since the early 1970's [2]. Water configurations considered include sprays, confined masses of water, and water sheets [2]. Numerical models of water sheets by M. Cheng and associates predicted that at a larger distance from the blast source, more water is needed to obtain the same level of mitigation seen at smaller distances [3]. From these models it was also predicted that the peak pressure transmitted through the water was not significantly affected by changing the standoff distance.

The objective of this research was to experimentally investigate the blast mitigation potential of a water sheet. Additional emphasis was placed on understanding the mitigating mechanisms. A water sheet experimental configuration was developed and utilized to study these objectives.

EXPERIMENTAL SETUP

An explosively driven shock tube was used to produce a laboratory size blast wave. Previous work has shown that an explosively driven shock tube can yield a blast profile similar to open field explosive tests [4, 5]. The explosively driven shock tube directs the energy from the blast in one direction allowing the use of less explosives as compared to an open field explosive test.

A schematic of the experimental setup is seen in Fig. 1. A sheet of water was generated with a custom fabricated water sheet generator, which operated at a constant flow rate of approximately

56 L/min, producing a laminar sheet approximately 3 mm thick. The incoming blast wave was approximately normal to the water sheet and the pressure gauges as seen in Fig. 1. Due to space constraints near the water sheet, typical pencil gauges could not be used without disrupting the flow of the water sheet. Therefore, PCB 113A22/113B22 piezoelectric dynamic pressure sensors where used. Based on an analysis using a high-speed shadowgraphy video and the Rankine–Hugoniot jump conditions [6], the measured pressure approximates the shock wave stagnation pressure.

In an experiment, the explosively driven shock tube was loaded with 3 grams of Primasheet 1000. By changing the distance of the shock tube from the water sheet (standoff distance), the characteristics of the incident blast wave were altered. Decreasing the standoff distance increased the overpressure experienced at the water sheet.

The experimental configuration included two pressure gauges placed behind the water sheet to measure the properties of the blast-wave after passage through the water sheet. In all experiments, the gauges were placed 5 cm and 23 cm behind the water sheet. In the results reported in the next section, blast tests at three standoff distances are considered: 49 cm, 38 cm, and 33 cm from the exit of the shock tube. To verify repeatability, all experiments were performed twice.

EXPERIMENTAL RESULTS

Figure 2 shows the pressure traces for all four pressure gauges with a standoff distance of 33 cm. Figure 3 shows a zoomed in view of the transmitted shock wave. Additionally, Tables 1, 2, and 3 show the free field blast parameters, pressure measurements after the water sheet (for the two air-gaps of 5 cm and 23 cm), and the mitigation seen for each standoff distance, respectively. Table 4 shows a comparison of these two different air-gap sizes at the different water sheet standoff distances. The standard error shown in Tables 1, 2 and 3 quantifies the variation observed between the two experiments performed at each condition.

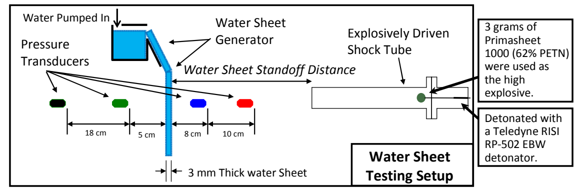

Figure 1. Experimental arrangement.

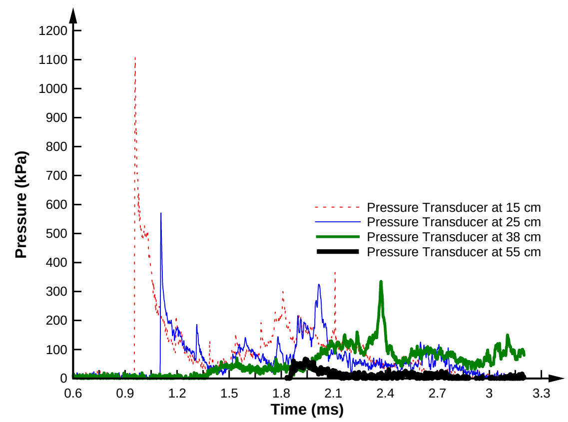

Figure 2. Pressure recorded when the water sheet is at a 33 cm standoff distance.

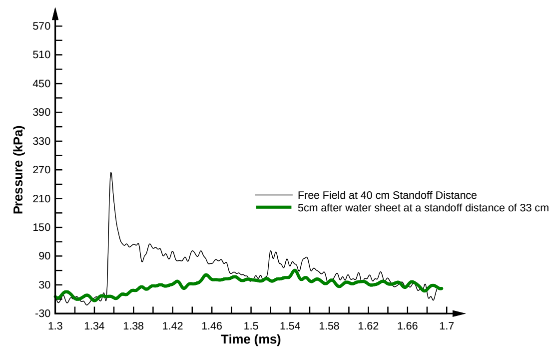

Figure 3. Pressure recorded 5 cm behind water sheet at 33 cm standoff distance vs. free field pressure at 41 cm standoff distance.

Table 1. Free field pressure readings.

Standoff Distance (cm)	Overpressure (kPa)		Pulse Pulse Duration (ms)		Impulse (kPa-ms)	
	Average	Standard Error	Average	Standard Error	Average	Standard Error
31	502.6	0.4	0.36	0.05	40.0	0.3
41	259.2	0.7	0.35	0.03	22.1	0.2
53	148.9	0.4	0.33	0.03	17.2	0.1
71	90.3	1.3	0.37	0.07	11.4	0.8

Table 2. Pressure readings 5cm and 23 cm after the water sheet.

Gauge distance after water sheet (cm)	Standoff Distance (cm)	Overpressure (kPa)		Pulse Pulse Duration (ms)		Impulse (kPa-ms)	
		Average	Standard Error	Average	Standard Error	Average	Standard Error
5	33	59.3	0.5	0.38	0.01	10.3	0.1
5	38	54.1	0.2	0.46	0.13	15.9	1.0
5	48	45.9	0.4	0.45	0.05	10.3	0.2
23	33	58.3	0.3	0.31	0.02	11.0	0.3
23	38	57.2	0.1	0.41	0.01	8.3	0.2
23	48	39.6	1.3	0.37	0.03	7.6	0.1

Table 3. Mitigation 5 cm behind the water sheet and 23 cm behind the water sheet.

	5 cm Behind the Sheet			23 cm Behind the Sheet		
Standoff Distance (cm)	Over-pressure Mitigation	Impulse Mitigation	Positive Pulse Mitigation	Over-pressure Mitigation	Impulse Mitigation	Positive Pulse Mitigation
33	80.4%	60.3%	-1.4%	58.7%	46.4%	17.8%
38	75.78%	26.6%	-22.3%	55.6%	60.2%	-4.2%
48	69.3%	48.8%	-20.7%	53.9%	58.7%	21.7%

Table 4. Comparison of effect of air-gap size at various standoff distances.

Water Sheet Standoff Distance (cm)	Pressure at 5 cm Air-gap	Pressure at 23 cm Air-gap	Percentage Difference
33	59.3 kPa	58.3 kPa	1.2%
38	57.2 kPa	54.1 kPa	5.1%
48	45.9 kPa	39.6 kPa	13.4%

The results show that the unconstrained free flowing water sheet significantly reduces the overpressure and impulse from the blast. At the 33 cm standoff distance the peak overpressure is reduced by 80% and the impulse is reduced by around 60%. At the smallest standoff distances considered, there is little variation in the pressure at the two separate air-gaps (Table 4). However, as the water sheet standoff distance increased, a larger variation was observed.

ANALYSIS AND DISCUSSION

The shock wave interaction with the water sheet was imaged with the shadowgraphy technique described in [7]. A video was taken at 11,494 fps and exposure of 26 μs using a Vision Research Phantom v7.3 digital high-speed camera and an Oriel 1000 W xenon arc lamp. Select images from the high-speed video are shown in Fig. 4. The video was taken without pressure gauges to minimize obstructions to the incident, reflected, and transmitted shock waves. The reflected wave seen in the third image is due to the impedance differences between the air and water. In the fourth image a weak transmitted shock wave is observed.

The speed of the incident shock wave and transverse wave were estimated from the spacing of the pressure gauges and recorded times between pressure peaks. The Mach numbers (M) were estimated (assuming the acoustic speed of sound of air, a=340.3 m/s at sea level in US standard atmospheric conditions) [6]. The estimated Mach numbers for the different water sheet standoff distances where all less than the free field tests. The Mach number was found for each water sheet distance to be above the speed of sound (M=1) indicating a shock wave has formed following the interaction with the water sheet. Comparison with the free field Mach numbers indicate that the transmitted shock wave has been attenuated by the water sheet.

The high-speed shadowgraphy images reveal a noticeable change in the thickness of the water sheet before the shock wave reaches the downstream pressure gauge. The observed shadow is believed to be caused by breakup of the liquid sheet into smaller fragments of water. The sheet breakup may explain the change in the pressure profile at 5.1 cm after the water sheet as seen in Fig. 3.

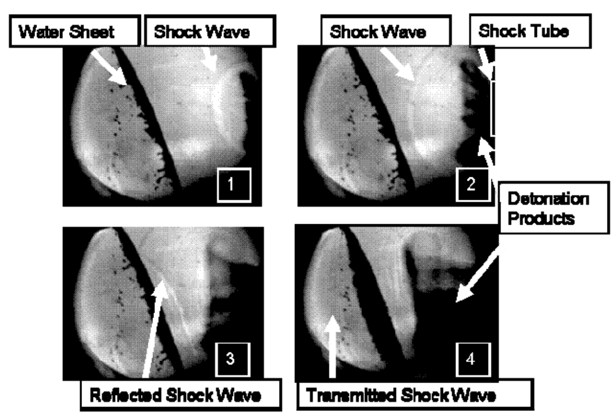

Figure 4. High speed shadowgraphy of water sheet at 33 cm standoff distance.

In Fig. 5, the peak overpressure after the water sheet is compared to the free field tests. This figure shows the relationship between the peak overpressure and the standoff distance (shock strength). At the smallest standoff distance, the largest peak overpressure mitigation was seen. Additionally, changing the standoff distance did not significantly affect the transmitted peak overpressure. These two findings agree qualitatively with numerical models of water shields studied by M. Cheng and associates [3].

CONCLUSIONS

Blast mitigation testing using a single water sheet of 3 mm thickness has been completed. An experimental configuration for generating a water sheet was developed and studied at three different water sheet standoff distances with an explosively driven shock tube. The water sheet mitigates the recorded peak overpressure up to 80% and impulse up to 60% at the smallest standoff distance. The peak overpressure mitigation is a function of the standoff distance (shock strength). The transmitted peak overpressure through the water sheet is roughly constant regardless of standoff distance. These two findings agree qualitatively with numerical models of water shields studied by M. Cheng and associates.

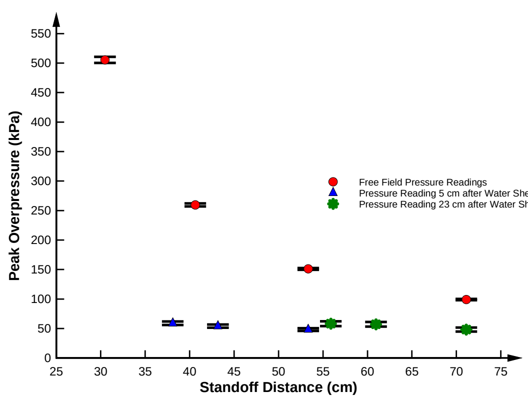

Figure 5. Peak overpressure as a function of standoff distance. (Error bars represent standard error between measurements)

Initially there was little variation in the pressure at the two separate air-gaps. However, as the water sheet standoff distance increased, a larger variation in the pressure at the two air-gaps was seen. The larger standoff distances and weaker incident shock have more dependence on the air-gap size after the water sheet. The water sheet appears to break apart and initially transmit a shock wave very close to the speed of sound (M=1).The experimental results show promise for water sheet mitigation as a possible solution for the protection of structures from explosive blast loading.

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REFERENCES

1. National Research Council. Protecting Buildings from Bomb Damage: Transfer of Blast-effects Mitigation Technologies from Military to Civilian Applications. Washington, DC: National Academy, 1995. Print.
2. Kailasanath, K., Tatem, P.A., Williams, F.W., and Mawhinney, J., "Blast Mitigation Using Water - A Status Report," NRL Memorandum Report 6410-02-8606, 15 March 2002.
3. Cheng M., Hung K.C., and Chong O.Y., "Numerical study of water mitigation effects on blast wave", Shock Waves, v. 14, n. 3, 2005, pp. 217-223.
4. Freiwald, D.A.; "Approximate Blast Wave Theory and Experimental Data for Shock Trajectories in Linear Explosive Driven Shock Tubes," Journal of Applied Physics, vol.43, no.5, pp. 2224-2226, May 1972 .
5. Alley, Matt D. "Explosive Blast Loading Experiments for TBI Scenarios: Characterization and Mitigation." Thesis. West Lafayette, IN / Purdue University, 2009. Print.
6. Zucrow, Maurice J., and Joe D. Hoffman. Gas Dynamics. New York: Wiley, 1976. Print.
7. Settles, G., "High-Speed Imaging of Shock Waves, Explosions, and Gunshots," in American Scientist, Vol. 94, No. 1, 2006, pp. 22-31.