INVESTIGATION INTO THE EFFECTS OF WATER-BASED CONTACT CHARGES

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ABSTRACT

Law enforcement agencies commonly use combinations of explosive charges and water containers. Commercial companies already propose off-the-shelf products based on water-tamped explosive devices using the principle of impulse profile modification. The objective of this concept is to characterize the efficiency of bare explosive charges while minimizing surrounding blast effects in order to mitigate collateral damage, as a significant part of the energy of the explosion is transferred to the water in the form of kinetic energy. Based on existing and already-in-use geometries and volumes, we designed reference explosive charges comprising C4 parallelepipedal charges and water containers. In this study, the loading of the system was evaluated using a ballistic pendulum able to record the total mechanical load transferred. By recording the trajectory of the pendulum, it is possible to determine the transferred impulse. Influence of the ratio between explosive and water was investigated to analyse the system breaching efficiency and potential collateral damages. Collateral damage includes not only water ram effect, but also air blast effects. A side-on pressure sensor was consequently installed near to the pendulum to evaluate the influence of the water on peak overpressure propagating in the breach environment. Initial propagation of the blast wave occurs in aqueous medium. Comparison with high-speed images recorded during previous underwater detonation tests conducted close to water surface or reflective surfaces was thus possible. This analysis provided guidelines for future work on the optimization of water-based contact charges.
Keywords: blast, explosion effects, combined effects, water-based experiments, protection of infrastructures, pressure sensors, high-speed videos.

1 INTRODUCTION

The use of water in close range to an explosive event to mitigate blast and fragment effect damage radius is well documented in literature. It is especially efficient for enclosed ammunition storage facility and flexible in the case of overseas military operations [1]. Water is cheap, readily available in most places, easy to scale up even for very large amounts of explosives and does not present any transport or storage challenge.

Demolition devices are often composed of a breaching charge responsible of the severance of metal elements and a kicker charge consequently able to break out of balance the damaged structure to achieve the destruction. Bauer et al. [2] investigated the use of water-cased kicker charges. The goal is to reduce the fragmentation of steel members, and the quantity of explosive needed due to the increased density, incompressibility, and impedance mismatch water provides, using numerical simulations and experimental tests. In Baciu et al. [3], the authors present a comparative study between breaching charges effects on reference doors, experimental results and numerical simulation. Different types of doors are analysed, showing the complexity of the interaction between a multiphase water-based charge and a realistic door. In order to unify the charge choice for the different types of door resistances classes defined in well-established international standards, Sedláček and Palasiewicz [4] proposed a global approach suitable for operational forces. The objective is to secure the entry while minimizing the necessary amount of explosive used for Czech Army applications.

In Rus et al. [5], the authors focused on the determination of collateral effects (on personnel and environment) of metal breaching explosive charges. They consequently tend to reduce the charge mass and increase their efficiency. On this occasion, they demonstrated that there are very large differences between the effect obtained with similar devices on surface compared to the effect obtained in immersion. Most of the time a quantity of explosive that on land led to the desired effect, under water only deformed the same metal structure; in order to obtain similar results, a significantly larger quantity had to be used. Moldovan et al. also investigated human vulnerability of breaching charges in Moldovan et al. [6]. To create breaches, two different kinds of special explosive devices were used, according to the obstacle: cutting and pushing charges. Cutting charges are based on metal projection, pushing charges on water projection, using the properties of a layer of water to alter the pressure load on the target.

Finally, water-based charges are also commonly used for blasting rocks. In Li et al. [7], the authors present a numerical study of the water coupling coefficient on the blasting effect of red sandstone samples analysed with CT scanning and 3D reconstruction. Their goal is to predict the observed damage on the samples by defining an optimal coupling coefficient.

At DEND (the French Institute for Protection and Nuclear Security), we decided to go one step back, from realistic pieces of opening devices to reference target, however realistic in size, submitted to explosive charges combined with water. One of DEND missions is to carry out studies to support expertise in the security of nuclear and radioactive materials, their installations and their transport, against malicious acts. Concretely, our actions consist in assessing the performance and vulnerability of a physical protection system such as a wall, a steel container, a concrete infrastructure, windows or multi-material security doors for instance. To achieve that, we have to conduct relevant experiments to evaluate the load transferred by these explosive devices. Given that water is an incompressible medium, it is natural that the effects of similar explosive charges notably differ between air and underwater environments [8]. Consequently, the direct output of a hybrid water explosive charge should also be different when the objective is to examine the resistance of a material. We believe that future research focusing on measuring the pressure evolutions produced by the shock wave front resulting from underwater detonations of various quantities of explosives would be useful to better understand mechanical effects of these specific explosive devices. In this work, we therefore propose an approach linked with theoretical and applied studies based on experimental setups designed to characterize shock waves generated by either submarine or aerial explosions. We used a ballistic pendulum in addition to pressure gauges to evaluate the effect induced by a C4 reference explosive charge combined with water onto a metallic plate placed in contact as well as through the surrounding environment in open field.

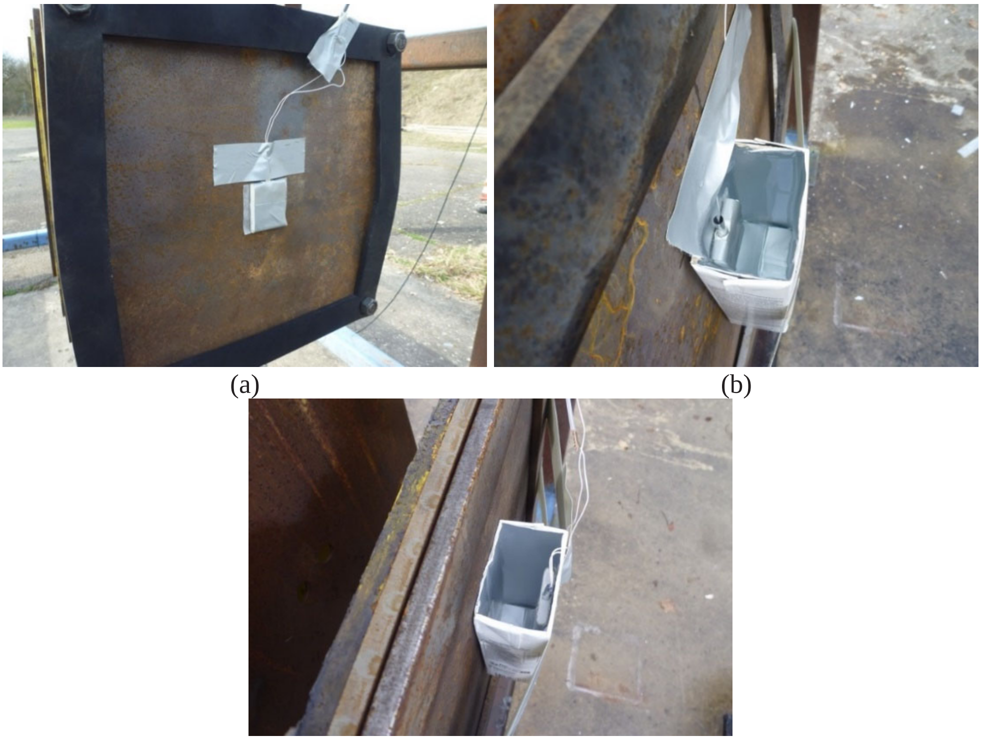
2 EXPERIMENTAL SETUP – METROLOGY

2.1 Explosive charges

Fig. 1 presents the 50 g C4 parallelepipedal charge combined or not with a 1,000 g water pack and an exploding bridgewire (EBW) RP83 detonator used for ignition.

Charge is placed in contact with a S235 steel (structural steel for building and welding) plate fixed with adhesive to the ballistic pendulum system described hereafter.

Three consecutive tests (#2735, #2728 and #2731) were conducted with the same C4 explosive charge. Test #2735 is performed with bare C4 charge, whereas the two other ones include water pack: water envelope is on the plate side for #2728 (namely front water pack)



(a) (b) (c)

Figure 1: Explosive charges. (a) Bare charge; (b) 1,000 g water pack in the back; and (c) 1,000 g water pack in front.

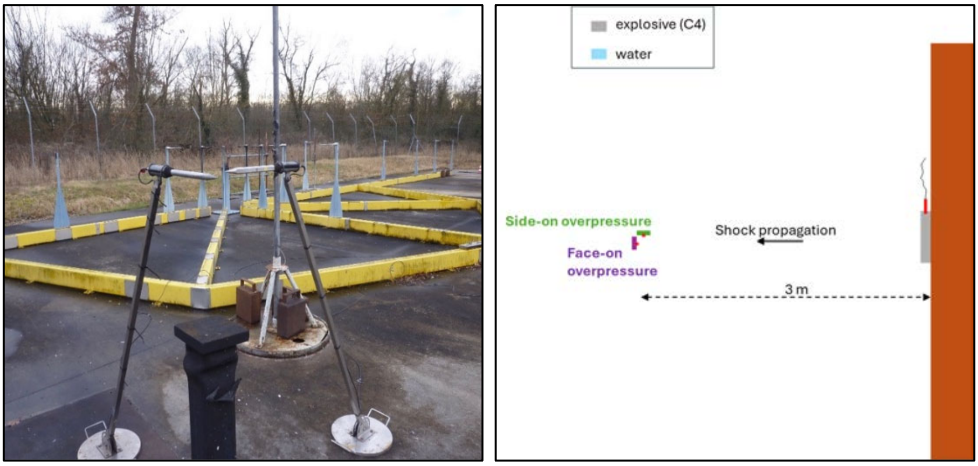
Table 1: Charge specifications and configurations.

Charge reference	C4 mass (g)	Front water pack (g)	Back water pack (g)
2735	50	–	–
2728	50	1,000	–
2731	50	–	1,000

and on the free field side for #2731 (namely back water pack). The three charges specifications and configurations are summarized in Table 1.

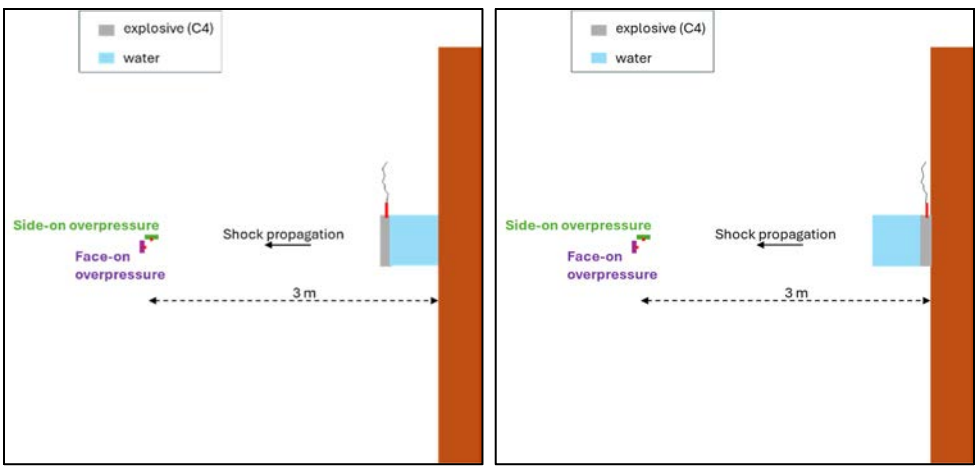
2.2 Pressure sensors

Two PCB 137 B pressure gauges were installed at 3 m in front of the ballistic pendulum, facing the centre of the plate. One gauge was recording the side-on evolution (or incident) while the other was recording the face-on evolution of pressure (or reflected). PCB pencil probes are shown in Fig. 2(a). Blast pencil probes are flush mounted on 1.5 m posts. Fig. 2(b) and Fig. 3 present schematic representations of the experimental configurations with or without water pack.



(a) (b)

Figure 2: (a) Side-on and face-on pressure gauges; and (b) Schematic of experimental setup with bare charge.



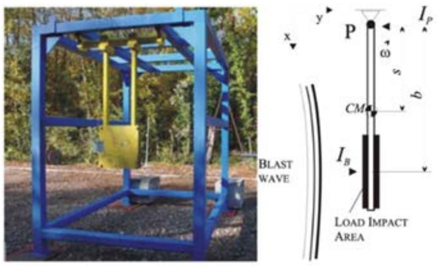
(a) (b)

Figure 3: Schematics of experimental setup with hybrid water charge. (a) Front water pack; and (b) Back water pack.

2.3 Ballistic pendulum

To evaluate the total loading generated by the various charges, we used ISL ballistic pendulum (Fig. 4), developed to assess heterogeneous blast effects [9]. The pendulum provides an evaluation of the total specific impulse (see eqn (1) below) transferred to its surface by measuring the maximum angle of deflection and using the principle of total energy conservation between the initial and the final position of the pendulum.

$$i_B = \frac{I_B}{A} = \frac{1}{A.b}\sqrt{2J_{Pz}\text{mgs}(1-\cos\varphi_{\max})}. \quad (1)$$



Quantity	Value
Distance s	0.47 m
Distance b	1.25 m
Surface of the impact plate (load impact area) A	0.25 m^2
Total pendulum mass m	155 kg
Moment of inertia at pivot point P J_{Pz}	88 kg m^2
Gravitational acceleration g	9.81 m/s^2

Figure 4: ISL Ballistic pendulum. *(Source: Sturtzer, 2008.)*

3 IMPULSE AND OVERPRESSURE

Table 2 presents ballistic pendulum results: maximum angle of deflection in degrees, corresponding impulse in bar.ms, and relative impulse in comparison to the bare charge (in %). Relative impulse is defined as the ratio between hybrid charge impulse and bare charge impulse.

Table 2: Ballistic pendulum results.

Charge reference	**Water configuration**	**Angle (°)**	**Impulse (bar.ms)**	**Relative impulse (%)**
2735	–/– (bare)	15	0.16	100
2728	1,000/– (front water)	23	0.24	153
2731	–/1,000 (back water)	37.5	0.39	246

We observe that the back water charge (C4 directly in contact with the pendulum plate) induces the highest increase of mechanical load on the steel plate with a 146% increase factor. This increase is almost three times higher than the one provided by the front water charge (seen in Fig. 5).

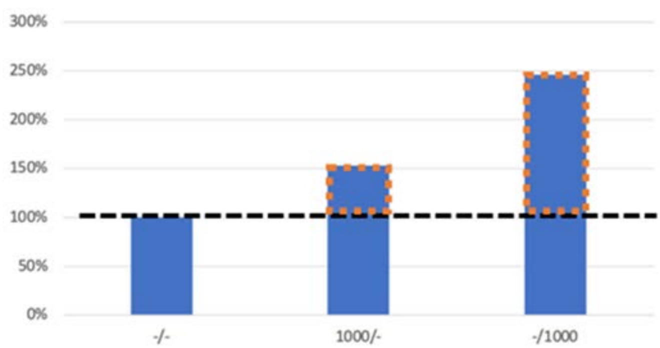


Figure 5: Relative impulses generated by explosive charges (the impulse increase provided by hybrid charges is represented in orange).

Table 3 reports pendulum results and experimental overpressures recorded at a 3 m distance by PCB sensors. P_i refers to incident overpressure measured by the side-on gauge, and P_r to reflected overpressure measured by the face-on gauge. Recorded times of arrival are respectively denoted ta_i and ta_r. For the sake of comparison, Kinney and Graham [10] (namely KG) theory values (incident overpressure, time of arrival and impulse) are presented for the bare charge in Table 4. Against all odds, pendulum impulse for the bare charge is equal to KG impulse obtained at a 3 m distance.

Table 3: Ballistic pendulum results in green, in comparison with pressure gauges measures at 3 m (in grey), and Kinney and Graham theory at 3 m for a bare TNT charge.

Charge reference	Water configuration	Impulse (bar.ms)	P_i (bar)	P_r (bar)	ta_i (ms)	ta_r (ms)
2735	–/– (bare)	0.16	0.2	0.5	5.15	5.16
2728	1,000/– (front water)	0.24	0.2	0.5	5.09	5.16
2731	–/1,000 (back water)	0.39	0.18	0.39	6.52	6.56

Table 4: Kinney and Graham (KG) theory blast parameters at 3 m for a bare TNT charge.

Charge reference	KG bare charge			
	Impulse (bar.ms)	P_i (bar)	P_r (bar)	ta_i (ms)
2735	0.16	0.22	0.49	5.7

Recorded incident and reflected overpressures as well as incident time of arrival are also in good correlation with KG theory with a difference of less than 10%. Hybrid charge with water in front provides same levels of overpressures at 3 m, meaning that influence of water is not noticeable at a reduced distance of 8 m/kg$^{1/3}$ for this charge. This tendency is slightly different when it comes to the hybrid charge with water in back, which leads to a 10% attenuation at 3 m for incident overpressure, a 22% attenuation for reflected overpressure (represented by grey dotted lines in Fig. 6), and a 27% attenuation for time of arrival.

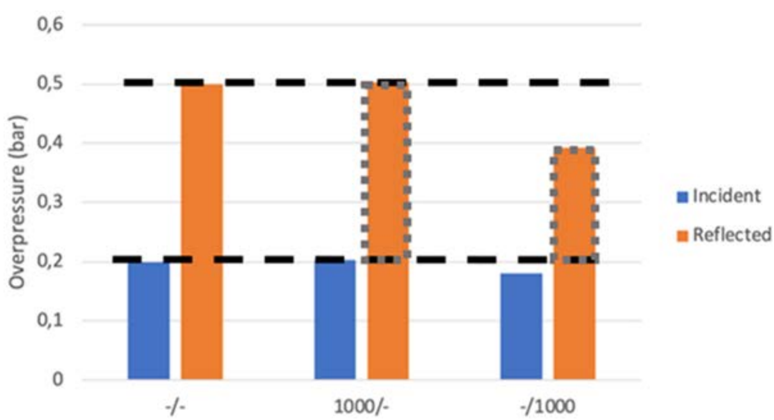


Figure 6: Peak overpressures (reflected in orange, incident in blue) at 3 m for 50 g C4 charges (the reflected overpressure attenuation provided by the hybrid back water charge is represented in grey).

4 HIGH-SPEED VISUALIZATION

Each test was filmed using a Phantom T3610 high-speed camera placed in the pendulum plate plane, at a 758 × 512 pixels resolution and 59,000 images per second.

Fig. 7 shows the detonation of the bare C4 charge. The pendulum plate is located on the right edge of the image. On the first image, the initial charge reaction is captured, with the intense light emission. On the second image, the fireball is developing, and the leading shock is progressively appearing on some part of the interface with fresh air. On the following images, the afterburning reactions intensity decreases, and the leading shocks separate from them, except for a visible central spike still propagating at a higher velocity, creating a conical shock wave. The remaining wave tends to become hemispherical.

Figure 7: High-speed visualization of the 2735 bare charge (–/–).

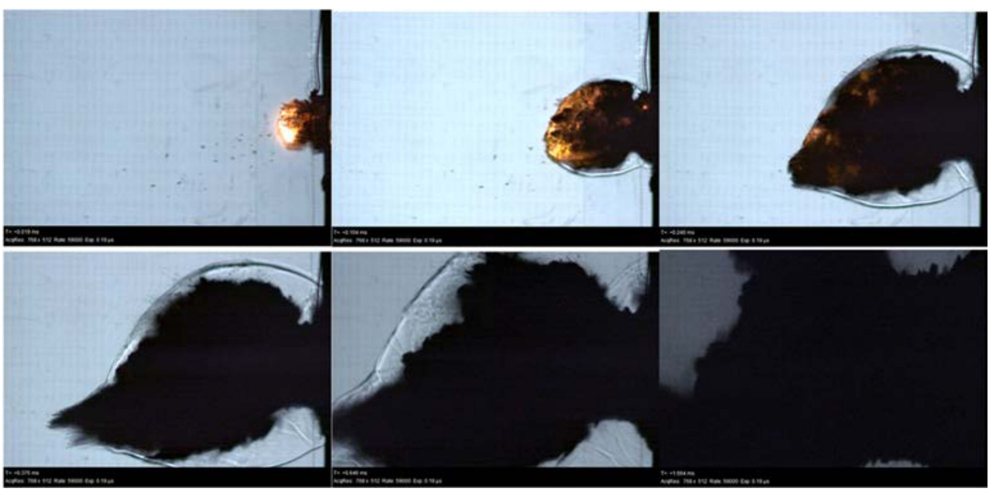


Figure 8: High-speed visualization of the 2728 charge with water in front (1,000/–).

In Fig. 8, the influence of front location of the water is visible: the fireball intensity is reduced in comparison with the bare charge as the afterburning reactions are quenched by the energy absorption of the dispersal and vaporization of water. From the third image, light emission is not visible anymore and the water volume jets out through the leading shock wave. The leading shock average propagation does not seem to be significantly affected by the presence of water, confirming the peak overpressure measurements at 3 m.

By setting the water volume behind the explosive charge (represented in Fig. 9), the propagation velocity of the leading shock is clearly slower as on the last image, it remains visible, unlike for the previous two tests. The water dispersion and vaporization decrease even further the intensity of afterburning reactions by blocking their access to fresh air and cooling them rapidly. The hemispherical shape of the leading is once again altered by a spike of projected water travelling at higher velocity.

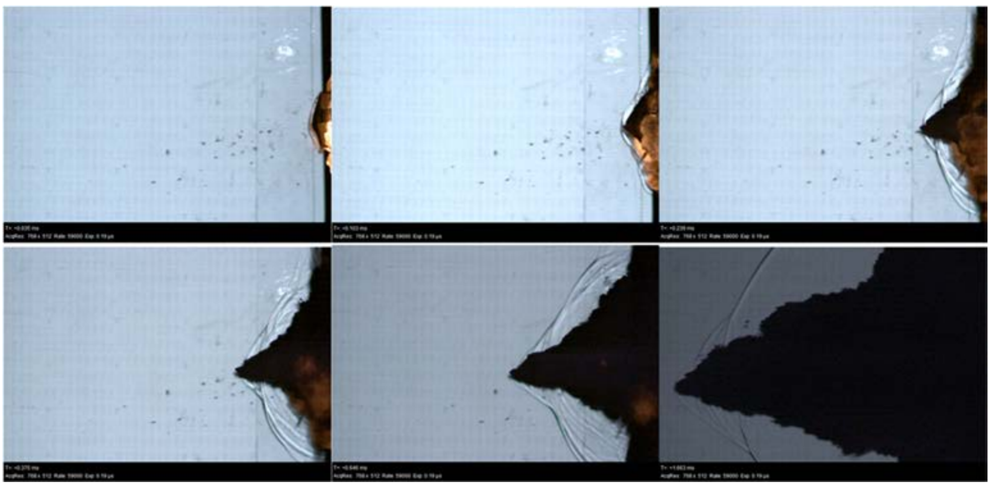


Figure 9: High-speed visualization of the 2731 charge with water in the back (–/1,000).

5 CONCLUSIONS

The influence of adding a volume of water to a reference explosive charge placed in contact to a metallic plate was assessed in this study. 1,000 g of water were placed in front and in the back of a 50 g C4 parallelepiped charge.

Total impulse and blast effects were assessed using a ballistic pendulum on which the explosive charge was fixed, free-field sensors facing the pendulum at 3 m and a lateral high-speed camera. Results showed a 53% and 146% increase of the total impulse transferred by the C4 charge by adding respectively the water in front of and behind it. Pressure measurements and high-speed images showed a significant decrease of the leading shock wave intensity for the water in the back and almost no alteration for the water in front.

Future work will include:

- the extension of the analysis of the peak overpressure field around the pendulum, using additional pressure sensor gauges with varying distances and azimuths, but also a larger field of view for the high-speed imaging, in order to record the shock velocity evolution with time and space, to compare both series of data;
- the further investigation of the ratio between the explosive and the water masses;

- the scalability assessment to larger explosive charges;
- a comparison with pressure profiles and high-speed images for underwater blast studies conducted in reduced-scale tanks (shown in Fig. 10 for instance).

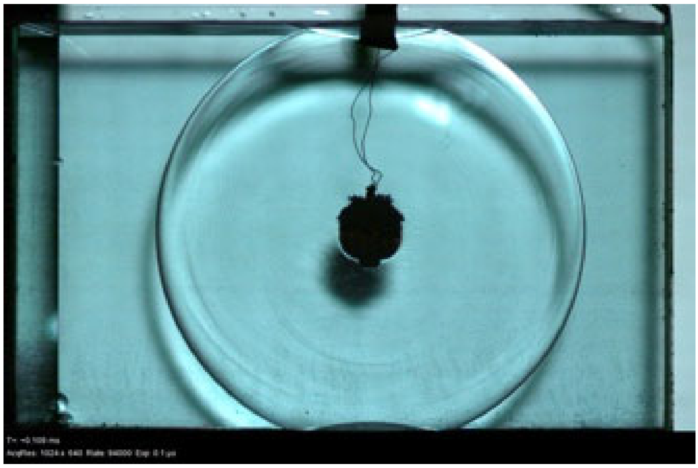


Figure 10: High-speed visualization of an underwater shock wave propagating in a reduced-scale fishtank [11].

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