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WATER PENETRATION BY HIGH VELOCITY PROJECTILES

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ABSTRACT

We report on an experimental and analytical study of the hypervelocity projectile penetration of water. The projectile was formed by a shaped explosive charge and its penetration characteristics were recorded with multiple flash radiography. Projectile penetration was supersonic with ablation occurring at the projectile tip; emanating from the tip region was an approximately 80° conical shaped, bow wave shock. A slender cavity was formed around the penetrating projectile. The penetration velocities predicted by a steady state penetration theory which includes consideration of compressibility at the projectile/water interface region are in reasonable agreement with experiment.

INTRODUCTION

The development of validated predictive models for the hypervelocity penetration of fluids and low density materials is important to several areas of defence technology. Relatively recent theoretical considerations by Flis and Chou (1983) and Haugstad and Dullum (1981) indicated that the omission of the effect of compressibility at the projectile/target interface could reduce predicted penetration depths by up to 50%. The compressibility effect was shown to be greatest where the target material is appreciably more compressible than the projectile i:e metal projectiles penetrating liquids and plastics. Experimental evidence by Woidneck (1986) using copper rods penetrating water did not support a significant compressibility effect. However, Chick et al (1990) using a slightly modified theoretical approach to that of Flis and Chou (1983), produced a much smaller compressibility effect that was in reasonable agreement with their experimental data obtained from a copper projectile penetration of plexiglas (polymethyl methacrylate); the presence of a compressibility effect produced a reduction in the computed penetration depth of about 10%.

In this paper we report on the experimental determination of the hypervelocity, copper projectile penetration of water and compare the results to analytical predictions which include considerations of compressibility at the projectile/water surface.

EXPERIMENTAL

The copper projectile was produced by a standard technique using a shaped explosive charge [Birkhoff et al 1948]. Our charge was 38 mm diameter and incorporated a 1 mm thick, hollow copper cone with a 42° apex angle in intimate contact with a conical cavity in the forward end of the explosive filling. Briefly, the formation of the projectile by this technique is that the detonating explosive collapses the metal cone to its axis in such a manner that it hydrodynamically forms a high velocity continuously stretching metal jet. The stretching jet normally breaks up after a jet flight distance equivalent to about 4-6 shaped charge diameters.,

Our 38 mm diameter shaped charge was filled with the explosive, Composition B (RDX/TNT, 55/45, density 1.65 g/cm^3) which produced a copper jet whose velocity decreased from 7.4 km/s at the tip to less than 2 km/s at the rear end; the jet diameter was about 1.5 mm [Chick et al 1987].

Projectile penetration velocities in water were measured using multiple flash radiography techniques of the type described by Bussell and Chick, 1992. This is a versatile and direct instrumental method that can be used to investigate a range of hypervelocity projectile interactions which occur inside a material, or which may be obscured by smoke, fire or other reaction products.

These experiments were carried out with a four channel flash X-ray system. Two orthogonal 300 kV and two orthogonal 600 kV pulsers were arranged around the common central axis-of-flight of the shaped charge jet.

The 300 kV and 600 kV flash X-ray pulsers produce 20 ns and 30 ns duration pulses respectively and their different energies were used to highlight different densities within the subject, to different degrees.

The flash X-ray pulsers were triggered from a probe positioned on top of the water column. A delay was set into the system to trigger the pulsers at times based on the estimated position of the jet a various distances into the water column.

Four flash radiographs were taken in each experiment over a range of jet positions from 40 mm to 220 mm into the water. Typical interframe times were a few tens of microseconds. Images were recorded by a film and a florescent intensifying screen combination placed in protective cassettes and positioned near the charge/water column. Jet penetration velocities were calculated from the radiographic images and recorded times.

The shaped charge was fired from 76 mm (two shaped change diameters) standoff down the central axis of a 69 mm diameter thin walled PVC cylinder filled with water. Fiducial points were included in the setup for the measurement of the jet position.

SUMMARY OF THE ANALYTICAL MODEL

An excellent survey of jet type projectile penetration models has been published by Walters et al (1988). The theoretical model used in our study is based on the treatment of Flis and Chou (1983) with some modifications by Frey as reported by Chick et al (1990).

The model assumes one dimensional steady state penetration and takes account of the velocity gradient along the jet. It also makes use of the virtual origin approximation which assumes that the jet is formed from a single point in space and time (Allison and Vitali, 1963). These principles form the basis of the DiPersio et al (1964) penetration equation for a continuous jet that is used in the model,

$$V_j = V_o \left[\frac{S}{P+S} \right]^{\gamma} \qquad (1)$$

where V_j is the jet velocity at a point in the target (water) of depth, P, V_o is the initial jet tip velocity, S is the distance from the virtual origin to the surface of the target and $\gamma = \sqrt{\rho_t/\rho_j}$ where ρ_t is the target density and ρ_j is the jet density. V_j is related to the observed jet penetration velocity, U, by

$$U = \frac{V_j}{1 + \gamma} \qquad (2)$$

Modified forms of this equation treat the cases where the jet breaks up during penetration or before penetration.

Theoretical considerations suggest that the total penetration depth of a jet type penetrator in a compressible material may be significantly less than that produced by classical incompressible, hydrodynamic theory; one reason is the need to consider the consequences of the standing shock that may be set up in the jet tip region and the target. The effect is expected to increase with jet velocity and with an increase in the relative difference in compressibility between the target and jet; both conditions are important in our study.

In order to determine the condition in the compressed zone, consider steady state penetration and view the process as seen from the stagnation point adjacent to the jet tip. At a distance, target material flows towards the stagnation point at a velocity, *U*, which is the penetration rate. Jet material moves towards the stagnation point at a velocity V_j - *U*. In our case, the penetration rate is supersonic with respect to the target, so there is a shock in the target propagating at velocity *U* with respect to the target. The changes in particle velocity, density and pressure across this shock are computed from the shock jump conditions (Rankine-Hugoniot equations) and the Hugoniot of the target material (Courant and Friedrichs, 1948).

Between the shock and the stagnation point we assume insentropic flow and apply the differential form of the Bernoulli equation,

$$VdV + \frac{dP}{\rho} = 0 \qquad (3)$$

where V is the flow velocity with respect to the stagnation point, P the pressure, and ρ the density. This equation has the same form as the incompressible Bernoulli equation, but the density is now a variable. To solve for P as a function of V, we combine the Bernoulli equation with the equation of state in differential form,

$$dP = \frac{\delta P}{\delta \rho}(\rho,e)d\rho + \frac{\delta P}{\delta e}(\rho,e)de \qquad (4)$$

which gives the pressure as a function of density, ρ, and internal energy, *e*, and we also use the first law of thermodynamics, which for isentropic flow is:

$$de = \frac{P}{\rho^2} d\rho \qquad (5)$$

Equations (3) - (5) may be integrated numerically to give the pressure P and the density ρ at the stagnation point as functions of the velocity V.

To determine the penetration velocity, U, for a jet element with velocity V_j an initial guess is made at U. Considering the target material first. If a shock is present we determine the properties of the target immediately behind the shock using the Rankine-Hugoniot equations. Then using equations (3) - (5) we integrate numerically to determine the pressure at the stagnation point, P_t. The same procedure is repeated coming from the jet side to determine P_j and a comparison is then made between the two pressures. If $P_t > P_j$ we guess a lower value of U, and if $P_t < P_j$ we guess a higher value of U. The process is repeated until P_t and P_j are equal.

This procedure determines U as a function of V. In carrying out these calculations we used the Gruneisen equation of state and the parameters tabulated by Flis and Chou (1983).

RESULTS AND DISCUSSION

Two flash radiographs of the copper, jet type projectile penetrating through a water column are shown in Fig 1. Note that some of the detail on the radiographs discussed below is not so clear in the reproductions shown in Fig. 1. Measured and calculated jet penetration velocities are compared in the graph in Fig. 2.

Our full sequence of flash radiographs showed that the major features set-up in the early stages of the penetration accompanied the projectile during its passage through the water; thus demonstrating the steady state

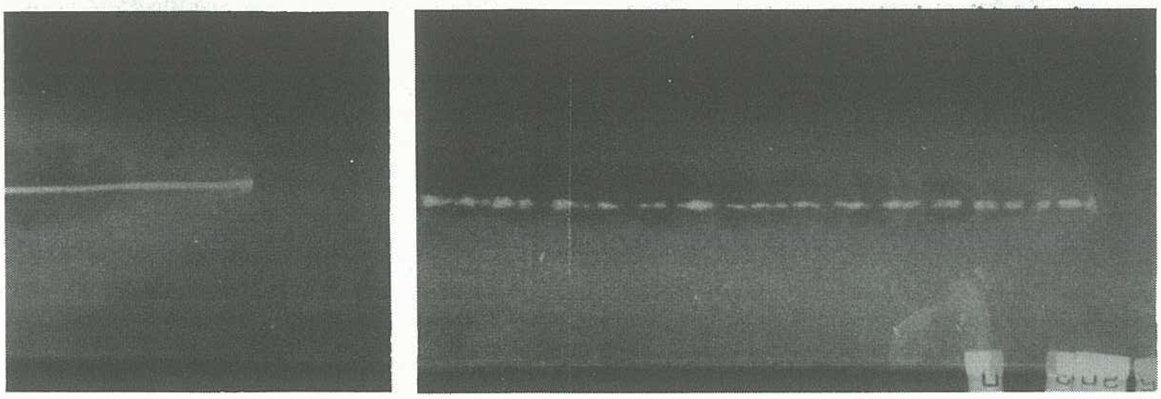
(a) (b)

FIGURE 1. Flash X-ray pictures of the copper jet penetration of water at distances of (a) 62 mm, and (b) 227 mm into the water.

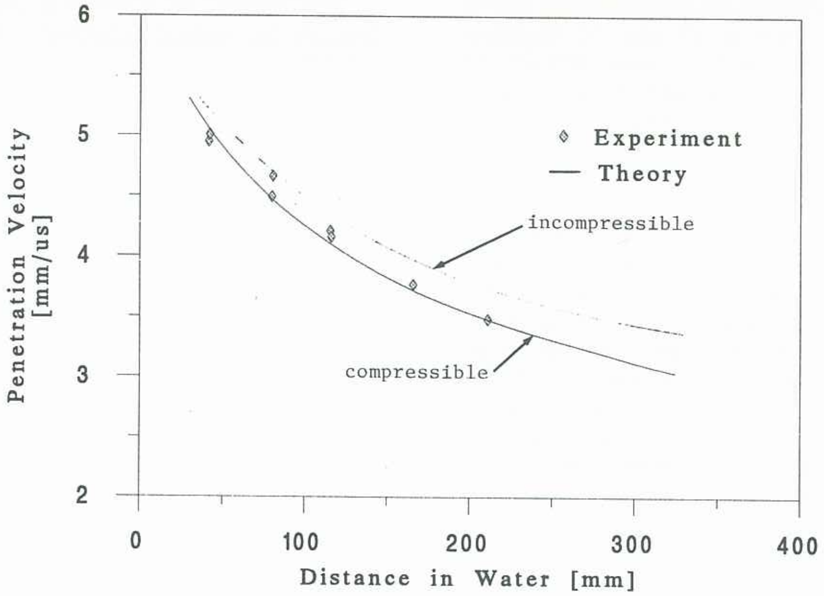

FIGURE 2. Penetration Velocity vs Distance into Water

nature of the process. Reference to Fig. 1(a)shows that a standing bow wave shock is formed a few millimetres in front of the jet tip. The bow wave is then observed expanding conically making an angle of about 40° to the jet axis. For a jet penetration velocity of 4.8 km/s this gives a shock velocity normal to the jet axis of 4 km/s which is close to 2½ times the sound speed in water. Also emanating from the projectile tip region is a slender conical cavity exhibiting marked turbulence at the water interface. Other radiographs show that near the water surface the cavity exhibits bulging which is attributed to the transient effects of initial projectile impact with the water. After about 150 mm penetration in the water the stretching jet starts to break up into short, rod shaped particles due to the internal velocity gradient imparted to it during formation. As penetration continues the velocity gradient increases the interparticular distance. During this phase of penetration flash radiography shows that the water forms "necks" into the cavity formed around the projectile (See Fig. 1(b)). The "necking" is attributed to the delay between the completion of the erosion of one jet particle and the impact of the following particle onto the forward face of the water cavity.

Fig 1(a) also shows mushroomed shaped ablation occurring at the jet tip. The high pressure and conditions which cause this effect are described by the compressible Bernoulli equations in the analytical model.

The results in Fig. 2 show that the jet is penetrating supersonically (sound speed in water about 1.4 km/s) and supports the assumption that the process can be regarded as steady state. Comparison of the experimental results with the theoretical predictions of the penetration rate (Fig. 2) shows that there is reasonable agreement with the compressible theory. The agreement allowed us to compute the effect of compressibility on penetration depth; this was done by considering all jet elements with a velocity greater than a selected value of V_j. The results show that compressibility effects are responsible for reducing the penetration depth by 10-15%. These conclusions are in accord with the results for the study of the hypervelocity penetration of plexiglas (Chick et al, 1990).

However, Woidneck (1986) did not detect a significant compressibility effect for a conventional copper rod penetrating water at an initial velocity of 3.7 km/s. His data suggests that the penetration rate was reduced by about 3.3% at the most by compressibility. We note that the penetration velocity in the study was significantly lower than the copper jet used herein and the difference may partly explain the different outcome from the two investigations.

Our study utilised a penetrator/target combination which, for a given penetration velocity, may be expected to maximise the compressibility effect; this suggests that its upper limit in the reduction of penetrator depth may be in the order of 10-15%.

It should be noted that we did not consider the latter stages of the metal jet penetration of water. This would involve factors not included in the model such as; (a) jet particles tumbling and moving off axis, (b) secondary penetration resulting from the large spaces between the particles and, (c) the type of penetration of the slower jet particles as they fall below the sonic limit.

CONCLUSION

Multiple flash radiography has been successfully applied to record the characteristics of hypervelocity projectile penetration of water. Important features of the supersonic penetration are ablation of the jet tip plus a conical shaped bow wave shock and a slender cavity around the projectile both of which emanate from the tip region. Predicted penetration velocities from an analytical model which assumes steady state penetration and includes the effect of compressibility at the penetrator/water interface are in reasonable agreement with experiment.

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