Effect of lateral confinement on penetration efficiency as a function of impact velocity

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Abstract

Numerical simulations are used to determine the dependence of normalized depth of penetration ($P/L$, where $L$ is the projectile length) as a function of the ratio of the target diameter to the projectile diameter ($D_t/D_p$) and impact velocity, $V_p$. The parameter space investigated was $3.25 < D_t/D_p < 20$, and $1.5 \text{ km/s} \leq V_p \leq 4.0 \text{ km/s}$. It was found that the penetration efficiency, $P/L$, at low impact velocities is a strong function of the normalized diameter (for $D_t/D_p < 20$), but that $P/L$ becomes less and less sensitive to $D_t/D_p$ as the impact velocity increases. The simulation results are used to understand this observation.

Keywords: penetration mechanics, confinement, penetration efficiency, target resistance, strength, inertial effects.

1 Introduction

It is well known that penetration is affected by the proximity of lateral boundaries of a target. Littlefield, et al. [1], conducted a systematic experimental and computational study to assess the dependency of penetration efficiency (as measured by the depth of penetration normalized by the initial projectile length, $P/L$) of tungsten-alloy, long-rod projectiles as a function of the ratio of target diameter ($D_t$) to projectile diameter ($D_p$). The targets were armor steel. The impact velocity in the experiments varied between 1.46 km/s to 1.55 km/s, and the results were adjusted to an impact velocity of 1.50 km/s. Agreement between the simulations and the experiments was excellent, as shown in fig. 1. It is seen in fig. 1 that the target appears to be essentially semi-infinite in lateral extent for $D_t/D_p > \sim 20$; but for $D_t/D_p < 15$, penetration begins to increase quite rapidly as $D_t$ decreases (for constant $D_p$).
In an idealized one-dimensional model, it might be thought that the projectile penetration pressure needs only to exceed the flow stress of the target material to penetrate. However, the projectile also needs to open a cavity (or penetration channel), that is, target material must flow radially [2, 3]. Thus, the resistance to penetration is significantly larger than that given by the target flow stress alone [3, 4]. Therefore, it can be reasoned that the penetration cavity should be easier to open if the lateral (radial) boundaries of the target are close to, in contrast to far way from, the penetration channel. In the study of Ref. [1], numerical simulations demonstrated that $P/L$ begins to increase when the extent of plastic flow in the target reaches the radial boundary, which occurred at $D_t/D_p \approx 15$.

In a recent experimental effort [5], it appeared that penetration performance was less affected by the presence of a lateral boundary at higher impact velocities (~3.5 km/s) than expected from the findings of Ref. [1]. Numerical simulations are used to investigate this observation, and to determine the dependence of $P/L$ as a function of $D_t/D_p$ and impact velocity. The same ratios of $D_t/D_p$ used in the previous study [1] where selected for this investigation (3.25 < $D_t/D_p$ < 20), and the impact velocity was varied between 1.5 km/s and 4.0 km/s in increments of 0.5 km/s.

2 Numerical simulations

Numerical simulations were conducted using the multi-material Eulerian wavecode CTH [6]. CTH uses the van Leer algorithm [7, 8] for second order accurate advection that has been generalized to account for a non-uniform and finite grid, and multiple materials. CTH is capable of simulating large
deformations in many types of materials, and has been improved to include advanced computational constitutive models [9, 10].

The Mie-Grüneisen equation of state was used to represent the pressure-density-internal energy response of the materials. The Johnson-Cook [11] viscoplastic model was used to determine the flow stress as a function of strain, strain rate, and temperature. Equation-of-state and constitutive parameters are given in Table 1. The melt temperatures for the projectile and targets materials were set to a high value to inhibit thermal softening, thereby permitting us to focus on confinement effects. The form of the Johnson-Cook constitutive model is given in Eqn. (1).

Table 1: Target and projectile material properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Projectile Tungsten Alloy</th>
<th>Target 4340 Steel Rc27</th>
<th>Target Al w/Rc27 Strength</th>
<th>Target Weak Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>17.7</td>
<td>7.85</td>
<td>2.70</td>
<td>7.85</td>
</tr>
<tr>
<td>$c_o$ (m/s)</td>
<td>3850</td>
<td>4500</td>
<td>5230</td>
<td>4500</td>
</tr>
<tr>
<td>$s$</td>
<td>1.44</td>
<td>1.49</td>
<td>1.37</td>
<td>1.49</td>
</tr>
<tr>
<td>$\Gamma_o$</td>
<td>1.58</td>
<td>2.17</td>
<td>1.97</td>
<td>2.17</td>
</tr>
<tr>
<td>$c_v$ (J/kg K)</td>
<td>135</td>
<td>450</td>
<td>922</td>
<td>450</td>
</tr>
<tr>
<td>$A$ (GPa)</td>
<td>1.35</td>
<td>0.735</td>
<td>0.735</td>
<td>0.00735</td>
</tr>
<tr>
<td>$B$ (GPa)</td>
<td>0.0</td>
<td>0.473</td>
<td>0.473</td>
<td>0.00473</td>
</tr>
<tr>
<td>$c$</td>
<td>0.06</td>
<td>0.014</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>$n$</td>
<td>1.0</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>$m$</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>$T_{melt}$ (K)</td>
<td>&gt;5000</td>
<td>&gt;5000</td>
<td>&gt;5000</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>$\sigma_{fail}$ (GPa)</td>
<td>2.50</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.30</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
</tr>
</tbody>
</table>

$$\sigma_{eq} = (A + B\varepsilon^n_p)(1 + C \ln \dot{\varepsilon}^*)(1 - T^*_m)$$

$$\dot{\varepsilon}^* = \dot{\varepsilon} / 1.0s^{-1} \quad T_e = \frac{T - T_{ref}}{T_{melt} - T_{ref}}$$

All simulations were performed assuming two-dimensional axial symmetry. Ten zones were used to resolve the projectile diameter; this zoning was maintained to a distance of 25 projectile diameters axially and 10 projectile diameters radially into the target. Beyond this large deformation region, zones were increased at a cumulative rate of 5%. The target material was modelled as 4340 steel heat treated to Rockwell C hardness Rc27. The projectile was modelled as a tungsten alloy, with a hemispherical nose, and a length-to-diameter ratio ($L/D_p$) of 10. The diameter of the projectile was 0.779 cm, and the length was 7.79 cm, including the hemispherical nose.

The diameters of the cylindrical targets were varied parametrically for the computational study: $D_t/D_p = 19.56, 13.04, 6.52, 4.89, 3.26$. As already mentioned, the impact velocity, $V_p$, was also varied from 1.5 to 4.0 km/s, in increments of 0.5 km/s.
3 Results and discussion

Results of the simulations are plotted in fig. 2. The curve for $V_p = 1.5$ km/s essentially reproduces the results shown in fig. 1. (There is a slight difference between the results shown in fig. 2 and those shown in fig. 1 for $V_p = 1.5$ km/s because thermal softening is inhibited in these simulations.) As expected, $P/L$ increases as the impact velocity increases. But as the impact velocity increases, the dependence on $D_t / D_p$ “flattens out,” that is, $P/L$ becomes less and less sensitive to $D_t / D_p$ with increasing impact velocity.

![Figure 2: Penetration efficiency vs. normalized target diameter.](image)

The same results are shown in fig. 3, except that $P/L$ is now plotted as a function of impact velocity, with the family of curves representing the various $D_t / D_p$ ratios. As already observed, $P/L$ is a strong function of the normalized diameter at 1.5 km/s. For large confinement, i.e., $D_t / D_p \geq 20$, $P/L$ increases with impact velocity as expected from other such studies, e.g., Ref. [12]. But as the impact velocity increases, the differences between the various $D_t / D_p$ ratios diminishes, and almost vanishes at $V_p = 4.0$ km/s.

The penetration (nose) and tail velocities of the projectiles are plotted vs. normalized penetration depth for the various $D_t / D_p$ ratios in fig. 4 for $V_p$ of 1.5 km/s. As the ratio $D_t / D_p$ decreases, the penetration velocity increases. Figure 5(a) shows the plastic strain (left side of figure) and plastic strain rate (right side of figure) contours for $D_t / D_p = 6.52$. The 5% plastic strain contours are at the edge of the target, implying that the target has begun to bulge. $P/L$ for $D_t / D_p = 6.52$ at 1.5 km/s is 1.06 (from figs. 2-4), considerably greater than the value of 0.82 for a target that is “semi-infinite” in the radial direction (a 29% increase in penetration depth).
Figure 3: Penetration efficiency vs. impact velocity.

Figure 4: Penetration and tail velocities vs. normalized penetration: \( V_p = 1.5 \text{ km/s} \).

The nose and tail velocities vs. penetration depth for the 2.5-km/s impact cases are shown in fig. 6. It is seen that there is a much smaller dependence of the penetration velocity on \( D_t/D_p \) than for \( V_p = 1.5 \text{ km/s} \) (fig. 4). These slight
differences in the penetration velocities for the various \( \frac{D_t}{D_p} \) ratios in fig. 6, increasing slightly as the ratio \( \frac{D_t}{D_p} \) decreases, ultimately result in slightly different depths of penetration. At 2.5 km/s, \( \frac{P}{L} \) increases only by 6.2% as \( \frac{D_t}{D_p} \) goes from a very large value (>19) to 6.52; a much smaller increase in \( \frac{P}{L} \) than for \( V_p = 1.5 \) km/s for the same range of \( \frac{D_t}{D_p} \). However, it is seen in fig. 5(b) that the target is visibly bulging (plastic strains greater than 10% at the boundary).

![Figure 5: Plastic strain and strain-rate contours, 40 µs after impact (strain contours: A=0.1%, B=0.5%, C=1.0%, D=2%, E=5%, F=10%, G=20%, H=50%, I=100%; strain-rate contours: number is the exponent, i.e., 10^x s^-1).](image)

The dependence of \( \frac{P}{L} \) as a function of \( \frac{D_t}{D_p} \) at low impact velocities is understood. As the target bulges, the overall target resistance to penetration decreases, making it easier for the projectile to penetrate. Therefore, the question becomes, why does the dependence on \( \frac{D_t}{D_p} \) decrease with increasing impact velocity, even though there is considerably more target bulging for the same ratio of \( \frac{D_t}{D_p} \)?

To answer this question, it was decided to conduct several more simulations where the density and strength of the target were varied. First, the target material was changed to aluminum, but the strength remained the same as the 4340 steel used in the previous simulations (see Table 1). The results for aluminum and steel targets, with the same strength, are shown in fig. 7 for an impact velocity of 1.5 km/s. For clarity, the results for only three of the \( \frac{D_t}{D_p} \) ratios are shown. Since the strength of the two target materials is the same, differences in the response are due to density. The initial penetration velocities are higher for the aluminum, but overall, the response is quite similar to that of the steel, except for the smallest diameter target. Thus, for ordnance-like impact velocities, it can be concluded that strength combined with lateral confinement dominate target resistance, and hence, the penetration response.
Figure 6: Penetration and tail velocities vs. normalized penetration: $V_p = 2.5 \text{ km/s}$.

Figure 7: Comparison of penetration performance for steel (dotted lines) and aluminum (dashed lines) targets with same strengths: $V_p = 1.5 \text{ km/s}$.
Figure 8: Penetration and tail velocities vs. normalized penetration, parametric study for target density and target strength: $V_p = 3.5$ km/s.

The results for aluminum and steel targets, again with the same strengths, at 3.5 km/s are shown in fig. 8 as the short dashed and dotted lines, respectively. For this high impact velocity, there is a noticeable change in the penetration velocities between the steel and aluminum targets, even though the strengths are equal. The hydrodynamic penetration velocity, $u$, is solely a function of the impact velocity, $V_p$, and the target and projectile densities, $\rho_t$ and $\rho_p$, and is given by:

$$u = \frac{V_p}{1 + \sqrt{\frac{\rho_t}{\rho_p}}}$$  \hspace{1cm} (2)

For the steel and aluminum target, the respective hydrodynamic penetration velocities are 2.10 km/s and 2.52 km/s, which agree quite well with the computational results in fig. 8 (the penetration velocities are slightly less than the hydrodynamic values because of strength effects [13]). Likewise, the normalized depth of penetration is given by:

$$\frac{P}{L} = \sqrt{\frac{\rho_p}{\rho_t}}$$  \hspace{1cm} (3)

For the steel and aluminum targets, Eqn. (3) gives $P/L$ values of 1.50 and 2.56, respectively. The penetration hydrodynamic limit does not account for the non-steady terminal phase of penetration, which results in total penetration being
greater than predicted by hydrodynamic theory [13, 14]. However, the $P/L$ values at the end of the nominal steady-state phase of penetration are in very good agreement with hydrodynamic theory. Thus, it is concluded that at high impact velocities, penetration response is controlled by the inertial effects (that is, the density). Lateral confinement (that is, the $D_t/D_p$ ratio) is a second-order effect.

To demonstrate that strength does not alter the conclusion reached in the previous paragraph, the results for a third set of simulations are plotted in fig. 8. The long dashed lines represent the penetration response for a steel target, but one whose strength has been reduced by a factor of 100 of the steel (and aluminum) used in the other simulations (see Table 1). The penetration velocity is only slightly higher than for the higher-strength steel target, consistent with the dominance of density over strength at this high impact velocity. $P/L$ at the end of the steady-state penetration phase has gone from approximately 1.45 to 1.58 because the penetration velocity is slightly higher, and hence, the erosion rate is slightly less, for the low-strength target. The final depth of penetration for the low-strength target, however, is considerably greater than that for the high-strength steel target since the terminal phase of penetration is dominated by strength effects. However, $P/L$ for the low-strength steel target is considerably less than that for the high-strength, but lower density, aluminum target.

4 Summary and conclusions

Numerical simulations were used to investigate the effects of lateral confinement on penetration velocity and efficiency as a function of impact velocity. The baseline simulations were for a tungsten-alloy penetrator ($L/D_p = 10$) into an armor steel target. Simulations were conducted for five $D_t/D_p$ ratios for impact velocities of 1.5 km/s to 4.0 km/s in increments of 0.5 km/s. The penetration efficiency, measured as the depth of penetration normalized by the initial projectile length ($P/L$), was found to be a strong function of $D_t/D_p$ at 1.5 km/s; however, as the impact velocity increased, the dependence of $P/L$ on $D_t/D_p$ decreased, becoming almost negligible at 4.0 km/s.

Target density and strength were varied to understand the dominant penetration mechanisms as a function of impact velocity. The roles of strength and density are present at all impact velocities. However, at low impact velocities ($<1.5$ km/s), penetration is dominated by strength effects. At high impact velocities ($>3.0$ km/s), penetration is dominated by inertial (density) effects. As the impact velocity increases from 1.5 km/s to 4.0 km/s, the effect of density transitions from a second-order effect to become the dominant mechanism governing penetration. In contrast, the strength, which is a dominating mechanism at 1.5 km/s, transitions to a very small second-order effect at 4.0 km/s.

From a practical aspect, it can be concluded that near edge hits on an armor, which usually is detrimental to armor performance, are mitigated as the impact velocity increases.
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References


