Multiple impact penetration of semi-infinite concrete

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Abstract

An experimental study was performed to gather multiple impact, projectile penetration data into concrete. A vertical firing range was developed that consisted of a 30-06 rifle barrel mounted vertically above a steel containment chamber. 0.41 m cubes of an Air Force G mix concrete were suspended in wet sand and positioned in the steel chamber. The concrete targets were subjected to repeated constant velocity impacts from 6.4 mm diameter steel projectiles with an ogive nose shape and a length to diameter ratio of 10. A laser sight was adapted to the rifle to ensure alignment, and a break screen system measured the projectile velocity. After each impact, the projectile penetration and crater formation parameters were recorded. The penetration and crater formation data were consistent with single impact penetration data from previous studies conducted at Sandia National Laboratories. In addition, an analytic/empirical study was conducted to develop a model that predicted the penetration depth of multiple impacts into concrete targets. Using the multiple impact penetration and crater formation data, a single impact penetration model, developed by Forrestal at Sandia National Laboratories, was extended to account for the degradation of the target strength with each subsequent impact. The degradation of the target was determined empirically and included in the model as a strength-modifying factor. The model requires geometry parameters of the ogive nose projectile, projectile velocity, the number of impacts, and target compressive strength to calculate the overall penetration depth of the projectile. Published by Elsevier Science Ltd.

Keywords: Multiple impact penetration; Concrete penetration; Target strength degradation

1. Introduction

The military’s interest in using geo-materials as an ordinance barrier has provided the motivation for studying projectile impact into concrete since the mid 1700’s. The interest lies in

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both the development of projectiles capable of penetrating barriers and the barriers capable of withstanding penetration. The bulk of the early work through the 1800’s consisted of experimental studies with a wide range of projectile sizes and striking velocities from 200 to 1000 m/s. These studies present graphical results of data such as penetration, perforation, crater formation, ricochet, and the effect of reinforcement for different impact velocities and angles [1, 2].

Starting in the 1940’s Government laboratories, such as the Ballistic Research Laboratory (BRL) and the Waterways Experimental Station (WES), began gathering experimental concrete penetration data for the development of empirical formulas [3]. Most recently researchers from Sandia National Laboratories (SNL) have performed numerous impact penetration studies on soil and concrete targets to gather experimental data required to develop some physics based, semi-empirical models to predict penetration [4].

All of the previous penetration studies of concrete have been conducted with a single projectile fired into virgin material, examining the effect of velocity, or projectile geometry on target penetration. In addition to the effect of velocity on penetration depth, the study conducted here examined the effect of multiple projectile impacts on the penetration of concrete. With multiple projectiles impacting the same point in a target, the accumulation of damage and crater formation with each impact becomes important to the overall penetration depth.

In order to develop a penetration model with a physical basis, research at Sandia National Laboratories (SNL) was begun by Forrestal to develop cavity expansion models for penetration into dry porous rock [7] and reinforced concrete [8] using the cavity expansion expressions developed earlier by Bishop [9] and Hill [10]. From these experimental studies, it appeared that the spherical cavity expansion model showed better agreement with experimental data than the cylindrical cavity expansion. This method uses the cavity expansion theory to predict the axial force on a rigid projectile as a function of velocity. With this force, the penetration depth can be determined. However, tri-axial material property data is required to calculate parameters used in the cavity expansion method.

In 1992, Forrestal et al. conducted a study to predict penetration of soil with a spherical cavity expansion model [5]. The experimental portion of the study used large instrumented projectiles fired from a gas gun into soil for comparison with model predictions for projectile deceleration and penetration. The results again agreed well, however the model required tri-axial material testing of the soil as inputs. To eliminate the need for the tri-axial material data to describe the behavior of the target material, Forrestal et al. (1994, 1996) and Frew et al. (1998) developed a semi-empirical equation for the penetration of ogive-nose projectiles into concrete [6,11,12]. From the results of a series of concrete penetration experiments and the projectile force expressions from their soil penetration work, they developed an equation that is dependent on one dimensionless constant, later shown to be a function of the target compressive strength. The equation was also used to accurately predict the penetration of large-scale projectiles from historical data.

In this study, the semi-empirical penetration models developed at SNL were extended to predict the penetration depth of multiple projectile impacts. A multiple projectile impact penetration study was also conducted to provide an experimental basis for this work.
2. Experimental set-up

2.1. Projectile impact: vertical gun set-up

To perform the impact testing a Remington Model 700, 30-06 rifle was mounted vertically above a steel test chamber. The rifle was slightly modified to allow remote operation. Fig. 1 shows the rifle and test chamber set-up.

Ogive-nose shape projectiles with a length/diameter ratio of 10 were designed and fabricated for use with the rifle test fixture. The projectile, which along with its geometry, is shown in Fig. 2, was fabricated from maraging steel and had a mass of 15 g. The material properties of maraging steel are listed in Table 1. A plastic sabot, also shown in Fig. 2, was designed and fabricated to allow the use of the 6.4 mm diameter projectile in the 7.82 mm diameter rifle bore. The mass of each sabot was 0.8 g. To align the rifle and target, a laser sight was mounted in the action of the rifle and the beam sent down the bore onto the target.

The semi-infinite targets were fabricated from G mix concrete mixed at Tyndall Airforce Base. Material properties for the G mix concrete are listed in Table 2. The 406 mm cube targets were placed in a plywood box and surrounded by wet sand. The size of the target, and the sand were an attempt to simulate a semi-infinite target by suppressing tensile stress wave reflections from the target walls resulting from the impacts. A concrete target loaded in the sand, inside the steel containment chamber, is shown in Fig. 1.

2.2. Velocity system

To measure the velocity of the projectile, a break screen system was fabricated. Two paper screens were held in a fixture, a known distance apart. The screens contained a conductive coating that was included in a high-speed flip-flop circuit. Recording the circuit output on an oscilloscope, a square wave is produced as the projectile passes through the screens. The width of the square wave was the time it took the projectile to travel the distance between the screens, giving the projectile velocity.
3. Experimental procedure

Projectile impacts into a particular target were conducted at a given velocity until the target failed, i.e. cracks propagated to the boundary of the cube in contact with the sand. Different velocities for each target were achieved by changing the amount of gunpowder loaded into each projectile. Fig. 3 shows the velocity versus gunpowder load curve for the 15g steel projectiles.
Table 1
Material properties for maraging steel projectiles

<table>
<thead>
<tr>
<th>Alloy</th>
<th>VASCOMAX C-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate strength (MPa)</td>
<td>2068</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>1999</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>8118</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>206.8</td>
</tr>
<tr>
<td>Charpy impact (N-m)</td>
<td>20 (10 mm)</td>
</tr>
<tr>
<td>Rockwell hardness C</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 2
Material properties for G mix concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>38.15</td>
</tr>
<tr>
<td>Splitting tensile strength (MPa)</td>
<td>3.14</td>
</tr>
<tr>
<td>Density (kg/cubic meter)</td>
<td>2337</td>
</tr>
</tbody>
</table>

Mixture for one cubic yard (kg)
- Limestone (9.5 mm diam): 757.5 kg
- Concrete sand: 592.4 kg
- Portland cement, Type 1: 164.7 kg
- Class “F” fly ash: 108.9 kg
- Water: 164.7 kg

Fig. 3. Velocity versus Gunpowder load curve for 15 g steel projectile fired from vertical 30-06 projectile impact stand.
generated during early calibration experiments. For each experiment the projectile and sabot were hand loaded into a standard shell casing with the proper amount of gunpowder for the desired velocity.

Prior to loading the bullet into the gun chamber, the target was positioned in the containment chamber using the laser sight to ensure proper alignment. The velocity system screen holders were mounted to a plywood cover for the target box, and placed over the target. The cover also helped to contain the target material ejected from the crater during the experiment. Due to the small size of the containment chamber, a cardboard baffle was used to suppress the muzzle blast at the end of the gun barrel. With the target loaded and velocity system in place and operational, the containment chamber was locked and the gun fired remotely using a series of cables.

4. Experimental results

After each projectile was fired, the gun system was immediately put into a safe condition, and the velocity data recorded. Upon opening the containment chamber, the projectile was usually found imbedded into the target as shown in Fig. 4. Along with the projectile, various amounts of material ejected from the crater were contained on the top surface of the target. The projectile was removed and the crater material collected for later examination. The primary data collected from each experiment was the overall depth of penetration.

To record penetration depth, a large parallel was placed across the crater and a probe was used to measure perpendicularly from the target surface to the bottom of the penetration tunnel. At least 6 measurements were taken and then averaged. Fig. 5 shows the concrete penetration depth of a 15g maraging steel projectile for multiple shots at various velocities. The data is also presented in tabular form in Table 3.

Observation of the penetration process during these experiments showed that the process consists of two parts; initial crater formation and projectile tunneling. This result is consistent with experimental results from other penetration studies [5,6]. To study the crater formation during multiple impact penetration, the crater volume, diameter and depth were recorded following each experiment. Figs. 6–8 show the crater depth, volume, and diameter respectively for

![Embedded Projectile](image)

Fig. 4. Target condition post experiment, with embedded projectile and crater material.
everypenetrationexperiment. As shown, regardless of the velocity or shot number, once the crater was fully formed, its size remained constant. To measure the crater diameter, five measurements were taken at different points around the crater and averaged to give one value. The crater depth was taken as the distance from the target surface to the bottom of the crater, and again five

Table 3
Multiple impact penetration data

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C001</th>
<th>C002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
<td>VG007</td>
<td>VG008</td>
</tr>
<tr>
<td>Shot number</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Projectile mass (kg)</td>
<td>0.0153</td>
<td>0.0151</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>616</td>
<td>298</td>
</tr>
<tr>
<td>Penetration depth (m)</td>
<td>0.13513</td>
<td>0.04003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C003</th>
<th>C004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
<td>VG014</td>
<td>VG015</td>
</tr>
<tr>
<td>Shot number</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Projectile mass (kg)</td>
<td>0.0149</td>
<td>0.0148</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>375</td>
<td>362</td>
</tr>
<tr>
<td>Penetration depth (m)</td>
<td>0.05807</td>
<td>0.08019</td>
</tr>
</tbody>
</table>
measurements were taken at different points and averaged. To measure the crater volume, fine red sand was used to fill the crater flush with the target surface. The sand was then removed and its volume measured in a graduated cylinder. The sand volume was taken as the crater volume. Forrestal observed this same phenomenon while conducting soil and concrete penetration tests using similar ogive-nose projectiles [5,6]. For Forrestal’s soil penetration, the crater depth was small compared to the overall penetration, and therefore was neglected when developing a predictive model. However for the concrete penetration the crater depth was no longer negligible, and was taken as a constant value, experimentally determined as 4 times the projectile radius. In our experiments the crater depth was observed to be approximately 5 times the projectile radius, 15.5 mm.
5. Development of concrete impact penetration model

5.1. Forrestal’s single impact penetration model [6,11,12]

As observed in soil penetration experiments [5], the penetration process is comprised of two components, crater formation and tunneling. The axial force, $F$, on the projectile ogive-nose during the tunneling region is given by

$$F = \pi a^2 \left( \tau_0 A + N B \rho V^2 \right),$$  \hspace{1cm} (1)

where $a$ is the projectile radius, $\rho$ is the target density, $V$ is the projectile velocity, and $N$ is given by

$$N = \frac{8\psi - 1}{24\psi^2}.$$  \hspace{1cm} (2)

$N$ is a function of the Caliber Radius Head (CRH), $\psi = s/2a$, where $s$ is the radius of the ogive-nose and $a$ is the projectile radius shown in Fig. 2. In Eq. (1), $\tau_0 A$ and $B$ are constants that can be determined by a cavity expansion analysis.

To eliminate the cavity expansion analysis, and hence the need for tri-axial material data, $\tau_0 A$ and $B$ can be approximated. Experimental data has shown that $B$ has a very small range for a wide variety of materials and can be approximated as 1.0. $\tau_0 A$ can be set equal to $S f''_c$ where $f''_c$ is the unconfined compressive strength of the target material, and $S$ is a dimensionless parameter that modifies the compressive strength. With this, Eq. (1) becomes

$$F = \pi a^2 (S f''_c + N \rho V^2).$$  \hspace{1cm} (3)

During crater formation during the soil penetration study [5], the projectile was shown to decelerate linearly so the axial force on the projectile during crater formation is taken as

$$F = cz,$$  \hspace{1cm} (4)
where \( z \) is the penetration depth from the target surface and \( c \) is a constant. Fig. 9 is a schematic of the penetration process.

Therefore, Eq. (4) is valid for the crater formation region only, \( z \) equals 0 to \( 4a \), and Eq. (3) is valid for the tunneling region, \( z \) equals \( 4a \) to the final penetration depth, \( P \). Using Newton’s second law Eq. (4) can be written for the crater region with the initial conditions \( z(0) = 0 \) and \( V(0) = V_s \), the impact velocity

\[
m \frac{d^2z}{dt^2} = -cz, \quad 0 \leq z \leq 4a. \tag{5}
\]

Solving the differential equation gives the position \( z \), velocity \( V \), and acceleration on the projectile as a function of time

\[
z = \left(\frac{V_s}{\omega}\right) \sin(\omega t), \tag{6}
\]

\[
V = \frac{dz}{dt} = V_s \cos(\omega t), \tag{7}
\]

\[
\frac{dV}{dt} = -\omega V_s \sin(\omega t), \tag{8}
\]

where \( \omega^2 = c/m \). \( V_1 \) and \( t_1 \) are defined as the velocity and time at the transition from crater to tunneling at \( z = 4a \). At this point there has to be continuous force, velocity, and displacement of the projectile. Using the continuity conditions, the velocity at this transition, \( V_1 \) can be determined as

\[
V_1^2 = \frac{mV_s^2 - 4\pi a^3 Sf c^2}{m + 4\pi a^3 N \rho}. \tag{9}
\]
The final depth of penetration can now be found by again applying Newton’s second law to Eq. (3) for the tunneling region

\[ mV \frac{dV}{dz} = \pi a^2 (Sf'c + N\rho V^2) \]

and integrating the right and left sides from \( V_1 \) to zero and \( 4a \) to \( P \), respectively, gives

\[ P = \frac{m}{2\pi a^2 \rho N} \ln \left( 1 + \frac{N\rho V_1^2}{Sf'c} \right) + 4a. \]  

In Eq. (11) every parameter is known except for the factor \( S \). To determine the \( S \) factor Forrestal used Eq. (11) to calculate \( S \) based on experimental data. From the data a relation for \( S \) was developed as a function of the compressive strength, \( f'c \), of the target material [12]. Fig. 10 gives this relation.

With this relation, a simple model can be used to calculate penetration of ogive-nose shaped projectiles into concrete as long as the projectile geometry and velocity, and the target strength are known.

5.2. Extension of model to multiple impact penetration

The Forrestal single impact penetration model is convenient because it is based on parameters that are readily measured or known; projectile geometry, mass, and velocity; and target material unconfined compressive strength and density. The model is semi-empirical in nature due to a factor \( S \) that was originally determined from experimental data, but has been shown to be a function of the unconfined compressive strength of the target material. Observations made during the multiple impact penetration experiments were similar to Forrestal’s observations in the single
impact experiments. In both studies, a crater was formed at the target surface, then the projectile tunneled into the material. Even upon subsequent impacts, the crater geometry remained unchanged, but the projectiles continued to tunnel. Also, the velocity range and target strength of the multiple impact experiments were similar to those used for the Forrestal Model development.

Due to these similarities, the Forrestal model was chosen as a starting point for empirically modeling the multiple impact penetration process. However, in the multiple impact experiments the crater depth was determined to be slightly deeper than in Forrestal’s experiments. To account for this, Eqs. (9) and (11) were recast using the transition from crater formation to tunneling as \( z = 5a \) as opposed to \( z = 4a \), the resulting equations were

\[
V_1^2 = \frac{mV_s^2 - 5\pi a^3 Sf'_c}{m + 5\pi a^3 Np},
\]

\[
P = \frac{m}{2\pi a^2 \rho N} \ln \left( 1 + \frac{NpV_1^2}{Sf'_c} \right) + 5a.
\]

Another difference noticed in the multiple impact experiments performed at the University of Rhode Island was the value of the \( S \) factor of the target material. Using the Forrestal relation shown in Fig. 10, the \( S \) factor is 11.03. However calculating \( S \) using Eqs. (12) and (13), and the initial impact penetration data for various velocities gives an average value of \( S = 15.47 \).

At a given velocity, the initial projectile penetration into a target material can be predicted using the standard Forrestal empirical model. For a second impact at the same velocity, hitting the same point in the target, the projectile no longer sees virgin material. Now the projectile impacts the bottom of the previous projectile’s tunnel region. Even though the projectiles are seeing the same target material, its condition has been altered, so the scaling factor \( S \), which modifies the unconfined compressive strength, must change with each impact. Since \( S \) is an empirically determined factor, it can be calculated using the reworked Forrestal model for each impact at the various velocities. Fig. 11 shows the back-calculated values of \( S \) for each test velocity as a function of shot number into the target.

As shown, the effective \( S \) for a given shot number decreases as a function of

\[
S_n = S_1(-0.4465 \ln(n) + 1),
\]

where \( n \) is the shot number and \( S_1 \) is the factor for the initial shot into the undamaged target. Now, the penetration depth for each subsequent shot can be predicted using Eqs. (12) and (13) by replacing \( S \) with \( S_n \) from Eq. (14) for the given shot number \( n \).

6. Model results

Using the above method to calculate the penetration depth as a function of velocity for multiple impacts, the family of curves shown in Fig. 12 was generated. As shown the experimental data agree reasonably well with the predictions.

Another way to use the impact penetration model is to back calculate a degraded compressive stress in the target material as a function of shot number. As shown in Fig. 13 this relation is identical to the relation for \( S \) shown in Fig. 11.
Fig. 11. $S$ as a function of shot number for multiple impact penetration of G mix concrete.

Fig. 12. Multiple impact penetration model predictions.
With shot number, \( n \), the compressive strength, \( f'_{cn} \), degrades with respect to the virgin unconfined compressive strength \( f'_c \) as

\[
f'_{cn} = f'_c (-0.4465 \ln(n) + 1)
\]

The family of curves shown in Fig. 14 was generated by plotting and fitting the multiple impact penetration data versus this degraded compressive strength. This plot could be used to estimate penetration depth into a concrete target as a measure of its degraded compressive strength.
7. Conclusions

A multiple impact penetration study was conducted at the University of Rhode Island. Ogive-nose shaped projectiles were fired from a standard 30-06 rifle into a semi-infinite concrete target. In order to develop an empirical model that predicts the multiple impact penetration depth, the Forrestal single impact penetration model was modified using observations made during the study, and to account for the changing of the target for each subsequent shot. To do this, the target strength modifying factor, $S$, was empirically determined as a function of shot number. This relation was introduced back into the Forrestal model to predict penetration depth for the multiple impacts. As shown, the model agrees reasonably well with the penetration data.

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