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Projectile Penetration into Representative Targets

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Projectile Penetration into Representative Targets

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Abstract

The differential equation representing the penetration of a "hard" projectile into semi-infinite, homogeneous target materials is solved for several generic combinations of the target material/projectile characteristics. A "hard" projectile is defined as one that does not change size or shape and does not lose mass during the penetration process. The target materials evaluated range from the structurally "soft" materials (liquids) to structurally "hard" materials (armor plate) with viscous and fluid dynamic drag considered. The solutions to the differential equation(s) are expanded in series form to demonstrate the underlying parameters governing projectile penetration and the way they interact to limit penetration in a given target material. It is shown that the fundamental parameter governing projectile penetration into structurally "firm" materials is the initial kinetic energy of the projectile divided by the frontal area of the projectile and the inherent structural characteristic of the target. Experimental data on the penetration of steel spheres into ballistic gelatin and for armor piercing bullets into armor plate materials are used to verify the characteristics of the solutions to the equation of motion for the projectile and to demonstrate how penetration can vary with projectile size and target characteristics. The penetration equation for a single "hard" target material is used to develop a solution for the penetration of multi-layered "hard" target materials.

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Contents

Preface.....	7
1. Introduction.....	9
2. Analysis.....	9
A. Structurally "Hard" Materials.....	12
B. Structurally "Firm" Viscous Materials.....	13
C. Structurally "Firm" Inviscid Materials.....	13
D. Structurally "Firm" Materials with Viscosity and Fluid Drag.....	14
E. Structurally "Soft" Materials.....	14
3. Experiments.....	15
A. "Soft" Target Materials.....	15
B. "Hard" Target Materials.....	16
4. Multi-Layered "Hard" Materials.....	22
5. Conclusions.....	24
References.....	24

Figures

1	Penetration Schematic and Nomenclature	11
2	The Variation of the Fluid Dynamic Drag Parameter, a , with Sphere Radius for Tests in 20% Gelatin.....	17
3	The Variation of the Fluid Friction Drag Parameter, b , with Sphere Radius for Tests in 20% Gelatin.....	18
4	The Variation of the Target Structural Resistance Parameter c , with Sphere Radius for Tests in 20% Gelatin.....	19
5	The Experimental Penetration Capability of Various Armor Piercing Bullets Against Rolled Homogeneous Armor as a Function of the Areal Kinetic Energy of the Total Projectile	20
6	The Experimental Penetration Capability of Various Armor Piercing Bullets Against Rolled Homogeneous Armor as a Function of the Areal Kinetic Energy of Only the Hardened Projectile Core	20
7	The Experimental Penetration Capability of Various Armor Piercing Bullets Against Aluminum Armor Plate as a Function of the Areal Kinetic Energy of the Total Projectile.....	21
8	The Experimental Penetration Capability of Various Armor Piercing Bullets Against Aluminum Armor Plate as a Function of the Areal Kinetic Energy of Only the Hardened Projectile Core	21
9	Multilayered Target Schematic and Nomenclature	23

Preface

The Nuclear Security Center of Sandia National Laboratories has been involved for years in the vulnerability of and in the ballistic protection for high value assets to small arms projectiles. This work has included experimental vulnerability testing of complex structures and the development of soft and hard armor blankets and protective structures. In the course of this work, the need for some theoretical basis for analyses, interpolation, or extrapolation of the limited experimental test data became apparent. This report presents some previously unpublished theoretical results and experimental comparisons developed several years ago to provide a firm foundation for the expanded application of existing and expensive test data.

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Projectile Penetration into Representative Targets

1. Introduction

The penetration of projectiles into representative targets has been of interest to mankind ever since man ceased to rely on rocks alone and graduated to arrows and spears. Even without any scientific background, it was soon observed that heavier, (i.e. larger) projectiles generally penetrated deeper into or through a given target material than smaller and/or lighter projectiles. With the advent of gunpowder, man came to possess the energy source necessary to deliver projectiles to targets with ever increasing velocity. Soon, the field of ballistics reached the point where projectile design and strength began to be a factor when the projectiles themselves began to fracture and breakup either when being launched or on impact with a target.

The physics of launching a projectile from a tube or barrel, (interior ballistics), is extremely complex and, as a result, even today it is basically an empirical science based on a tremendous amount of experimental observations. The flight of a projectile from the barrel muzzle to the target, (exterior ballistics), is amenable to theoretical analysis and has been the subject of mathematicians and engineers for decades and today is rather well explained and understood. The penetration of a projectile into or through a target (terminal ballistics) is theoretically difficult in detail, but the bulk process is amenable to an extension of the techniques of the exterior ballisticians where the target is now much more dense and has more inherent structural integrity than air.

The continued development of special penetration ammunition (i.e. Saboted Light Armor Penetrator [SLAP], Long Rod Penetrators, etc.) make the problem of penetration prediction and protection more critical for security, safety and survivability. The purpose of this report is to present some previously developed theories for use in future analyses of potential penetration vulnerabilities of high value assets.

2. Analysis

Arthur Dzimian presents the results of some excellent penetration tests of steel spheres into 20% gelatin representing animal tissue and discusses the several proposed theories for predicting projectile penetration in various target materials. The tests involved spheres with radii of 3/16, 1/4, 3/8, and 7/16 inches and impact velocities up to 3300 feet/second. By accurately differentiating the experimental data, Dzimian found that the deceleration of the projectile during penetration was governed* by the differential equation:

$$M dV/dt = -[AV^2 + BV + C] \quad (1)$$

*Equation 1 was first proposed by W. A. Allen, E. B. Mayfield, and H. L. Morrison, who then argued that it was not applicable to experiments in sand.

where,

M = the projectile mass (assumed constant)

V = the projectile velocity

t = the independent variable time

A = a classical fluid dynamic drag parameter

B = a deceleration parameter due to kinetic friction on the surface of the projectile

C = the deceleration force due to the inherent structural characteristics of the target material.

By the nature of the experimental tests and the physics of the problem, Equation 1 is valid when the target material can be considered as a semi-infinite slab and boundary effects are negligible. As expected, Reference 1 found that when the impact velocity was small, (a few tens of meters per second), the penetration was heavily influenced by boundary effects. In addition, Reference 1 points out that Equation 1 encompasses all of the other penetration theories proposed at that time.

For Equation 1, nondimensional analysis of the fluid dynamic forces shows that the fluid dynamic drag force is equal to the density of the target material, a constant depending on the projectile shape, (drag coefficient), and the frontal area of the projectile, i.e.

$$A = \rho_m \cdot C_D \cdot R^2 \cdot \pi / 2 \quad (2a)$$

where C_D is independent of projectile size.

Similarly, the friction force can be shown to be equal to

$$B = \rho_m \cdot C_F \cdot R^2 \cdot \pi / 2 \quad (2b)$$

where, however, C_F should depend on the projectile size (fluid Reynold's Number).

The resistance force of the target material due to its inherent structural characteristics is difficult to describe analytically because the penetration process necessarily occurs in the plastic regime of material characteristics but a consideration of the two special cases of a flat nosed projectile (punch press shear) and a conical projectile (pierce press with radial material flow) suggests that the constant C can be described in the form:

$$C = \rho_m \cdot C_m \cdot R^2 \cdot \pi / 2 \quad (2c)$$

where C_m is dependent on the material characteristics in the plastic regime and should be dependent on the projectile shape. R in Equations 2a through 2c is the cross-sectional radius of the projectile. A schematic showing the geometry of the problem and illustrating the variables is presented in Figure 1.

Figure 1 Penetration Schematic and Nomenclature

Dividing Equation 1 through by the projectile mass, M , and changing the independent variable from time to distance traveled into the target material, S , gives the following:

$$dS/dt = V$$

$$VdV/dS = -(aV^2 + bV + c) \quad (3)$$

where,

$$a = A/M, \text{ etc.} \quad (4)$$

Equation 3 is variable separable and can be rearranged in the form:

$$\frac{VdV}{aV^2 + bV + c} = -dS \quad (5)$$

Solutions to Equation 5 can be easily obtained from any Table of Integrals for various combinations of parameters a , b , and c . (See. Reference 2.)

A. Structurally Hard Materials (armor plate, etc.), $a = b = 0$.

For a structurally hard target material where any fluid drag force can be neglected and the friction drag force on the surface of the projectile can be assumed small, the solution to Equation 4 is:

$$V^2 = -2cS + \text{constant} \quad (6a)$$

If we apply the boundary conditions that $V = V_0$ when $S = 0$, and $V = 0$ when $S = P$ (total penetration), then we can write Equation 6a as:

$$P = V_0^2/2c. \quad (6b)$$

Substitution of Equations 2c and 4 into Equation 6b gives:

$$P = (MV_0^2/2 \pi R^2) \cdot 2/\rho_m c_m \quad (6c)$$

which states that the total projectile penetration is proportional to the initial kinetic energy of the projectile per unit area divided by the target material structural parameters.

B. Structurally Firm Viscous Materials (sand, * loose soils, etc.), $a=0$.

When $a = 0$, the solution to Equation 5 is given by,

$$b^2S = c\ln(c + bV) - bV + \text{constant} \quad (7a)$$

Again applying the boundary conditions to Equation 7a gives:

$$b^2P = bV_0 - c\ln(1 + bV_0/c) . \quad (7b)$$

If the logarithmic function is expanded in series form, the result can be shown to be,

$$P = \frac{MV_0^2}{2C} \frac{1}{(1 + bV_0/2c)} \{1 + \dots\} \quad (7c)$$

Again, the penetration is proportional to the initial kinetic energy of the projectile divided by the target material structural parameters but it is reduced somewhat by a term containing the ratio of the viscous parameter divided by the structural parameter in the denominator.

C. Structurally Firm Inviscid Materials $b = 0$. If $b = 0$, the solution to Equation 5 is given by:

$$2aS = -\ln(c + aV^2) + \text{constant} \quad (8a)$$

which, when the boundary conditions are applied, can be written as:

$$2aP = \ln(1 + aV_0^2/c) . \quad (8b)$$

Expanding Equation 8b in series form gives the result:

$$P = \frac{MV_0^2}{2C} \frac{1}{(1 + aV_0^2/2c)} \{1 + \dots\} \quad (8c)$$

Again, the total penetration is proportional to the initial kinetic energy of the projectile divided by the target material structural parameter but, in this instance, it is reduced by a term in the denominator containing the projectile fluid drag parameter divided by the target structural parameter.

*W. A. Allen, E. B. Mayfield, and H. L. Morrison³ conducted experiments of projectile penetration in sand and concluded through some faulty reasoning and questionable mathematics that for sand $c = 0$, (i.e. there was no structural integrity); at the same time, Reference 3 discusses the importance of crushing sand particles.

D. Structurally Firm Materials with Viscosity and Fluid Drag (ballistic gelatin, supersaturated soils, etc.)

If all of the target material/projectile parameters are non-negligible, Equation 5 has the full solution:

$$2aS = \frac{2b}{\sqrt{4ac-b^2}} \tan^{-1} \frac{[2aV+b]}{\sqrt{4ac-b^2}} - \ln(aV^2+bV+c) + \text{constant} \quad (9a)$$

Again, applying the boundary conditions to Equation 9a gives the result:

$$2aP = \ln(1+bV_0+aV_0^2) - \frac{2b}{2c} \frac{\tan^{-1} \frac{[V_0/2\sqrt{4ac-b^2}]}{[1+bV_0/2c]}}{\sqrt{4ac-b^2}} \quad (9b)$$

If the transcendental functions in Equation 9b are expanded in series form, it can be shown that Equation 9b can be written as,

$$P = \frac{MV_0^2}{2C} \frac{1}{(1+bV_0/2c)(1+bV_0/2c+aV_0^2/2c)} \{1+\dots\} \quad (9c)$$

Again, the predominant factor in penetration is the initial kinetic energy of the projectile divided by the structural parameter of the target but, here, the penetration is reduced by the effects of both the penetration viscosity and a fluid dynamic drag force.

It must be noted that we have not assumed the relative magnitudes of the individual terms in Equations 6 through 9 and we have not truncated any of the series expansions! All that has been done in Equations 6 through 9 is that the common terms have been collected in front of the series expansions.

E. Structurally "Soft" Materials (liquids, etc.), $c = 0$.

If the target material is so weak structurally that it cannot support itself, i.e., $c = 0$, then the solution to equation 5 is found to be:

$$aS = -\ln(aV + b) + \text{constant} \quad (10a)$$

which, when the boundary conditions are applied, becomes:

$$aP = \ln(1 + aV_0/b) . \quad (10b)$$

Again, expanding Equation 10b in series form gives:

$$P = \frac{MV_0}{B} \frac{1}{(1 + aV_0/b)} \{1 + \dots\}, \quad (10c)$$

where, in Equation 10c, the penetration is governed by the initial impact momentum of the projectile, rather than by the initial kinetic energy.

3. Experiments

A. "Soft" Target Materials

As mentioned earlier in explaining the development of Equation 1, Arthur Dzimian¹ conducted an excellent series of penetration tests of steel spheres into ballistic gelatin, (20% water). By measuring the instantaneous penetration of a particular sphere as a function of time, Dzimian was able to accurately differentiate the data and to obtain quantitative values for the parameters a, b, and c. For this particular target material, a partial justification of the form of Equation 1 can be obtained if the parameters a, b, and c do indeed vary with sphere diameter as suggested by Equation 2.

For a sphere in viscous flow, (Stoke's Flow), the viscous drag coefficient in Equation 2b is given by Reference 4 as:

$$C_F \propto 1/R, \quad (11)$$

and, since the mass of a spherical projectile can be written as:

$$M = (4/3) \pi R^3 \rho_s, \quad (12)$$

then, Equations 2, 4, 11 and 12 can be combined to give, theoretically,

$$a = k_a/R \quad (13a)$$

$$b = k_b/R^2 \quad (13b)$$

$$c = k_c/R \quad (13c)$$

where k_a , k_b , and k_c are indeed constants of the target material and the material density of the spherical projectile.*

*It should be noted that when equations 13 are substituted back into the complete equation of motion or any solutions containing the viscous parameter, the dynamics of the projectile do not scale linearly with projectile size as several investigations have expected or tried to explain.

Experimental results for the parameters a, b, and c, were taken from Reference 1 for the various sizes of spherical projectiles and are shown versus sphere radius in Figures 2 to 4, respectively. As can be seen, the variation of these experimental results does indeed follow the predicted variation given by Equations 13 surprisingly well.

B. "Hard" Target Materials

Experimental data for the penetration of armor piercing bullets into typical armor plate materials were taken from Reference 5 and were compared to the predicted behavior for "hard" target materials given by Equation 6c. The armor piercing bullets selected have a rather soft jacket material surrounding a hardened steel core with a soft lead filler.

The first comparison of experimental data** with Equation 6c is shown in Figure 5 for "rolled homogeneous armor plate" where the initial kinetic energy of the projectiles is based on the total mass of the respective projectiles. While it can be seen in Figure 5 that the penetration of the individual projectiles does indeed follow a linear variation with initial kinetic energy divided by the projectile diameter squared, as theoretically predicted, the three curves shown do not collapse into a single line representing a single target material constant. When the construction of the bullets is considered, it appears reasonable to expect the soft bullet jacket material and the lead filler to be easily stripped away by the hard target material and a better comparison might be to use the initial kinetic energy of the bullet core only. Such a comparison is shown in Figure 6 where it can be seen that using only the kinetic energy of the core does collapse the three curves in Figure 5 into a single line as the theory predicts.

One feature of Figures 5 and 6 (that is not theoretically predicted) is that the data do not appear to pass through the origin of the figures. There are two phenomenon that the theory does not account for in its present form. One mentioned earlier is boundary effects on the front and back faces of the target material. For very small penetrations of thick targets, the cratering effect on the front surface may have a significant influence on the penetration process. In addition, experiments have shown that complete penetrations of finite thickness targets frequently result in a material "spall" of the rear surface. If the rear face of the target "spalls," the "penetration" will be greater than predicted.

The second phenomenon that has not been considered is that, at low initial projectile kinetic energy, the deformations of the target material will occur in the "elastic regime" while at higher energies, the deformation will certainly be in the "plastic regime" assumed by the theory. This dramatic difference in target material characteristics for low initial kinetic energy impacts probably will cause the experimental data to bend toward the origin of the figures. There are some experimental indications of this behavior at low impact kinetic energies but it is for softer "ball" ammunition and the results cannot be considered conclusive.

**Traditionally, ballisticians have worked with projectile calibers, i.e. diameters, as an independent variable. The comparisons in Figures 5 through 8 use the traditional projectile parameters E_0/D^2 , rather than $E_0/\pi R^2$.

Figure 2. The Variation of the Fluid Dynamic Drag Parameter, a , with Sphere Radius for Tests in 20% Gelatin

Figure 3. The Variation of the Fluid Friction Drag Parameter, b , with Sphere Radius for Tests in 20% Gelatin

Figure 4. The Variation of the Target Structural Resistance Parameter, c , with Sphere Radius for Tests in 20% Gelatin

Figure 5. The Experimental Penetration Capability of Various Armor Piercing Bullets Against Rolled Homogeneous Armor as a Function of the Areal Kinetic Energy of the Total Projectile

Figure 6. The Experimental Penetration Capability of Various Armor Piercing Bullets Against Rolled Homogeneous Armor as a Function of the Areal Kinetic Energy of only the Hardened Projectile Core

Figure 7. The Experimental Penetration Capability of Various Armor Piercing Bullets Against Aluminum 2024-T4 Armor Plate as a Function of the Areal Kinetic Energy of the Total Projectile

Figure 8. The Experimental Penetration Capability of Various Armor Piercing Bullets Against Aluminum Armor Plate as a Function of the Areal Kinetic Energy of Only the Hardened Projectile Core

A second comparison of the predictions of Equation 6c with experimental data for softer aluminum armor plate is shown in Figure 7 where it can be seen that a similar separation of the individual curves is again evident when the total mass of the projectile is used. Figure 8 shows the same comparison when only the mass of the hardened core of the projectile is considered in the initial kinetic energy of impact. Using only the kinetic energy of the core results in the correlation of the penetration data on three different armor piercing bullets as predicted by the theory. Again, the fact that the experimental data do not appear to pass through the origin of the figures, as discussed above, is again evident.

4. Multi-Layered "Hard" Materials

Since the experimental data confirm the theoretical predictions of Equation 6c for a single "hard" target material, Equation 6a can be used to develop a penetration theory for a multi-layered* hard target material illustrated in Figure 9. It is assumed that the projectile possesses sufficient energy to completely penetrate k layers of the target and is stopped in layer $k+1$. Applying the new boundary conditions to Equation 6a that $V = V_0$ when $S_1 = 0$, and $V = V_1$ when $S_1 = T_1$; $V = V_1$ when $S_2 = 0$ and $V = V_2$ when $S_2 = T_2$; etc, a series of equations are developed as follows:

$$V_0^2 - V_1^2 = 2c_1 T_1, \quad (14a)$$

$$V_1^2 - V_2^2 = 2c_2 T_2, \quad (14b)$$

etc., with the final equation for layer $k+1$ as

$$V_k^2 = 2c_{k+1} P_{k+1}, \quad (14c)$$

where the projectile stops in layer $k+1$ with $V_{k+1} = 0$, when

$$S_{k+1} = P_{k+1} \leq T_{k+1}. \quad (14d)$$

Combining Equation 14 a, b, c, d gives the result:

$$V_0^2 = 2c_1 T_1 + 2c_2 T_2 + \dots + 2c_{k+1} P_{k+1}. \quad (15)$$

The total penetration is given by:

$$P = T_1 + T_2 + \dots + P_{k+1}. \quad (16)$$

An "effective" structural constant, c^* , is defined as:

$$P = V_0^2 / 2c^*. \quad (17)$$

*Each layer is assumed to be a "hard" material or an airgap.

Figure 9 Multilayered Target Schematic and Nomenclature.
 (Each Layer is assumed to be a "Hard" Material or
 an Airgap)

Equation 17 can now be used with experimental data for a layered "hard" target to determine the value of the effective structural constant, c^* , which then can be used to estimate the performance of other projectiles and/or the effect of different initial impact velocities on the same layered target.

5. Conclusions

A family of solutions to the general equation motion for a "hard" projectile penetrating semi-infinite generic target materials has been developed and compared to existing experimental data for two types of targets. The comparison showed that, for these two target materials, the theory adequately predicts the general characteristics of the penetration process with the exception of very small penetrations at low initial impact velocities. The solution for a "hard" projectile penetrating a single layer of target material was used to develop an equation for estimating the penetration behavior for a "layered" target using experimental data to define an effective value for the target structural constant. The solutions should be very useful in predicting the performance of various projectiles against a particular target material or conversely, the protection provided by various target materials against a particular projectile.

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