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ANALYSIS OF PROJECTILE PENETRATION INTO CONCRETE AND ROCK TARGETS

by

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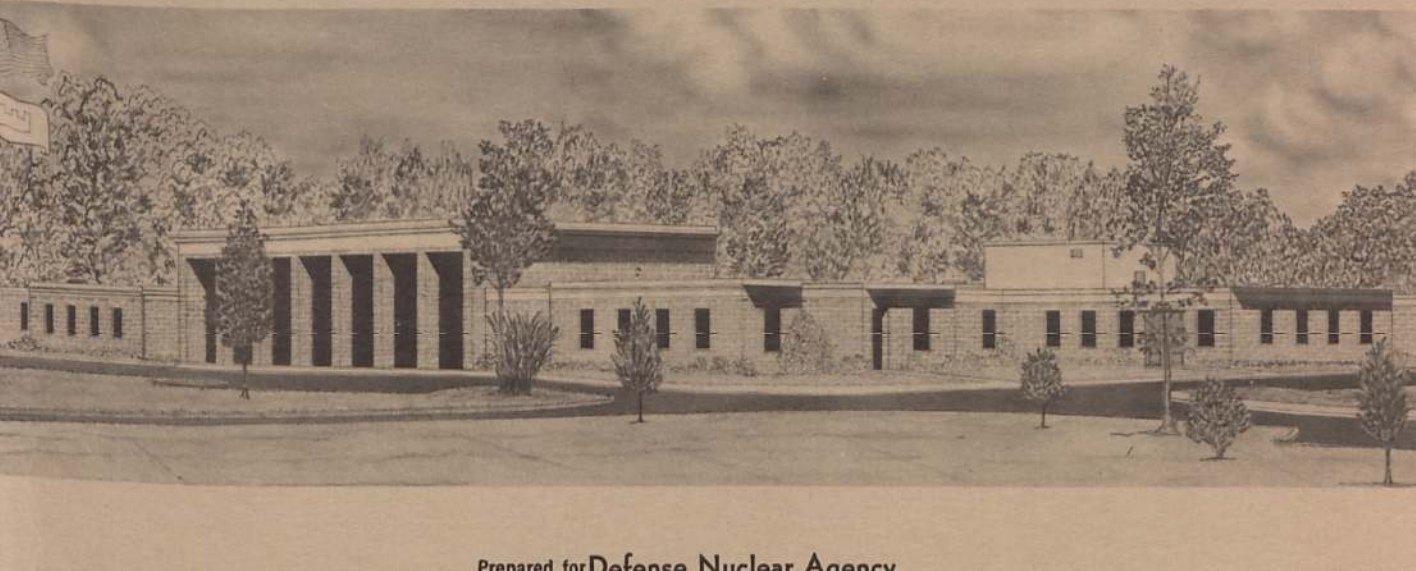

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This report presents several examples of penetration calculations for rigid projectiles impacting concrete and rock targets. The calculations were performed with a computer code which is based on the theory of dynamic cavity expansion in an elastic-plastic compressible continuum. The results of the penetration calculations compare favorably with available data from field experiments and with the results from published finite-difference code calculations. The influence of various target material parameters, different initial

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20. ABSTRACT (Continued)

impact velocities, and projectile size and shape changes on concrete and rock penetration was also assessed. The accuracy and range of application of the penetration model, however, must still be determined experimentally under more diverse impact conditions.

PREFACE

This paper was prepared for presentation at the Defense Nuclear Agency's (DNA) FY 74 Earth Penetrating Weapon (EPW) Program Review held at DNA Headquarters in Alexandria, Virginia, on 13 August 1974.

The paper briefly summarizes the results of some of the projectile penetration studies conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for DNA. These studies involve penetration calculations for large projectiles impacting concrete and rock targets.

The paper was prepared by Dr. B. Rohani of the Soil Dynamics Division (SDD), Soils and Pavements Laboratory (S&PL). Dr. J. G. Jackson, Jr., was Chief of SDD, and Messrs. J. P. Sale and R. G. Ahlvin were Chief and Assistant Chief, respectively, of S&PL during the preparation of this paper. The Director of WES was COL G. H. Hilt, CE, and the Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
slugs per cubic foot	515.3788	kilograms per cubic metre
pounds (force) per square inch	6894.757	pascals
kips (force) per square inch	6894.757	kilopascals
feet per second	0.3048	metres per second

ANALYSIS OF PROJECTILE PENETRATION INTO CONCRETE AND ROCK TARGETS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The problem of predicting the penetration of an object with known geometry, mass, and velocity into materials such as soil, rock, and concrete has been of interest for many years. A number of techniques have been developed over the past 200 years for making such predictions. The prediction techniques can be divided generally into four categories: (a) empirical approach, (b) assumed force law approach, (c) analytical approach, and (d) numerical approach (hydro codes). Summaries of various empirical and force law equations are documented in References 1-4. These equations contain several empirical parameters that are not defined explicitly in terms of the constitutive properties of the target material and the characteristics of the projectile. The numerical values of these parameters must be determined directly from penetration experiments. The reliability of the penetration equations is, therefore, limited to the range of test conditions for which the empirical parameters have been evaluated.

In the analytical approach, a simple constitutive law which approximates the gross physical behavior of the target material is first postulated. Once a useful constitutive law has been established it is possible to formulate a geometrically simple boundary-value problem and derive an expression for the force on part of the boundary which is consistent with a simple field of motion. This force is then assumed to be the resisting force on the projectile during the penetration event. The simple boundary-value problem which has been adapted to the penetration process with most success is that for dynamic spherical cavity expansion in an elastic-plastic, strain-hardening compressible medium (References 5-7). Unlike the empirical and assumed force law equations, the penetration equations generated by the analytical approach do not contain empirical parameters that must be evaluated from penetration experiments. The parameters appearing in the penetration equations are defined explicitly in terms of the physical properties of the target material (which can be determined independently rather than from a penetration test) and the characteristics of the projectile (such as its weight, diameter, and nose shape). Accordingly, these equations can be used for predicting penetration for a variety of projectiles for any target material that can be approximated within the framework of the constitutive law adopted for the theoretical analysis. The accuracy and range of application must be determined from actual penetration experiments and obviously depend upon the degree of relevance of the simple boundary-value problem as an approximation to the postulated penetration event. It should be noted that the penetration equations resulting from the analytical approach are often relatively simple mathematical expressions which can be solved quickly and inexpensively. The cavity expansion-based penetration equations reported in References 5-8 represent the outcome of the analytical approach.

The most comprehensive approach to projectile penetration problems is the numerical approach using two-dimensional axisymmetric finite-difference computer codes (References 9-11). Such codes are frequently referred to as hydro codes. Most of them were originally developed in conjunction with armor penetration research but they are also applicable to other target materials. An application of two-dimensional finite-difference computer codes to rock penetration is given in Reference 12. A unique feature of the hydro codes is their capability for treating the projectile as a deformable elastic-plastic body. Such a treatment is necessary in order to determine the loading environment within a projectile, both at impact and during the penetration event, for use in structural analysis of the projectile and in the design of its internal components.

The above-mentioned four procedures comprise the available tools for analysis of projectile penetration into any target material. None of these procedures can fully describe all the phenomena associated with projectile penetration and impact. Nevertheless, they provide realistic engineering solutions to the majority of projectile penetration problems of interest. Each approach has its pros and cons and each has some application, depending on the nature of the penetration problem at hand.

1.2 PURPOSE

The purpose of this paper is to briefly present the results of some of the projectile penetration studies conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Defense Nuclear Agency (DNA). These studies involved penetration calculations for large projectiles impacting concrete and rock targets. The results from the concrete penetration studies are given in Chapter 2. The results from the rock penetration studies are given in Chapter 3.

CHAPTER 2

PENETRATION INTO CONCRETE

Figure 2.1 depicts the physical characteristics of two projectiles (A and B) which were simulated in calculation studies of penetration into a concrete target (References 13 and 14). The projectiles were assumed to be rigid. The nose shape for both projectiles was defined as a 1.5-caliber ogive. The pressure-density relation for the concrete target is shown in Figure 2.2; the initial density of the concrete was assumed to be 4.66 slugs/ft^3.[1] Figures 2.3 and 2.4 illustrate the results of the penetration calculations for projectiles A and B, respectively. The calculation results are given for a 5000-psi concrete target of infinite thickness in terms of the depth of penetration versus impact velocity relation for a velocity range of 500 to 1500 ft/sec. These calculations were performed with a computer code developed at WES for predicting the depths to which normally impacting rigid projectiles will penetrate into layered targets. The code is based on dynamic spherical cavity expansion theory applied to problems involving projectile impact with elastic-plastic, strain-hardening, compressible materials (Reference 7). In addition to the WES calculations, each figure also contains the results of penetration calculations which employed the British and TM 5-855-1 equations. The British and TM 5-855-1 equations (References 15 and 16, respectively) are two of the more commonly used empirical equations for predicting projectile penetration into concrete targets. Both equations were derived from broad experimental data bases.

The TM 5-855-1 equation has a reported accuracy of ±15 percent. Input values required for this equation are the projectile's weight, diameter, and impact velocity, and the static compressive strength of the concrete target; the equation does not account for variations in projectile nose shape or the concrete's density and compressibility.

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[1] A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

The British equation has a reported accuracy range of ±26 percent. Input values to be specified are all of those required for the TM 5-855-1 equation plus a maximum aggregate size for the concrete target (a maximum aggregate size of 3/4 inch was used in the calculations for this study). It is observed from Figures 2.3 and 2.4 that the results of the WES theoretical calculations compare very favorably with the results obtained using the empirical equations.

Figure 2.5 depicts the results for the 2000-pound British AP bomb (projectile A) penetrating into a three-layer target composed of a well compacted soil backfill sandwiched between a concrete detonation slab and the concrete roof of an underground structure. The calculations were performed with the cavity expansion-based penetration code for impact velocities of 1300 and 1500 ft/sec. Both the detonation slab and the roof slab were assumed to be constructed of 5000-psi structural concrete. As depicted in Figure 2.5, the AP bomb at 1300 ft/sec perforates the detonation slab and comes to rest in the backfill within 6-1/2 inches of the structure roof. The roof is "sensed" by the projectile, causing it to decelerate abruptly just before contacting it. Thus, even at 1500 ft/sec, the AP bomb does not penetrate the concrete roof.

In order to determine the role of target compressibility in penetration into concrete, a series of parameter studies was conducted in which the compressibility of the target was varied. The results of these calculations are shown in Figure 2.6 for the case of projectile A and a 5000-psi concrete target. During each calculation the compressibility of the target was held constant. Zero percent compressibility corresponds to an incompressible target and provides the lower bound to penetration depths. Five percent compressibility corresponds to a fairly compressible concrete. From Figure 2.6 it is observed that the compressibility of the target material does indeed influence the penetration results. Also shown in Figure 2.6 are the British and TM 5-855-1 penetration curves with their corresponding limits of accuracy. It is interesting to note that the accuracy limits established for both the British and the TM 5-855-1 equations define bounds for their predicted penetration depths that are approximately the same as those calculated to depict effects due to compressibility variations.

Figure 2.7 depicts the results of a set of calculations performed to study the effects of the compressive strength of the concrete on the depth of penetration for projectile A. Concrete compressive strengths of 3750, 4150, and 5000 psi were used for the calculations. It is observed from Figure 2.7 that, within the range of strengths studied, the penetration depth is only mildly dependent on compressive strength.

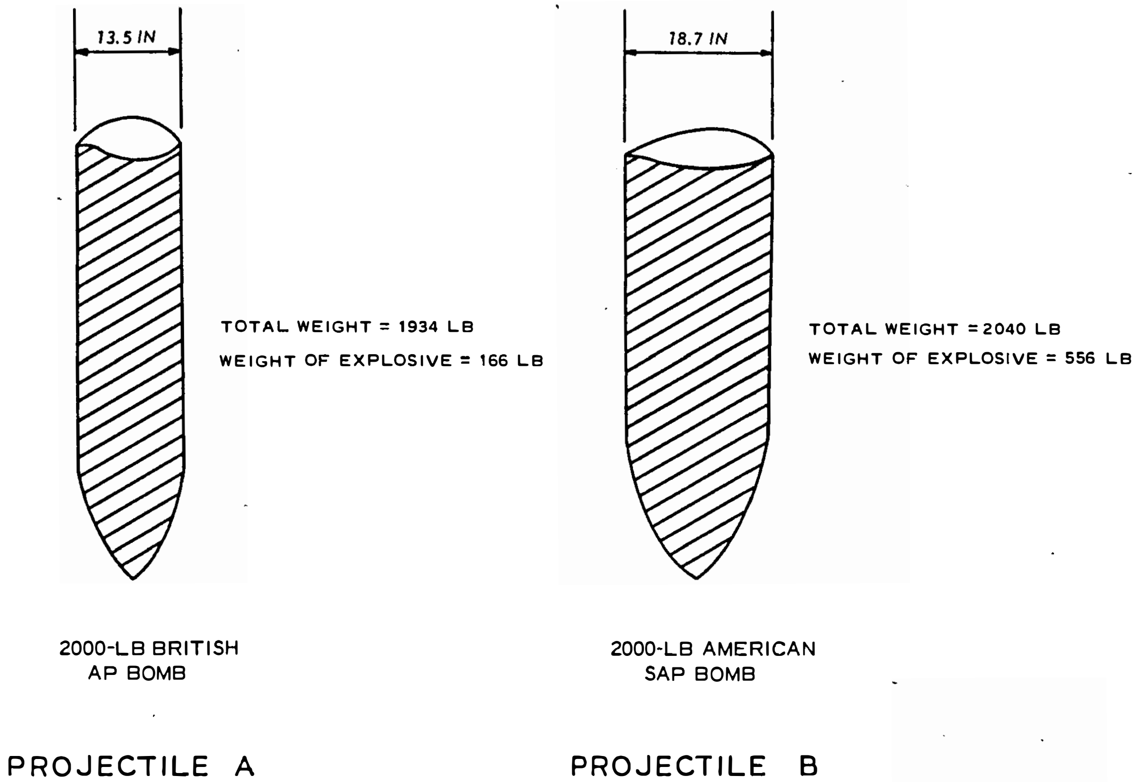

Figure 2.1 Physical characteristics of bombs used in concrete penetration calculations.

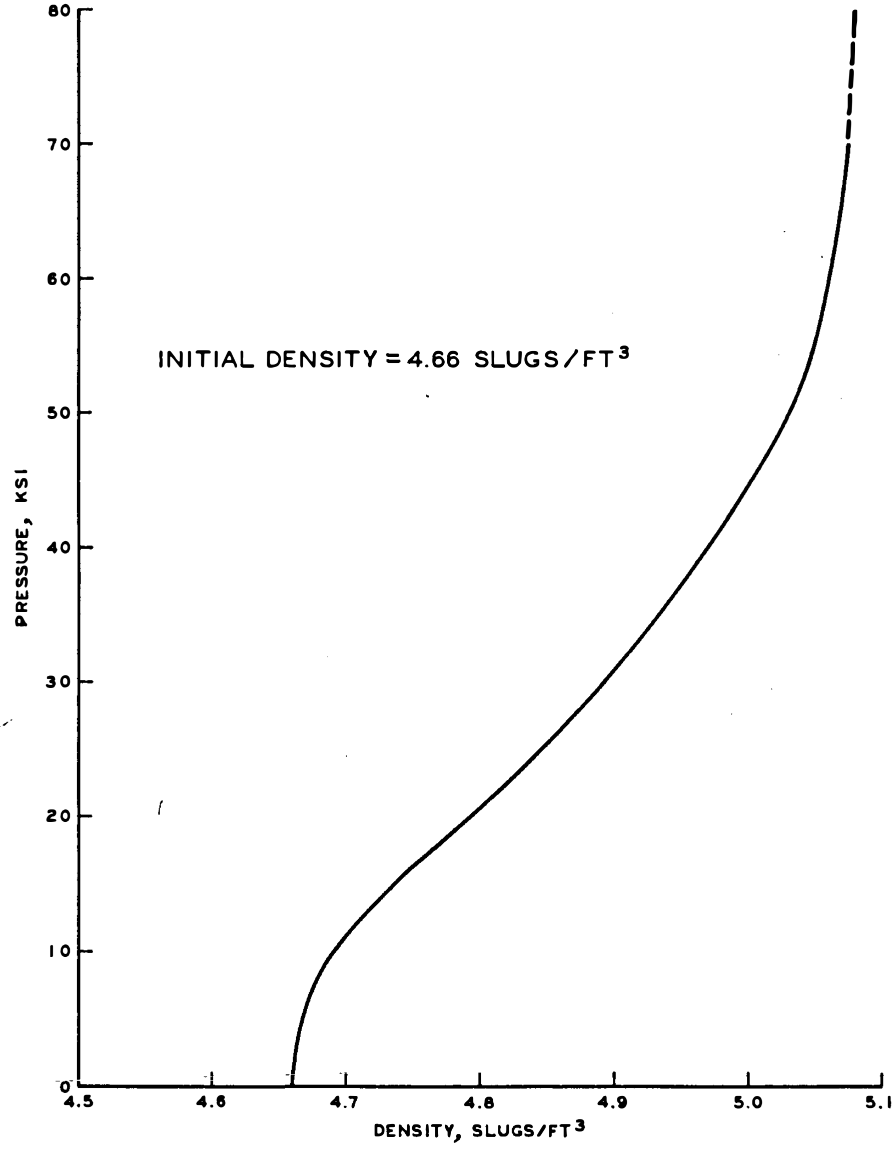

Figure 2.2 Concrete pressure-density relation used for penetration calculations.

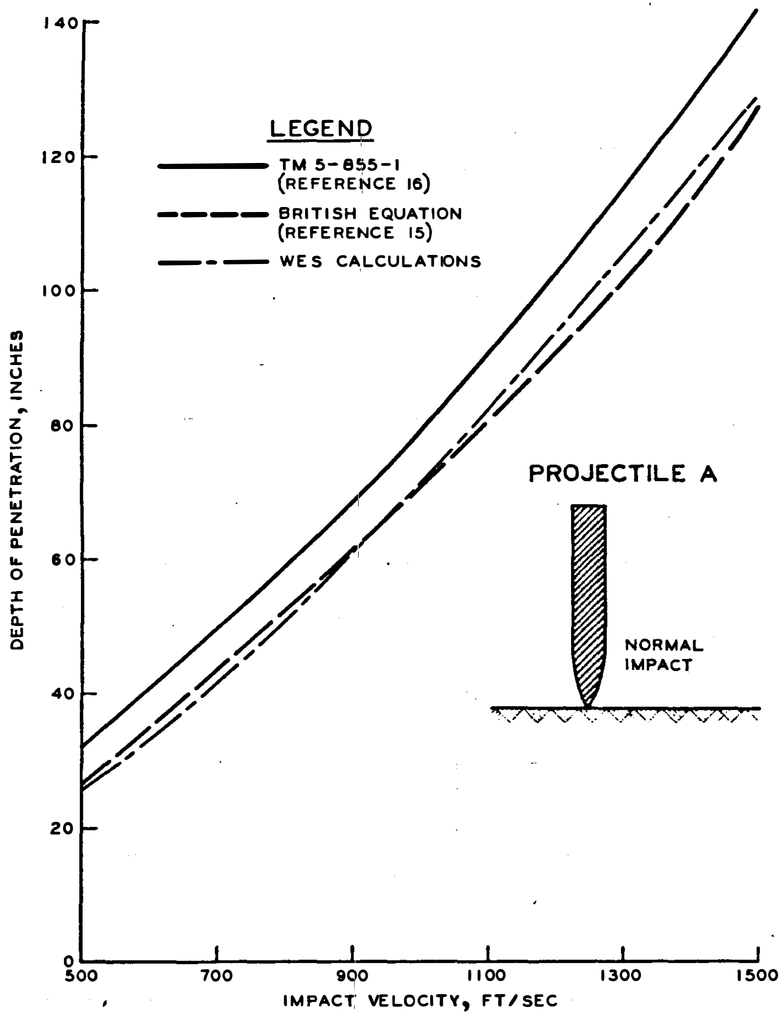

Figure 2.3 Depth of penetration versus impact velocity relations for normal impact of projectile A with 5000-psi concrete target.

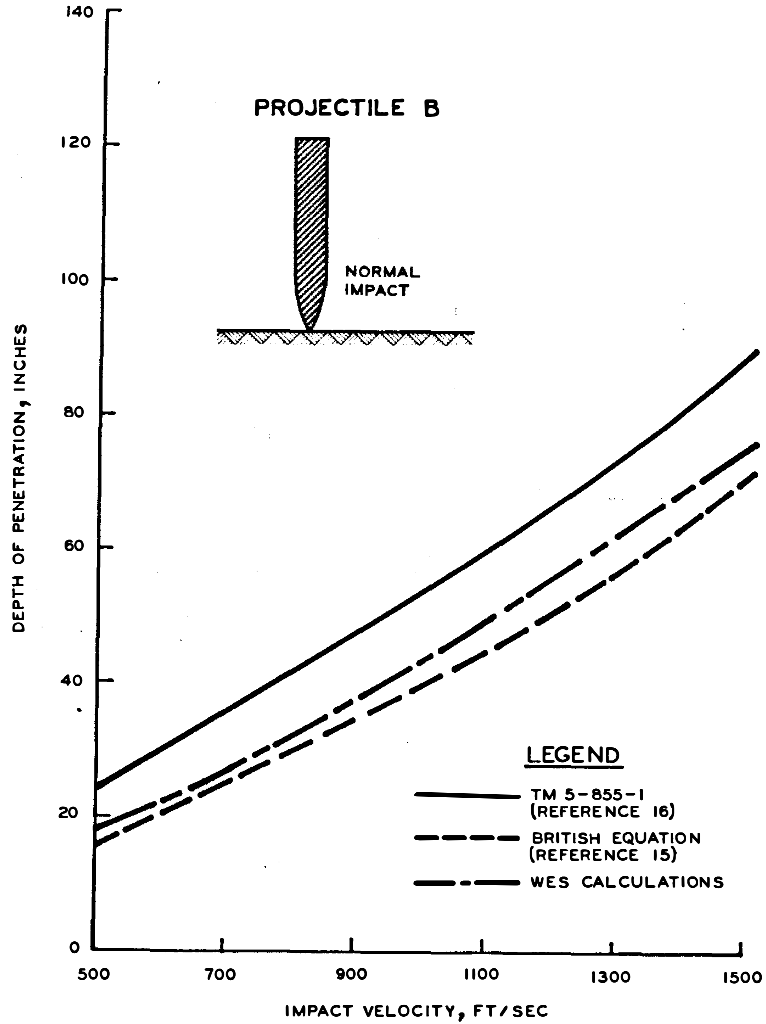

Figure 2.4 Depth of penetration versus impact velocity relations for normal impact of projectile B with 5000-psi concrete target.

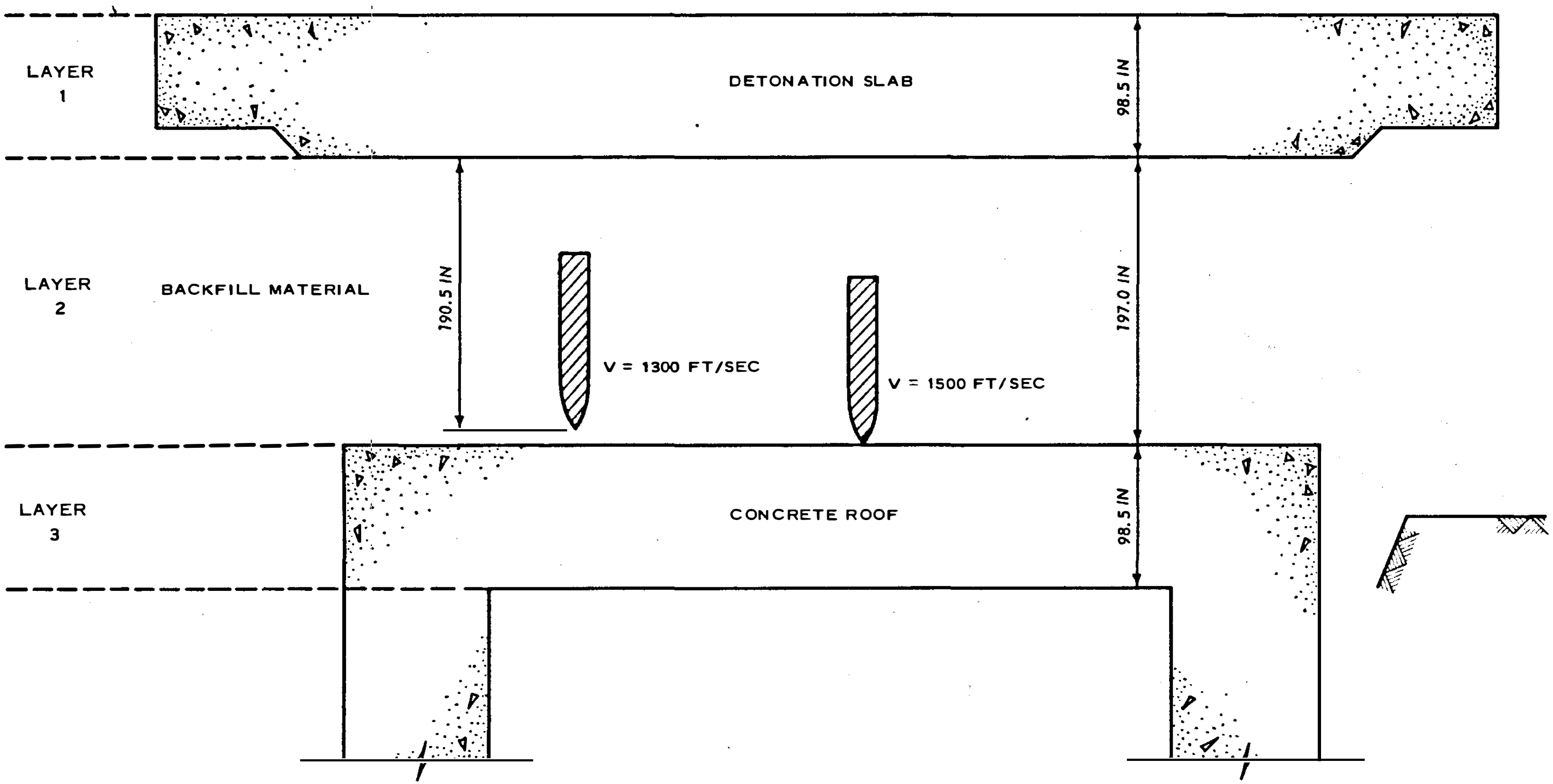

Figure 2.5 Normal penetration of 2000-pound British AP bomb into layered target at 1300- and 1500-ft/sec impact velocities.

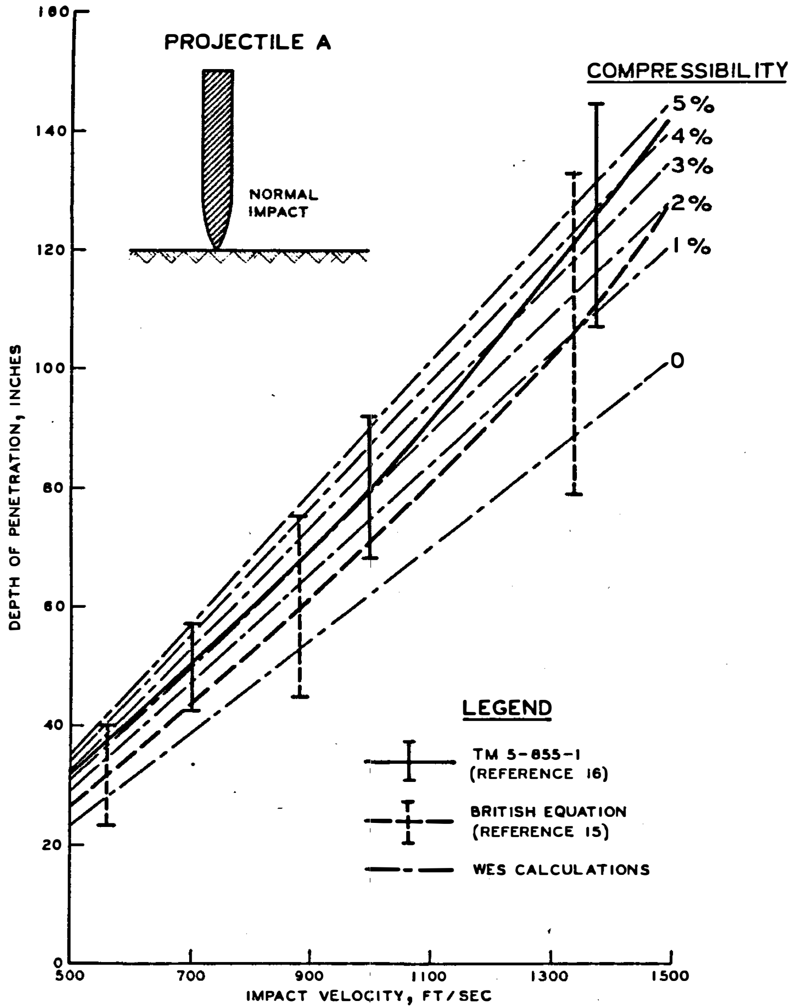

Figure 2.6 Depth of penetration versus impact velocity relations for normal impact of projectile A with 5000-psi concrete targets of varying compressibility.

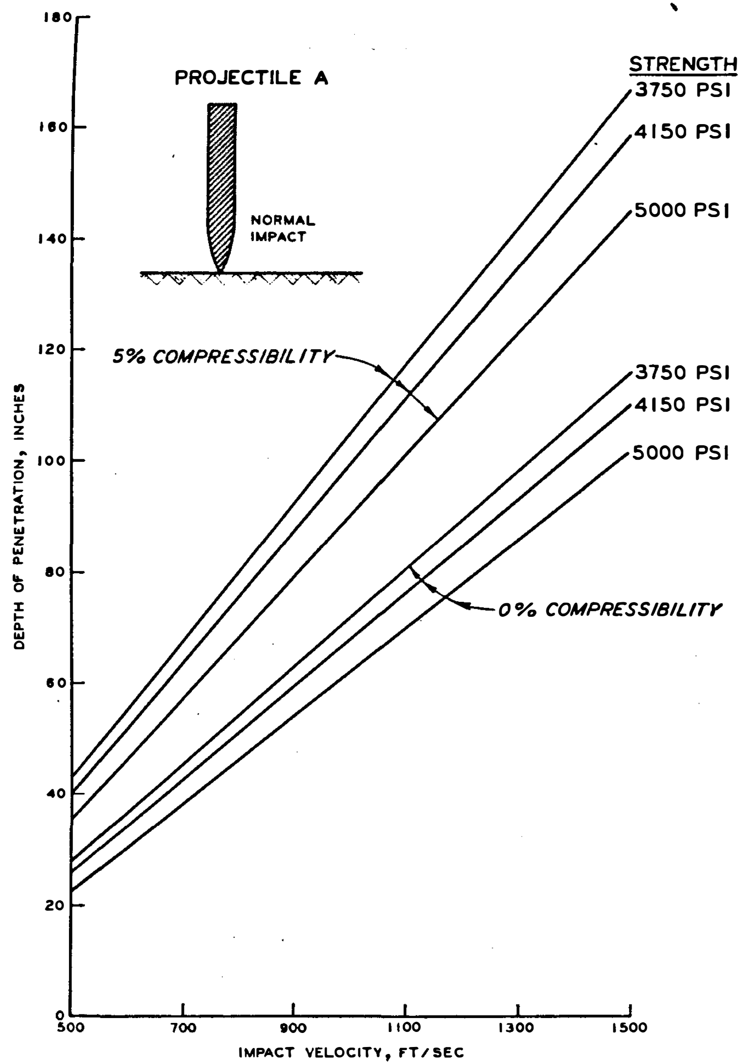

Figure 2.7 Calculated depth of penetration versus impact velocity for normal impact of projectile A with 5- and 0-percent compressible concrete targets of varying strengths.

CHAPTER 3

PENETRATION INTO ROCK

Efforts are presently under way at WES to study the penetration of large projectiles into rock targets. The investigation includes a comparative study with the results of rock penetration tests conducted by Sandia Laboratories (Reference 17). Figure 3.1 shows the results from one of the rock penetration calculations for a 9.25-caliber ogive, 8-inch-diameter, 675-pound projectile impacting into limestone at 570 ft/sec. The limestone target has an unconfined compressive strength of 13,690 psi and a density of 168 lb/ft^3. Figure 3.2 presents the results of a rock penetration calculation for a 6-caliber ogive, 9-inch-diameter, 1000-pound projectile impacting into welded tuff at 695 ft/sec. The tuff target has an unconfined compressive strength of 5510 psi and a density of 115 lb/ft^3. Also shown in Figures 3.1 and 3.2 are the results from finite-difference calculations conducted by Sandia Laboratories (Reference 12).

It is observed from Figures 3.1 and 3.2 that the agreement between the two sets of calculations is very favorable for the depth and velocity versus time histories. The deceleration-time histories from the finite-difference calculations, where the projectile is treated as a deformable body, are oscillatory in nature while the WES deceleration-time histories, which correspond to rigid body deceleration of the projectile, are not. The oscillations in the deformable body calculations represent particle motion due to stress wave propagation within the projectile. Figure 3.3 shows the comparison of the WES rigid body deceleration with the corresponding deformable body calculation results for a point located on the nose tip of the projectile. Again it is observed that the deformable body deceleration curve oscillates. The oscillations are more pronounced than those shown in the previous figure (Figure 3.2) because in that case the particle was located on the centerline of the projectile one nose length from the nose tip. Particle deceleration calculations are, of course, significant for design of the internal components of the projectile. It is important to understand both the so-called rigid body and the wave propagation contributions to the total response.

In order to determine the reliability of the cavity expansion-based penetration model for rock penetration prediction, five field tests were selected from Reference 17 for correlation with the model. The test information is summarized in Table 3.1. A description of the rock targets is given in Reference 18. The rock is classified according to the scheme presented in Table 3.2. The test information from Table 3.1 was used in conjunction with the rock descriptions in Table 3.2 to obtain upper and lower limit penetration predictions for each test. The predicted depths are plotted versus measured depth of penetration in Figure 3.4 (the perfect correlation line is shown for reference). The upper and lower limits of penetration for each test were calculated using the lower and upper limits, respectively, of the compressive strength for a given intact rock classification as given in Table 3.2 (i.e., a factor of two variation in strength). Since no compressibility data were available for the rock targets, it was assumed that the lower and upper limits of compressive strength correspond to 20 and 1 percent compressibility, respectively. Other reasonable combinations of compressive strength and compressibility will result in predicted penetration depths which fall within the upper and lower limits shown in Figure 3.4. It is observed from Figure 3.4 that the use of extreme ranges of properties still produces ranges of predicted penetration depths which are acceptable for many engineering applications.

Figures 3.5 through 3.7 depict the results of a parameter study of Sandia Test No. 120-106. The purpose of this study was to determine the sensitivity of penetration depth predictions to properties of the target and projectile impact velocity; projectile size and shape parameters were not varied. Figure 3.5 illustrates the effect of the target yield strength Y, within the range of 4000 to 8000 psi, on the predicted penetration versus impact velocity relations. The target elastic modulus E, the initial density ρ_o, and the compressibility ρ_p/ρ_o were held constant during the calculations. It is observed from Figure 3.5 that for the impact velocity range of 500 to 1900 ft/sec, a factor of two variation in Y produces about a 40 percent change in the predicted depth of penetration. Figure 3.6 depicts the effect of E on the predicted penetration versus impact velocity relations. In Figure 3.6, E is varied by a factor of 20 and the effect on the predicted penetration depth is seen to be less than 5 percent over the entire impact velocity range. The effect of target compressibility ρ_p/ρ_o on the predicted penetration depth is investigated in Figure 3.7. As shown in Figure 3.7, a variation of approximately 20 percent in ρ_p/ρ_o affects the predicted depth of penetration on the order of 20 percent in the upper range of compressibility (say $1.11 \leq \rho_p/\rho_o \leq 1.35$). For the relatively incompressible range (say $1.00 \leq \rho_p/\rho_o \leq 1.01$), on the other hand, a variation of only 1 percent affects the predicted depth of penetration on the order of 15 percent. Within the impact velocity range of 500 to 1900 ft/sec, however, the value of ρ_p/ρ_o should be in the range of $1.01 \leq \rho_p/\rho_o \leq 1.20$ for most rocks. The results of this study indicate that a reasonable range of variation in Y has a more significant influence on the predicted depth of penetration than a reasonable range of variation of any other parameter in the penetration theory.

The cavity expansion-based penetration model was also used to parametrically investigate the effects of projectile nose shape (ogive geometry, CRH) and weight-to-area ratio (sectional pressure, W/A) on the predicted depth of penetration into three types of rock for impact velocities of 1000, 2000, and 3000 ft/sec. The details of this study are documented in Reference 20. The rock targets are classified as low strength (6000-psi compressive strength and 20 percent compressibility), medium strength (12,000-psi compressive strength and 13 percent compressibility), and high strength (24,000-psi compressive strength and 11 percent compressibility). The results of the parameter study are shown in Figures 3.8-3.12. Figures 3.8 and 3.9 illustrate the effect of nose caliber CRH on the predicted depth of penetration for the low- and medium-strength rock targets, respectively. Within the range of CRH studied, the nose caliber is seen to have little effect on depth of penetration for a given impact velocity and rock strength; the effect of CRH is greatest for high impact velocity and low-strength rock. The effect of W/A on the predicted depth of penetration is shown in Figures 3.10-3.12 for the low-, medium-, and high-strength rocks, respectively; W/A varies from 10 to 15 psi. The sensitivity of depth of penetration to W/A is seen to increase with increase in impact velocity and/or decrease in rock strength.

Further application of the cavity expansion-based penetration model to rock penetration problems is demonstrated in Figures 3.13 and 3.14. Figures 3.13 and 3.14 depict motion-time histories for a 9.25-caliber ogive, 6.5-inch diameter, 400-pound projectile impacted into Nevada Test Site (NTS) granite and NTS tuff, respectively, at 1500-ft/sec velocity. The unconfined compressive strengths for the NTS granite and NTS tuff are 13,500 and 5,800 psi, respectively. The initial densities of the granite and tuff targets are 165 and 109 lb/ft^3, respectively. From Figures 3.13 and 3.14 it is seen that the penetration into the tuff target is about 2.3 times the penetration into the granite target.

TABLE 3.1 SANDIA ROCK PENETRATION TEST DATA (REFERENCE 17)

Sandia Test Number	Projectile Description	Rock Type[a]
120-77	W = 859 lb Diam = 9 in CRH = 9.25 V_i = 1065 ft/sec	TTR welded agglomerate D RQD = 60%
120-106	W = 613 lb Diam = 8 in CRH = 9.25 V_i = 860 ft/sec	Weathered granite DH RQD = 32%
120-127	W = 674 lb Diam = 8 in CRH = 9.25 V_i = 950 ft/sec	Madera limestone CH RQD not determined
120-112	W = 1148 lb Diam = 10.188 in CRH = 9.25 V_i = 825 ft/sec	Sandstone DH RQD = 37%
339-16	W = 1018 lb Diam = 9 in CRH = 6.0 V_i = 650 ft/sec	TTR welded tuff DL RQD = 80%

[a] See Table 3.2 for classification definitions.

TABLE 3.2 ENGINEERING CLASSIFICATION FOR INTACT ROCK (After Deere and Miller, Reference 19)

I. On Basis of Strength

Class	Description	Uniaxial Compressive Strength psi
A	Very high strength	Over 32,000
B	High strength	16,000 to 32,000
C	Medium strength	8,000 to 16,000
D	Low strength	4,000 to 8,000
E	Very low strength	Less than 4,000

II. On Basis of Modulus Ratio

Class	Description	Modulus Ratio[a]
H	High modulus ratio	Over 500
M	Average modulus ratio	200 to 500
L	Low modulus ratio	Less than 200

Classify rock as BH, BM, BL, etc.

III. On Basis of Rock Quality Designation (RQD)

Rock Quality Designation, %	Description of Rock Quality
0 to 25	Very poor
25 to 50	Poor
50 to 75	Fair
75 to 90	Good
90 to 100	Excellent

[a] Modulus ratio = E_t/σ_a (ultimate)

where

E_t = tangent modulus at 50 percent ultimate strength;

σ_a = uniaxial compressive strength.

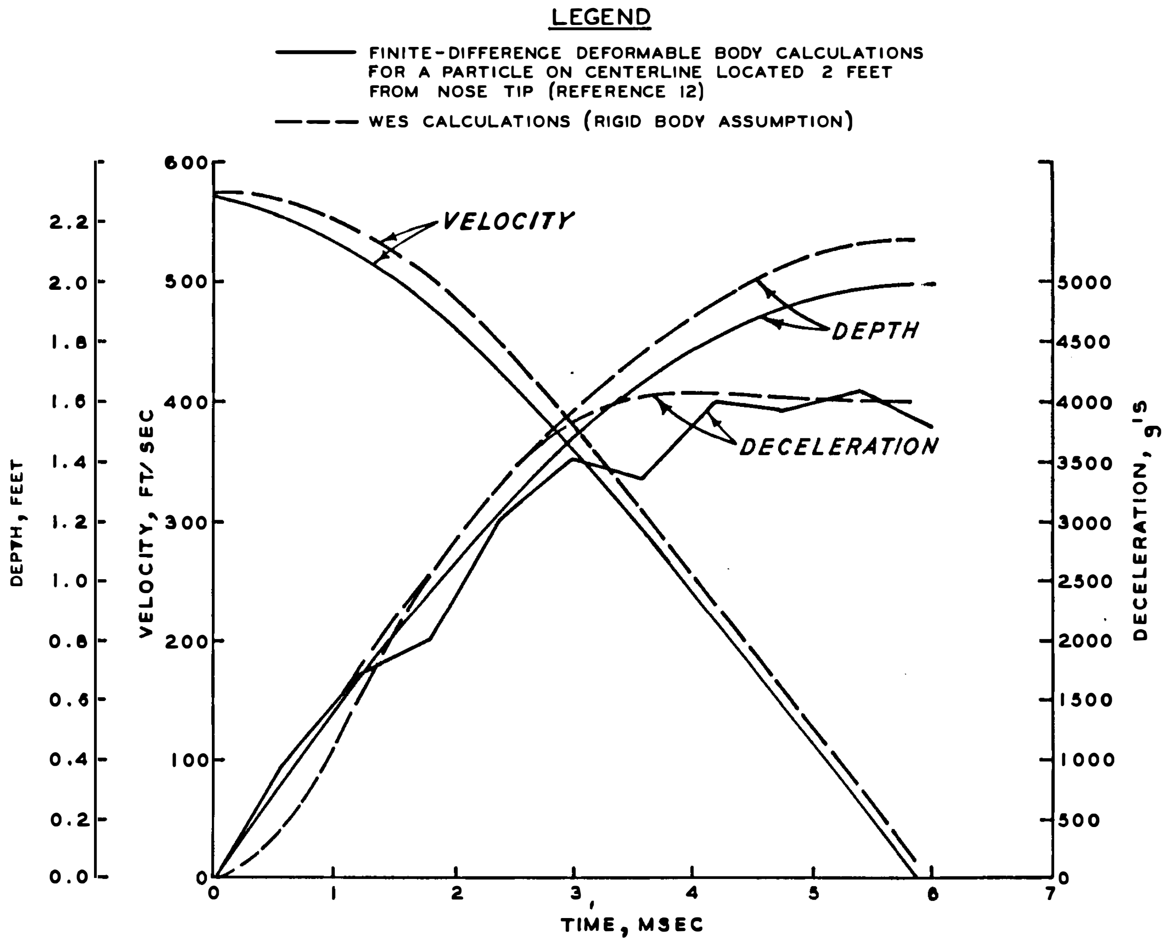

Figure 3.1 WES rigid body motion-time histories superimposed on finite-difference deformable body calculations for penetration of a 9.25-caliber ogive, 8-inch-diameter, 675-pound projectile into limestone.

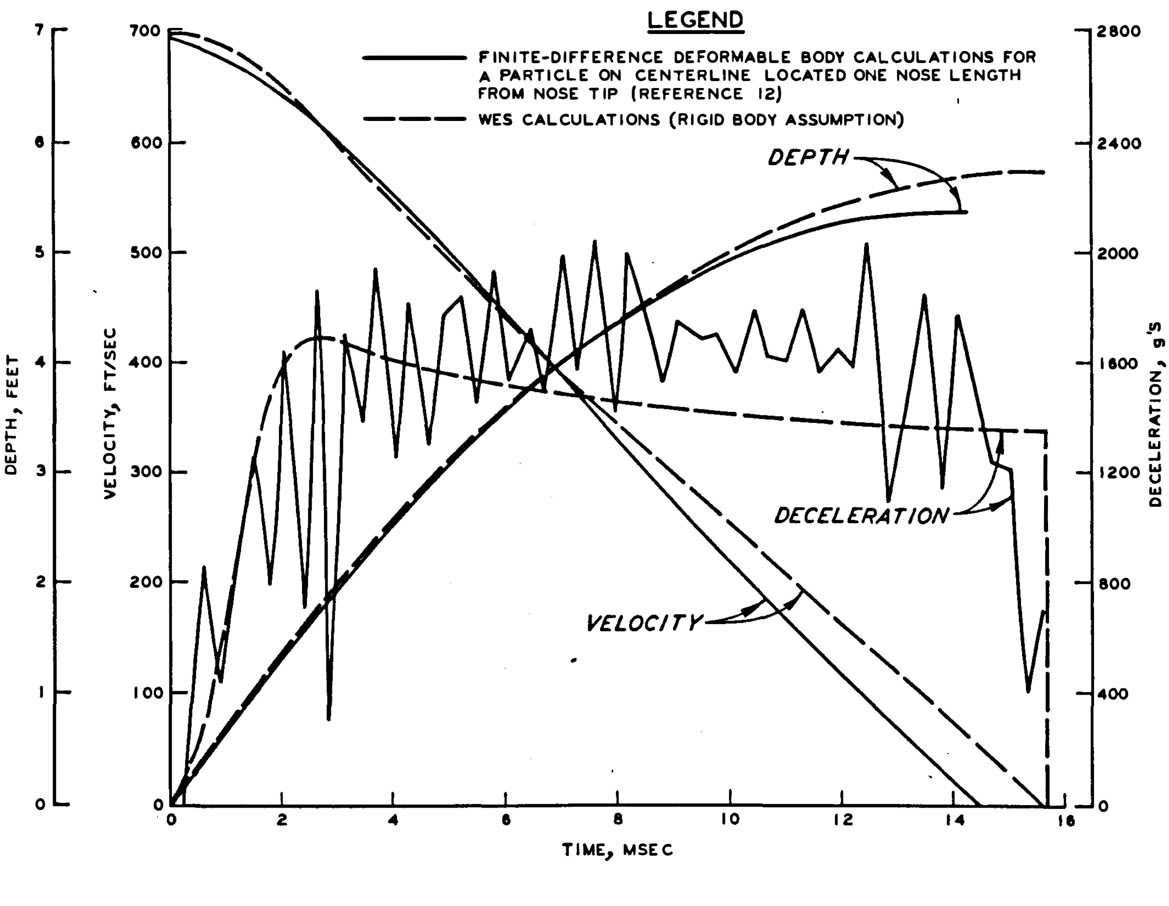

Figure 3.2 WES rigid body motion-time histories superimposed on finite-difference deformable body calculations for penetration of a 6-caliber ogive, 9-inch-diameter, 1000-pound projectile into tuff.

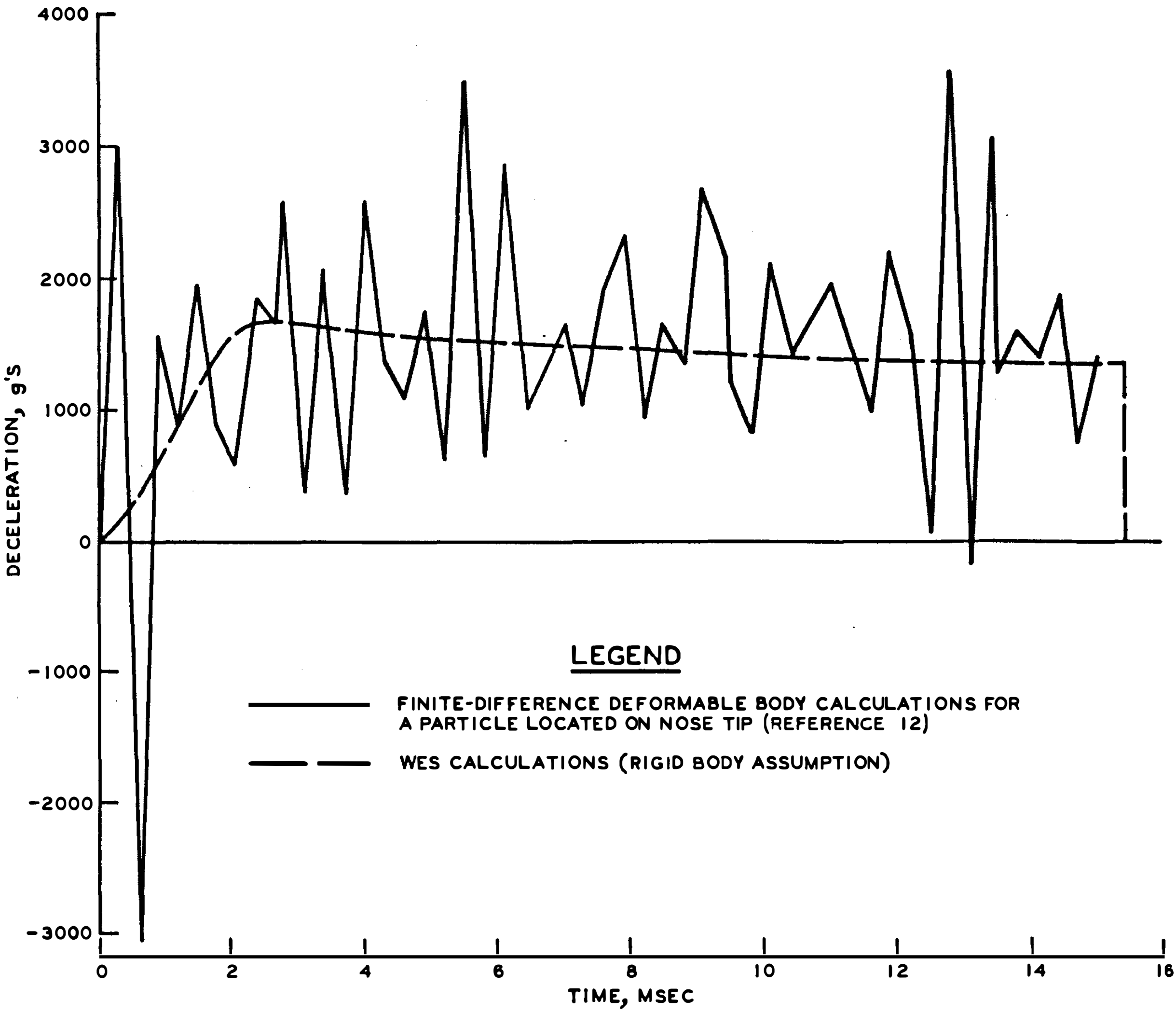

Figure 3.3 WES rigid body deceleration-time history superimposed on finite-difference deformable body calculations for penetration of a 6-caliber ogive, 9-inch-diameter, 1000-pound projectile into tuff.

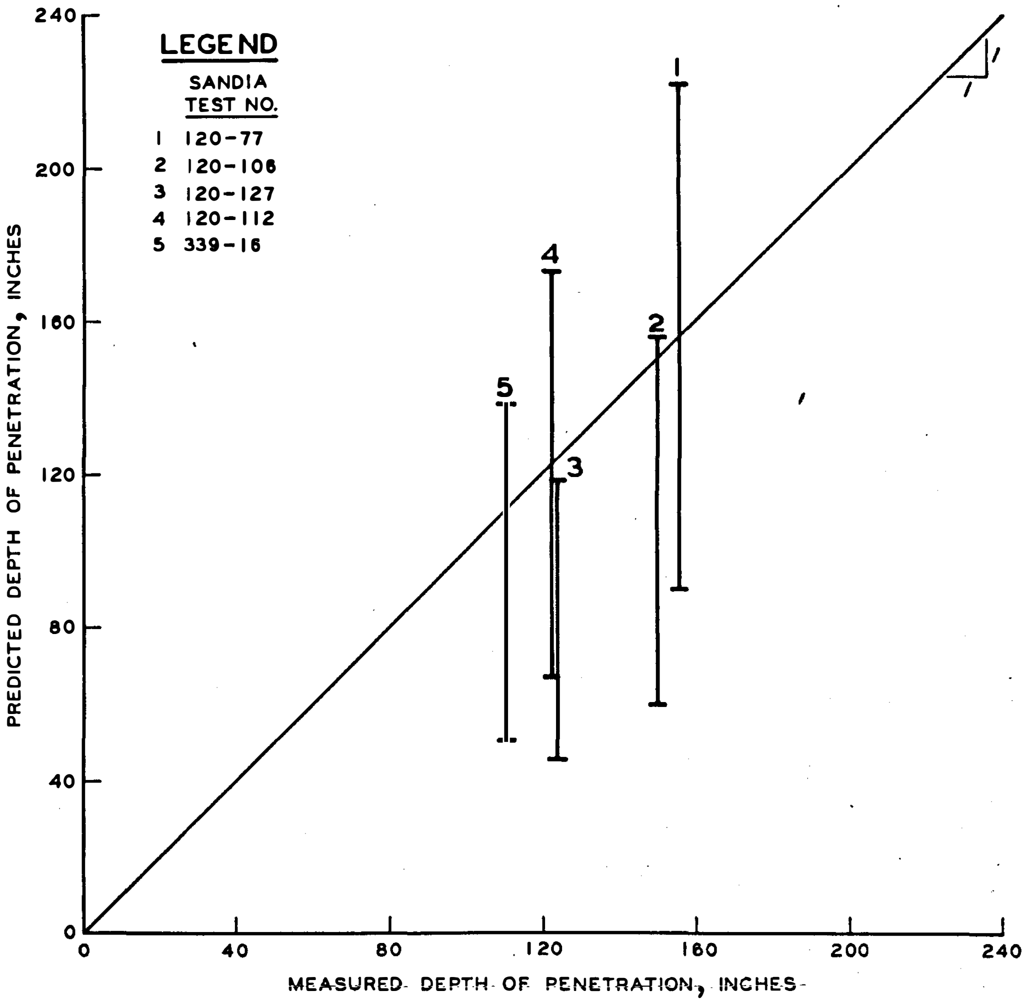

Figure 3.4 Measured versus predicted depth of penetration into rock targets.

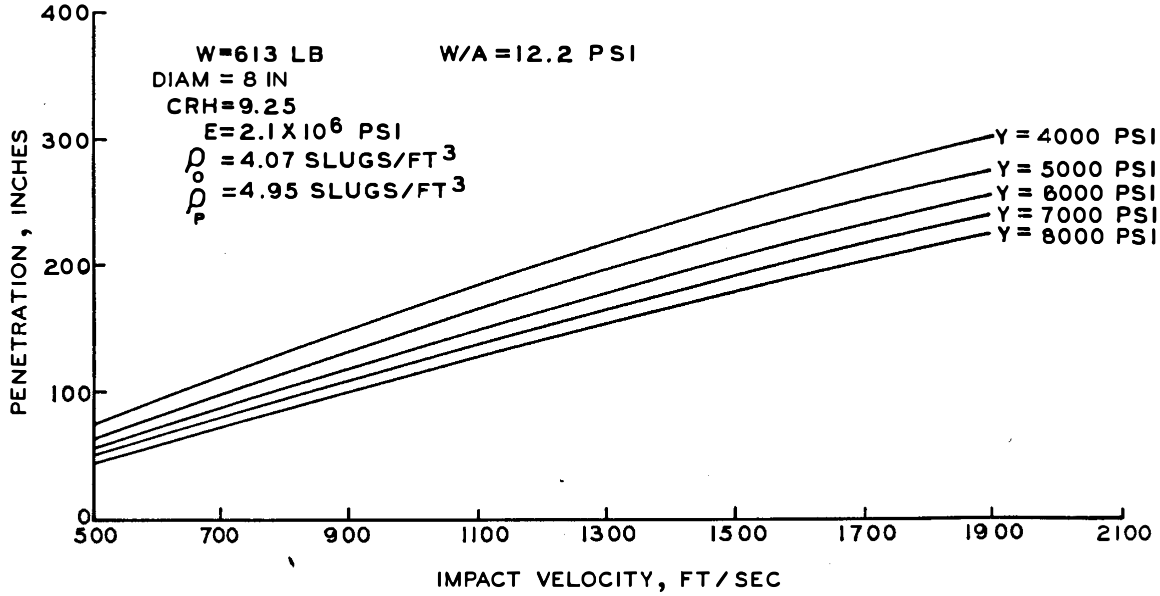

Figure 3.5 Effect of varying yield strength Y on penetration versus impact velocity relations.

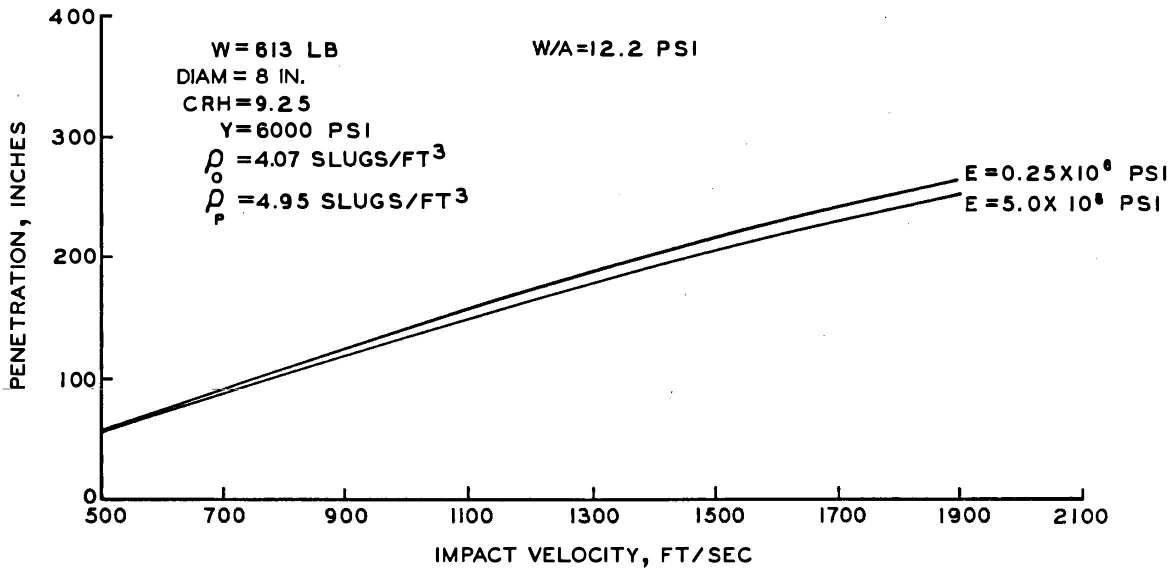

Figure 3.6 Effect of varying modulus of elasticity E on penetration versus impact velocity relations.

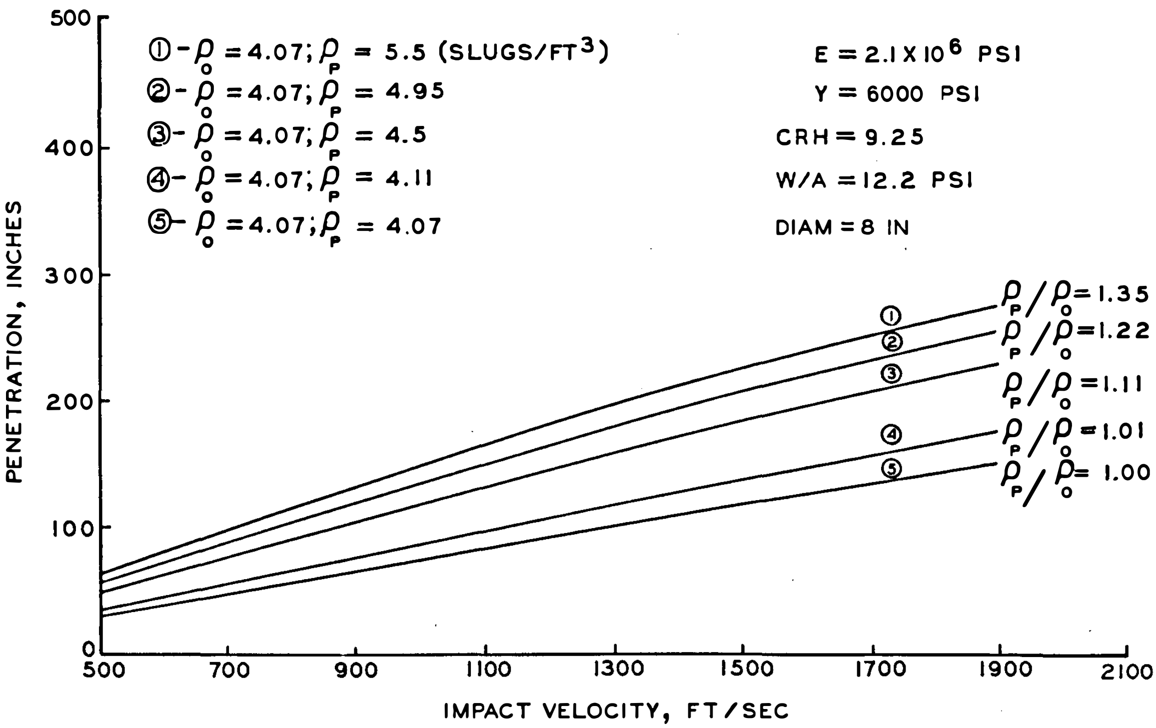

Figure 3.7 Effect of varying compressibility ρ_p/ρ_o on penetration versus impact velocity relations.

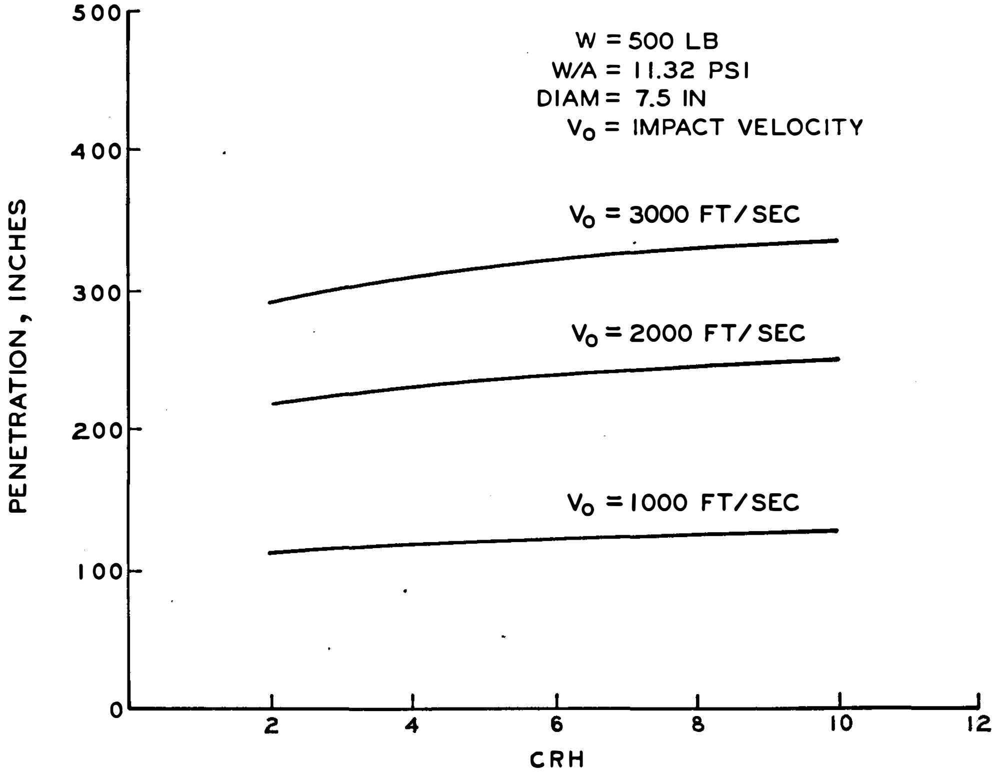

Figure 3.8 Effect of nose caliber CRH on predicted penetration into low-strength rock.

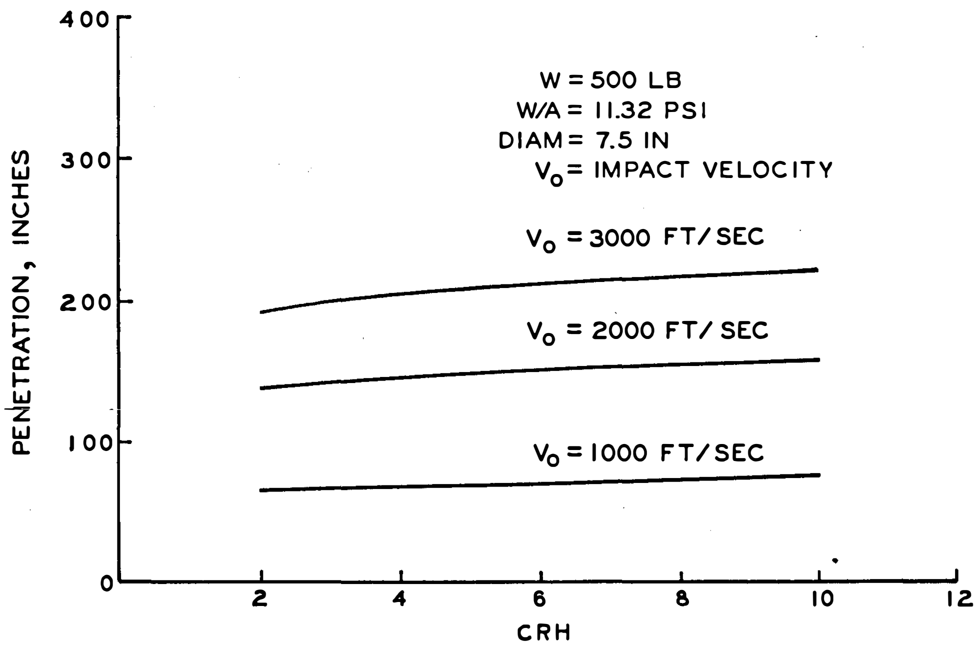

Figure 3.9 Effect of nose caliber CRH on predicted penetration into medium-strength rock.

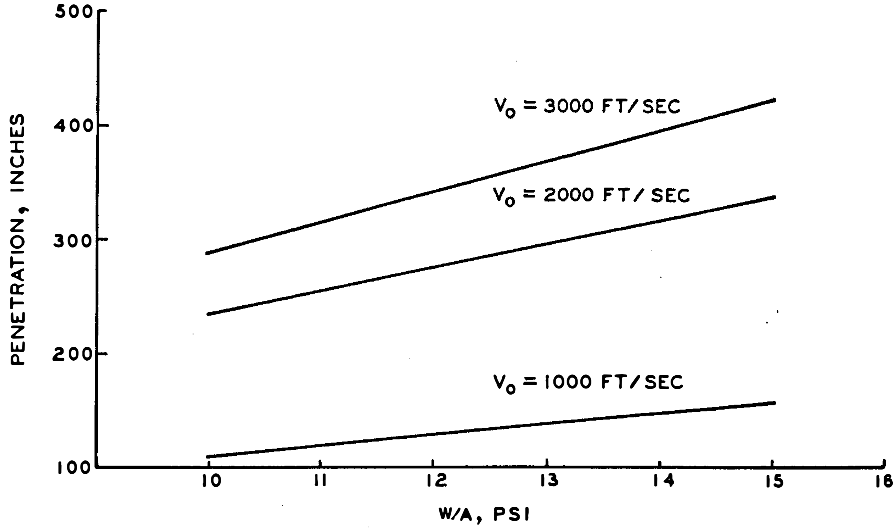

Figure 3.10 Effect of weight-to-area ratio W/A on predicted penetration into low-strength rock, CRH 6.

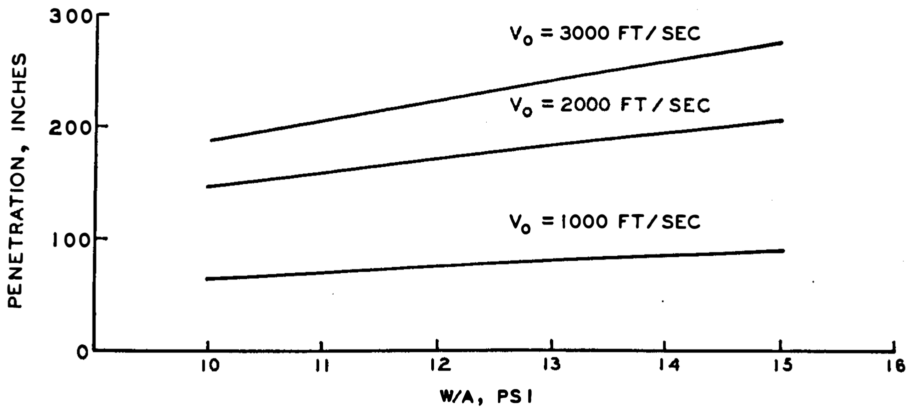

Figure 3.11 Effect of weight-to-area ratio W/A on predicted penetration into medium-strength rock, CRH 6.

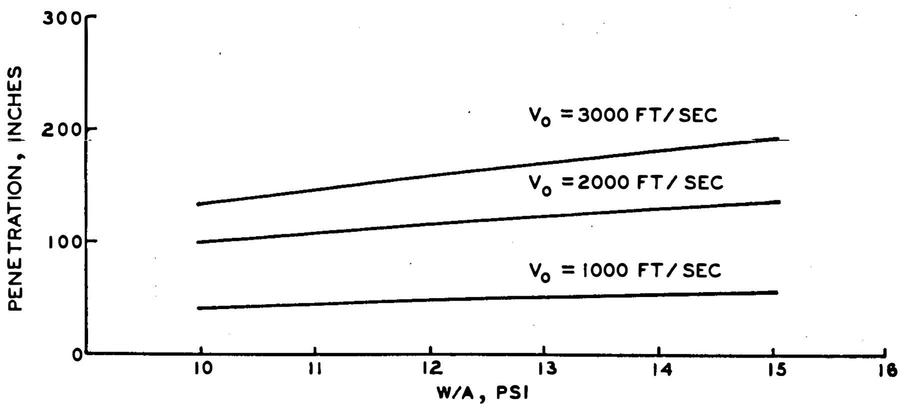

Figure 3.12 Effect of weight-to-area ratio W/A on predicted penetration into high-strength rock, CRH 6.

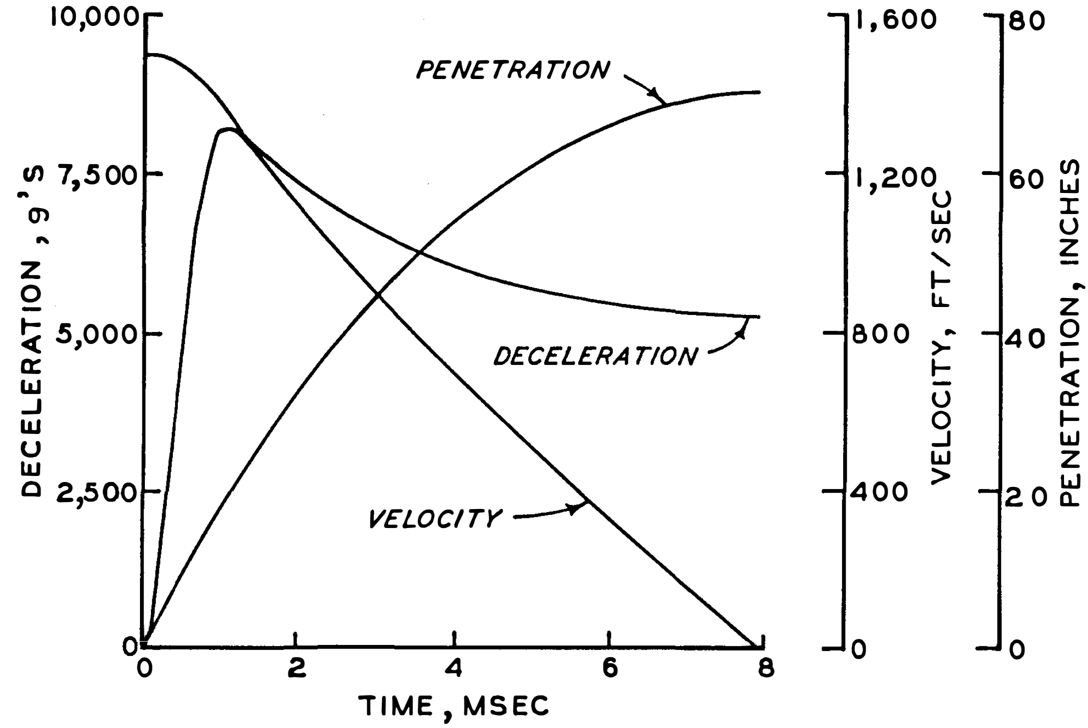

Figure 3.13 Calculated motion versus time histories for normal penetration into NTS granite (W = 400 pounds, D = 6.5 inches, CRH = 9.25).

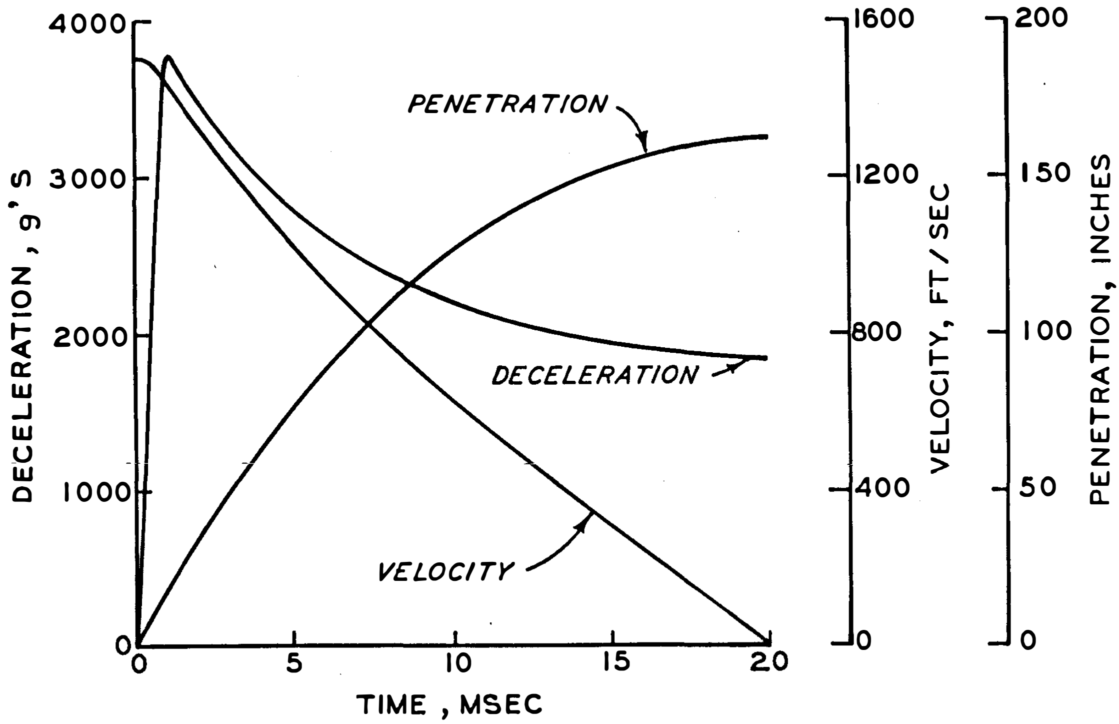

Figure 3.14 Calculated motion versus time histories for normal penetration into NTS tuff (W = 400 pounds, D = 6.5 inches, CRH = 9.25).

CHAPTER 4

SUMMARY

Several examples of penetration calculations for concrete and rock targets are presented. The calculations were performed with a computer code which is based on the theory of dynamic cavity expansion in an elastic-plastic, strain-hardening, compressible continuum. The results of the penetration calculations compare favorably with available data from field experiments and with the results from published finite-difference code calculations. The influence of various target material parameters, different initial impact velocities, and projectile size and shape changes on concrete and rock penetration was also assessed. The accuracy and range of application of the penetration model, however, must still be determined experimentally under more diverse impact conditions.

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