27.
-11-80
pub
24th
SAND80-0248

Unlimited Distribution

UC-2

MASTER

COMPARISON OF EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR REVERSE BALLISTIC TESTS INTO FOUNDRY CORE

P. Yarrington, F. R. Norwood & D. E. Grady

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Department of
Energy under Contract AT(29-1)-789

Printed March 1980

Sandia National Laboratories

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia Laboratories, operated for the United States
Department of Energy by Sandia Corporation.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy \$5.25; Microfiche \$3.00

SAND80-0248
Unlimited Distribution
Printed March 1980

UC-2

COMPARISON OF EXPERIMENTAL AND COMPUTATIONAL RESULTS
FOR
REVERSE BALLISTIC TESTS INTO FOUNDRY CORE

by

Paul Yarrington
Frederick R. Norwood
Computational Physics and Mechanics Division II 5533

Dennis E. Grady
Geomechanics Division 5532
Sandia National Laboratories, Albuquerque, New Mexico 87185

ABSTRACT

A series of nine laboratory-scale penetration tests was conducted in which impact velocity and geometry of the projectile were varied. In all tests, displacement histories were obtained for the penetrator via displacement interferometric techniques. From the data, accelerations were deduced and compared with numerically-calculated accelerations. For the numerical work, the codes PENAP and WONDY were used to model the penetration events. For penetrators with a conical nose, agreement between calculated and measured accelerations could be brought within 15% for all tests, except for one PENAP/test comparison, by introducing a constant coefficient of Coulomb friction of 0.1 at the penetrator target interface. For penetrators with an ogival nose, on the other hand, a greater discrepancy was found between calculated and measured results.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1-2 *See*

CONTENTS

	<u>Page</u>
I. INTRODUCTION	6
II. EXPERIMENTAL METHOD AND RESULTS	8
Target Material Preparation	8
Target Material Characterization	9
Penetrator Characterization	10
Experimental Procedure	10
Experimental Results	11
Experimental Discussion.	13
III. CALCULATIONAL TECHNIQUES	
A. General	31
B. Constitutive Modelling	33
IV. COMPARISON OF CALCULATIONAL AND EXPERIMENTAL RESULTS . . .	43
V. CONCLUSIONS.	48
REFERENCES	50

LIST OF FIGURES

	<u>Page</u>
Figure 1. Schematics for the Experimental Set-Up.	17
Figure 2. Recovered Penetrators Showing Erosion	18
Figure 3. Time Correlated Interferometric Fringe History.	19
Figure 4. Time Resolved Motion for Test FS-101.	20
Figure 5. Time Resolved Motion for Test FS-102.	21
Figure 6. Time Resolved Motion for Test FS-103.	22
Figure 7. Time Resolved Motion for Test FS-104.	23
Figure 8. Time Resolved Motion for Test FS-105.	24
Figure 9. Time Resolved Motion for Test FS-106.	25
Figure 10. Time Resolved Motion for Test FS-107.	26
Figure 11. Time Resolved Motion for Test FS-108.	27
Figure 12. Time Resolved Motion for Test FS-109.	28
Figure 13. Displacement and Velocity Histories for Tests FS-103, FS-108, and FS-109.	29
Figure 14. Displacement and Velocity Histories for Tests FS-106 and FS-107	30
Figure 15. Comparison of the PENAP Model for Hydrostatic Response with Experimental Curves for Foundry Core.	37
Figure 16. Comparison of the PENAP Model for the Failure Envelope with the Experimental Data	38
Figure 17. Hydrostatic Loading and Unloading for Foundry Core.	39
Figure 18. Comparison of the WONDY Model for Hydrostatic Response with the Experimental Curves for Foundry Core.	40
Figure 19. Triaxial Test Results for Foundry Core.	41
Figure 20. Comparison of the WONDY Model for the Failure Envelope with the Experimental Data for Foundry Core.	42

LIST OF FIGURES (Con'd.)

	<u>Page</u>
Figure 21. Comparison of Measured and Calculated Accelerations	46
Figure 22. WONDY and PENAP Comparison of Normal Stress Distribution	47

LIST OF TABLES

TABLE I. Experimental Penetrator Properties	16
TABLE II. Experimental and Calculated Acceleration	45

I. INTRODUCTION

The experimental and analytical results presented here are intended to provide an assessment of two approximate calculational techniques for predicting boundary loads on earth penetrating projectiles. In this study, reverse ballistic tests were conducted using laboratory scale projectiles and a "prepared" soil-like target material (foundry core). The small-scale reverse ballistic test configuration permitted the accurate measurement of projectile velocity histories, while the use of a "prepared" target material greatly reduced the uncertainty in material properties present in field testing with natural earth targets.

A series of nine tests was conducted in which the impact velocity and geometry of the projectile were varied. In all tests, displacement histories were obtained for the penetrator using displacement interferometry techniques. "Rigid body" velocity and acceleration were then deduced from the individual displacement histories.

Calculations of rigid body acceleration were made for each test using the computer codes WONDY [1] and PENAP [2]. WONDY is a general-purpose, one-dimensional, Lagrangian, finite difference wavecode. PENAP, on the other hand, is a one-dimensional, Lagrangian, shock-fitting code which was developed specifically for earth penetration calculations. A brief description of each code is presented below. Comparisons are also shown between the material response for foundry core as measured in the lab, and as predicted by the constitutive models used in each code.

The major conclusions of this study were the following:

- (1) Small scale (laboratory scale) reverse ballistic tests provide a convenient, reliable and accurate technique for validating earth penetration calculation techniques.

- (2) Variation in material properties appear to contribute, roughly, a 10% uncertainty to the experimental data,
- (3) WONDY and PENAP give reasonably consistent predictions of penetrator loading, with WONDY results being generally in better agreement with the data, and
- (4) For penetration with a conical nose, agreement between calculated and measured accelerations could be brought within 15% for all tests, except for one PENAP/test comparison, by introducing a constant coefficient of Coulomb friction of 0.1 at the penetrator/target interface. For penetrators with an ogival nose, a greater discrepancy was found between calculated and measured results.
- (5) WONDY predictions were generally found to be in better agreement with data than were the PENAP results.

II. EXPERIMENTAL METHOD AND RESULTS

To assess the predictive capability of current earth penetration calculational methods, it is necessary to perform experiments where model sensitive parameters such as nose geometry and impact velocity are varied in a consistent way. It is imperative that variations in other experimental parameters such as target properties and penetrator impact angle be minimized, or very carefully controlled, and that experimental responses, such as penetrator acceleration history be measured accurately. Toward this end, scaled reverse ballistics were conducted using a prepared target medium. A large bore gas gun was used to accelerate the target, and displacement laser interferometry was used to measure the time resolved axial motion of the projectile during penetration.

Target Material Preparation

Foundry core was selected as the target material in the model earth penetrator experiments. Selection of this material was the result of a search for a soil, or soil analog, which was sufficiently competent to survive inertial stresses resulting from reverse ballistic testing, and yet could be obtained or prepared with sufficient sample to sample material property uniformity. Foundry core consists primarily of silica sand with sufficient binder ingredients such that when oven fired it results in a low density sand brick. The material is commonly used for metal casting.

The ingredients for the foundry core developed in the present series of experiments were combined in the following ratios:

- * 100 lbs silica sand; grade 5040
- * 100 lbs silica sand; grade C-30
- * 3 lbs 4 oz Western Bentonite clay.
- * 2 lbs 12 oz Unicore serial binder.

- * 7 lbs Thiem 100-N core oil.
- * 9 lbs 8 oz water.

The ingredients were placed in a muller in the order listed and mixed for 5 minutes.

Two molds were constructed in which right circular cylinders of foundry core could be prepared. Sample dimensions were 3-1/2" diameter by 2-1/2" length used for reverse ballistics tests and 2-1/8" diameter by 3" length used for static compression tests conducted by Waterways Experimental Station.

Specific amounts by weight of the foundry core mixture were hand packed into the molds with a one inch diameter wooden tamping tool. Samples were then fired at 380°F in an air-circulating oven for 6 hours. Reduction in mass by a few percent occurs during firing and must be accounted for in the initial weight to achieve a desired uniform density. The density of the samples prepared was 1.48 Mg/m^3 with a sample to sample variation of less than $\pm 1\%$.

Several batches of samples were prepared initially to test our ability to duplicate sample properties. Samples were visually uniform. Density was determined from the total weight, and volume and densities obtained on sectioned pieces were consistent with those measured on complete samples.

Target Material Characterization

Only density (1.48 Mg/m^3) and ultrasonic velocity (2.15 km/s) measurements were conducted at Sandia National Laboratories. The remaining material characterization, including static confined compression, hydrostatic compression, and uniaxial strain compression, were conducted at Waterways Experimental Station. These results are used in model development and calculations presented in the following section. For a more detailed presentation the reader is referred to the WES report [3].

Penetrator Characterization

Solid steel penetrators 12.7 mm in diameter and approximately 50 mm in length were used in the present tests. Several nose geometries including two conical and one ogival shape were used. Exact dimensions for each experiment are provided in Table I. Penetrators were machined from D6A-C steel and polished to a number 32 finish. A silvered circular region several thousand angstroms thick was vapor deposited on the back of the penetrator to provide a specularly reflecting surface for the axial displacement measuring laser beam.

Experimental Procedure

Measurement of the motion of the penetrator was achieved by conducting the tests in a reverse ballistics configuration. The experimental details are illustrated in Figure 1. Cylindrical samples of foundry core (3-1/2" diameter by 2-1/2" length) were placed in aluminum supporting cups which were in turn mounted on aluminum projectiles. Each aluminum supporting cup had a 3/16" cylindrical wall and back plate thickness, and provided a tight fit for the foundry core samples. A 4" diameter light gas gun, Fowles, et al. [4] was used to accelerate the projectiles to a prescribed terminal velocity prior to impact. The terminal velocity was measured with electrical contact pins and controlled to within 0.5%. Normal incidence at impact was maintained within a few tenths of a degree.

The penetrator was lightly mounted in a stationary polyurethane supporting plate (12.7 mm thickness) as shown in Figure 1. This assembly was then mounted at the muzzle end of the light gas gun and aligned with the steel penetrator axis parallel to the gun axis. A thin coat of aluminum paint was placed on the front of the foundry core sample. At initial impact an electrical triggering circuit provided a time of arrival fiducial for triggering recording instrumentation and determining transit times through the penetrator.

Displacement interferometry, Barker and Hollenbach [5] was used to measure axial displacement of the center of the penetrator back surface for approximately the initial 1-1/2 nose lengths ($\sim 100 \mu\text{s}$) of penetration. In this technique, the back surface of the penetrator is used as one of two mirrors in a Michelson displacement interferometer. As the back surface of the penetrator moves, the interferometer provides a fringe signal directly proportional to the surface displacement. For the He-Ne laser used, each fringe corresponded to $0.3164 \mu\text{m}$ displacement.

Continuous displacement-time recording during the full time of interest could not be achieved with the 8 oscilloscopes available, due to the large number of fringes occurring. The technique established consisted of using 3 to 4 oscilloscopes to measure continuous displacement-time histories during the initial 30 to 40 μs of penetration, during which fringe accumulation was relatively slow. The remaining oscilloscopes sampled discrete intervals of time ($\sim 1.0 \mu\text{s}$) out to approximately 100 μs of recording time. In these intervals 20 to 30 displacement fringes were measured and, by differentiating the data, provided a measure of the velocity at that interval in time. Based on the instrumentation capability an error of less than 2% was estimated in the absolute velocity. Greater sample to sample errors were incurred, however, and will be discussed later.

Tilting (rotating) of the penetrator during penetration was a limiting factor in the interferometer technique. A tilt of 0.2 degrees is sufficient to cause loss of superposition of the beams and, hence, loss of fringe contrast. This frequently happened between 80 and 120 μs . This was not a serious difficulty, however, since this was close to the time at which impact between foundry core sample and the polyurethane penetrator mounting plate was calculated to occur.

In every test the penetrator was recovered, either in the back compartment of the aluminum projectile or in the projectile catcher tank. Although penetration through the foundry core sample was subsequently followed by penetration through one or two plates of aluminum, surface abrasions due to the considerably harder sand particles could easily be distinguished from that due to the softer aluminum. Interesting correlations between initial velocity and interface detachment could be observed from these surface abrasions. The relative erosion experienced by the different penetrators is clearly observed on the recovered penetrators shown in the photograph in Figure 2.

Experimental Results

The principal objective of the present experimental program was to test developed calculational methods against controlled model earth penetrator experiments in a well-characterized medium. Penetrators with conical noses and differing cone angles, and penetrators with ogival noses were constructed. Initial impact velocities were determined by sensitivity of the models to the foundry core material property data. During the course of the experiments some questions were raised regarding reproducibility. Several tests were redirected toward this problem.

In Table I specific properties are documented for all of the experiments which were conducted. The designated sequence does not indicate the order in which the tests were performed.

In Figure 3, the raw time correlated interferometer fringe history for the interval of penetration in which continuous recording was attempted is displayed for all of the tests conducted. Some appreciable gaps occur in the

data for the first tests conducted, however, as the series of tests progressed and a better understanding of the expected motion was achieved, an appreciable interval of the initial penetration was recorded. In Figure 3 time zero corresponds to initial impact of the penetrator tip and the foundry core sample. First motion is expected to occur after a transit time corresponding approximately to the bar wave velocity in the steel penetrator. Comparison of the measured first motion with the calculated bar velocity is in reasonable agreement for the 44.45 and 50.8 mm penetrators.

The fringe frequency from first motion varies smoothly for about 10 μ s at which time a second wave arrival occurs. This arrival occurs at about 17 μ s for the 44.45 mm length penetrators (FS-103, 105, 108, 109) and about 19 μ s for the 50.8 mm length penetrators. Comparison in Figure 3 with the transit time calculated for shear wave velocity shows a somewhat later arrival. The erratic fringe behavior subsequent to arrival of the second wave represents nonrigid body, high frequency displacement of the penetrator back surface.

A detailed presentation of the measured time resolved motion for the nine experiments conducted are provided in Figures 4 through 12. Both displacement history and velocity history are provided. Displacement is measured directly by the interferometer technique. Velocity is determined by differentiation using a standard numerical technique (Bailey et al. [6], 1974). Briefly, a third degree polynomial was incrementally fitted to 9 data points and used to provide the differential at the intermediate point. Noise in the velocity histories represents measurement error of very short time increments between fringes.

Experimental Discussion

During the period that the model penetrator experiments were being conducted several unexpected features appeared. The degree of nonrigid

body response experienced by the projectile during approximately the first 30 μ s was greater than expected. Some aspects of this nonrigid body motion appeared to continue, to a lesser extent, during the total recording time as a noticeable modulation superposed on the rigid body response. This is thought to be responsible for the irregularity in slope determined from the discrete late time velocity points.

Some irregularities which occurred during analysis of some of the initial experiments suggested that test to test reproducibility was not as good as previously expected. Several duplicate tests were conducted to evaluate this problem. Experiments FS-103, FS-108, and FS-109 were conducted with identical projectile geometries and impact velocities. The velocity histories for all three tests are compared in Figure 13. The absolute error for the three experiments is about 12% which is significantly greater than the approximately 2% errors expected from the interferometer technique. Since the displacement interferometer had not previously been used for the extended recording times required in the present tests, considerable effort was expended in locating heretofore unknown interferometer errors. Such possibilities as extraneous fringes due to projectile rotation and to depth of field changes were explored but none were sufficient to increase errors above the initial 2% estimation.

We currently believe that variability of the foundry core properties may be responsible for the observed differences. In construction of the samples the foundry technician added about 1 inch of the ingredients at a time and manually tamped to the required volume. This technique may not be adequate to achieve the material control needed. We have considered, but not tried, an alternative ultrasonic tamping technique to obtain more uniform samples.

The two ogive experiments were also duplicates and comparisons are shown in Figure 14. Agreement of the data out to 40 μ s is remarkable. The source of the large late time discrepancy is not understood.

TABLE I
Experimental Penetrator Properties

Test	Initial Velocity (m/s)	Nose [*] Shape	Nose Length (mm)	Body Length {Diameter} (mm)	Mass (gm)
FS-101	403	C	25.40	25.4 {12.7}	33.68
FS-102	557	C	25.40	25.4 {12.7}	33.87
FS-103	312	C	19.05	25.4 {12.7}	31.72
FS-104	240	C	25.40	25.4 {12.7}	33.61
FS-105	239	C	19.05	25.4 {12.7}	31.82
FS-106	290	O	25.40	25.4 {12.7}	39.48
FS-107	236	O	25.40	25.4 {12.7}	39.39
FS-108	310	C	19.05	25.4 {12.7}	31.72
FS-109	313	C	19.05	25.4 {12.7}	31.74

* C - conical; O - ogival

○

Figure 1. Schematics for the Experimental Set-Up.

Figure 2. Recovered Penetrators Showing Erosion

Figure 3. Time Correlated Interferometric Fringe History.

Figure 4. Time Resolved Motion for Test FS-101.

Figure 5. Time Resolved Motion for Test FS-102.

Figure 6. Time Resolved Motion for Test FS-103.

Figure 7. Time Resolved Motion for Test FS-104.

Figure 8. Time Resolved Motion for Test FS-105.

Figure 9. Time Resolved Motion for Test FS-106.

Figure 10. Time Resolved Motion for Test FS-107.

Figure 11. Time Resolved Motion for Test FS-108.

Figure 12. Time Resolved Motion for Test FS-109.

Figure 13. Displacement and Velocity Histories for Tests FS-103, FS-108, and FS-109.

Figure 14. Displacement and Velocity Histories for Tests FS-106 and FS-107.

III. CALCULATIONAL TECHNIQUES

A. General

Two computer codes, WONDY [1] and PENAP [2], were used in this study to calculate penetrator boundary loads and accelerations. Only brief descriptions of these codes will be presented here, since complete documentation is available in the references cited above.

Important features shared by the codes are:

- (1) The governing equations are the continuum equations of mass and momentum balance (applied to the target medium),
- (2) each infinitesimal layer in the target is assumed to deform in plane strain (radial motion only), and
- (3) the penetrator is treated as a rigid body.

The geometry and impact velocity of the penetrator determine the boundary conditions on material motion in each infinitesimal target layer. These boundary conditions insure that target material remains on, or outside, the penetrator boundary.

PENAP solves the governing equations using a shock fitting method. With this method, the balance equations for the target are integrated between the radially propagating wavefront (where the Hugoniot jump conditions apply) and the interface with the penetrator. The result of these calculations is the radial (component of the normal) stress on the penetrator. WONDY, on the other hand, is a general-purpose, Lagrangian, finite difference wavecode. In WONDY, a calculational grid is set up to model a region of the target, and the local balance equations, in difference form, are solved at each grid point.

The result of calculations with either code is the stress history necessary to open a (circular) cavity in the target according to the prescribed

boundary conditions. This cavity stress is interpreted, then, as the radial component of the normal stress which is exerted on the penetrator. The stress at any particular axial position on the penetrator can be related directly to the stress at a particular time in the calculated history through the penetrator velocity (i.e., position = velocity x time). It is implicitly assumed that there is no "communication" between infinitesimal target layers, or that axial gradients are negligible compared with radial gradients. It is also assumed that the penetrator velocity does not change significantly during a nose length of penetration. Thus, the codes calculate, essentially, a "steady state" distribution of stress on the penetrator at the given velocity.

Coulomb friction is assumed at the penetrator/target interface. The frictional stress is found by multiplying the normal stress at any point, as calculated above, by the Coulomb coefficient. Normal stress and frictional stress are then superimposed to give the total traction at that point on the penetrator.

B. Constitutive Modelling

The target constitutive models used in the two codes are quite different, and will be described separately below. Particular attention will be given to the modelling used to fit the foundry stone data.

In PENAP, the target is modelled as a locking solid. The locking solid model has been used for earth media in many earlier studies (see, e.g., [7] or [8]). The present model is somewhat different from these earlier models, however, with the principal differences being that, in the present model:

- (1) elastic effects are neglected, and
- (2) the bulk modulus, on loading, is continuous with volumetric strain; whereas, in the early models the material could assume only discrete values (typically no more than two) of volumetric strain.

The hydrostatic response in PENAP is assumed to be piecewise linear and/or quadratic in the volumetric strain. In shear, the material is assumed to be yielding plastically so that the state of stress lies on the yield surface. The yield surface used in PENAP is described by a linear and/or constant principal stress difference as a function of hydrostatic pressure.

Target material constants which must be supplied in PENAP include:

- (1) the initial density (ρ_0),
- (2) a linear bulk modulus (K_1),
- (3) a quadratic bulk modulus (K_2),
- (4) an initial slope of the yield surface (principal stress difference versus pressure) (β),
- (5) a maximum shear strength ("Mises" limit), or maximum principal stress difference (τ_0).

It should be noted that, for any particular problem one of the bulk moduli may not be needed and/or one of the yield surface constants may not be needed. Thus, at least three and at most five constants characterize the constitutive response of target material in PENAP.

To model the foundry core response the following constants were chosen for PENAP calculations:

$$\rho_0 = 1170 \text{ kg/m}^3$$

$$K_1 = 165 \text{ MPa}$$

$$K_2 = 1.36 \text{ GPa}$$

$$\beta = 0.85$$

$$\tau_0 = 150 \text{ MPa}$$

The hydrostatic response and failure envelope which result with these material parameters are compared with foundry stone data in Figs. 15 and 16.

A variety of material models is available in WONDY, including a standard elastic-plastic model (with various hardening and yield surface options), a porous material model based on Herrmann's P- α model [9] (modified slightly from the usual WONDY treatment in order to account for material shear strength) and an elastic-plastic cap model (see, e.g., [10]).

From Fig. 17 it can be seen that foundry core exhibits a relatively large amount of irreversible compaction, essentially characteristic of pore collapse. Thus the foundry core was modelled as a porous solid in the WONDY calculations.

The input constants describing the volumetric response in the WONDY porous solid model are (using the usual WONDY notation):

$$\text{bulk density } (\rho_o) = 1460 \text{ kg/m}^3,$$

$$\text{solid density } (\rho_{so}) = 1850 \text{ kg/m}^3,$$

$$\text{initial distention ratio } (\alpha_o) = 1.267,$$

$$\text{bulk sound speed } (c_o) = 400 \text{ m/s},$$

$$\text{sound speed in the solid } (c_{so}) = 3200 \text{ m/s},$$

$$\text{limit pressure for elastic pore collapse } (P_e) = 0,$$

$$\text{limit pressure for total pore collapse } (P_s) = 75 \text{ MPa}.$$

Components of deviatoric stress, $\underline{S}$, and strain, $\underline{\epsilon}$, are related in WONDY through Hooke's law:

$$\dot{\underline{S}} = G \dot{\underline{\epsilon}}. \quad (1)$$

For the foundry core, the shear modulus, G , was assumed to vary with distention ratio, α , according to:

$$G = G_o + \frac{\alpha_o - \alpha}{\alpha_o - 1} (G_s - G_o) \quad (2)$$

In Eqn. (2), G_o is the initial (undisturbed) shear modulus and G_s is the modulus of the material when all porosity has been destroyed. The constants (limiting values of the shear modulus) used in Eqn. (2) for foundry stone were

$$G_o = 700 \text{ MPa}$$

$$G_s = 1.6 \text{ GPa}$$

The deviatoric stresses are limited in WONDY calculations through the yield condition:

$$Y(\underline{S}) = \sqrt{s_2} = \begin{cases} \frac{P}{P_y} Y_1, & 0 \leq P \leq P_y, \\ Y_1, & P > P_y, \\ Y_o, & P < 0, \end{cases} \quad (3)$$

where J_2 is the second invariant of the deviatoric stress tensor, P is the mean compressive stress (hydrostatic pressure), and Y_0 , Y_1 , and P_y are material constants. For the foundry core, the following values were chosen to fit the yield surface

$$Y_0 = 4 \text{ MPa}$$

$$Y_1 = 150 \text{ MPa}$$

$$P_y = 176 \text{ MPa}$$

Figure 18 compares laboratory data and the WONDY model results for hydrostatic behavior of the foundry core. The shear moduli specified above were determined from unloading moduli in triaxial tests, as shown in Fig. 19. Triaxial test data were also used to determine the yield surface constants in Eqn. (3), as shown in Fig. 20.

Figure 15. Comparison of the PENAP Model for Hydrostatic Response with Experimental Curves for Foundry Core.

Figure 16. Comparison of the PENAP Model for the Failure Envelope with the Experimental Data.

Figure 17. Hydrostatic Loading and Unloading for Foundry Core

Figure 18. Comparison of the WONDY Model for Hydrostatic Response with the Experimental Curves for Foundry Core.

Figure 19. Triaxial Test Results for Foundry Core.

Figure 20. Comparison of the WONDY Model for the Failure Envelope with the Experimental Data for Foundry Core.

IV. COMPARISON OF CALCULATIONAL AND EXPERIMENTAL RESULTS

For each test in the series, PENAP and WONDY calculations of the "steady-state" acceleration were made as described in the previous section. In the experiments, it was assumed that this "steady state" was reached shortly after nose embedment. The penetrator loading at that time is viewed essentially as a constant velocity drag force. Implicitly, it is assumed that free surface effects from the target face, back surface, and radial boundary are negligible, and that the penetrator velocity is still a small fraction of the penetrator/target relative velocity. The assumption that radial boundary and back surface effects are negligible can be justified by considering wave transit times in the target. The assumption that effects of the free surface at the target face are negligible cannot be as easily justified, and should be viewed as one of the limiting assumptions of the comparisons presented below. The fact that penetrator velocity remains a small fraction of impact velocity can be easily seen by comparing penetrator velocity data presented in Section II (Figs. 4-12), and the corresponding impact velocities listed in Table I.

The steady-state penetrator acceleration was found from the slope of the velocity history at a time shortly after nose embedment. Figures 4-12 show the velocity history data points for each test which were used to approximate the slope at steady-state conditions. For each test, the acceleration was computed by using the points for the later times shown in the lower plots of Figures 4 through 12. These experimentally-determined accelerations, together with the computed values, are given in Table II. The table shows calculated results for two choices of penetrator/target interfacial friction, viz., $\mu = 0$ and $\mu = 0.1$. In Figure 21, measured and calculated accelerations are compared for each test, and for both

both calculational methods. From this figure, one may conclude that, using a coefficient of friction of 0.1, the calculated results are within 15% of the measured values in all tests with conical noses (except for one PENAP comparison). For the two tests involving ogival noses (FS-106 and FS-107), a somewhat larger discrepancy was found between calculated and experimental values.

For conical-nosed penetrators, PENAP and WONDY results were found to be in very good agreement with each other. For the ogival-nosed penetrator, however, the PENAP prediction of acceleration is significantly lower than that calculated with WONDY.

It is believed that the difference between PENAP and WONDY calculations for ogival-nosed penetrators is due to differences between material models used in the two codes. In PENAP, it is assumed that elastic effects are negligible and that the material locks on unloading. WONDY, on the other hand, treats the material as elastic-plastic both during loading and unloading. The effect of this difference can be seen in Fig. 22, which compares the distributions of stress using both codes for the ogival-nosed penetrator test, FS-106. It can be seen that WONDY predicts attachment of penetrator and target over a larger axial region of the nose, and that the levels of stress on the regions with high area to axial length ratios (back toward the nose/afterbody tangency point) are generally higher in the WONDY calculations. These differences are felt to be attributable to the elastic rebound of target material allowed in WONDY. Furthermore, these effects account for the higher accelerations calculated in WONDY.

TABLE II

Experimental and Calculated Acceleration

Test	Data	PENAP		WONDY
FS-		$\mu = 0$	$\mu = .1$	$\mu = .1$
101	3.3	2.25	3.16	2.89
102	4.5	3.15	4.40	4.33
103	2.9	2.48	3.22	3.03
104	1.5	1.27	1.78	1.61
105	2.5	1.85	2.40	2.21
106	1.6	.803	1.02	1.27
107	1.93	.771	.98	1.27
108	2.98	2.46	3.20	3.03
109	2.98	2.46	3.23	3.03

The factor 10^5 meters/sec² should be included in all table entries.

Figure 21. Comparison of Measured and Calculated Accelerations.

SANDIA FOUNDRY STONE TEST FS-106

WONDY AND PENAP COMPARISON

Figure 22. WONDY and PENAP Comparison of Normal Stress Distribution.

V. CONCLUSIONS

This work was intended to provide an assessment of two approximate one-dimensional calculational techniques for predicting boundary loads on earth penetrating projectiles. For this purpose, nine reverse ballistic tests were conducted using laboratory scale projectiles and a foundry core target. It was found that the experimental technique yielded reproducible results. Corresponding to each ballistic test, calculations of rigid body acceleration were made using the computer codes WONDY [1] and PENAP [2], and the calculations were compared with the experimental results. Thus, the following conclusions were reached:

- (1) Small scale (laboratory scale) reverse ballistic tests provide a convenient, reliable and accurate technique for validating earth penetration calculation techniques,
- (2) Variation in material properties appear to contribute, roughly a 10% uncertainty to the experimental data,
- (3) WONDY and PENAP give reasonably consistent predictions of penetrator loading, with WONDY results being generally in better agreement with the data,
- (4) For penetration with a conical nose, agreement between calculated and measured accelerations could be brought within 15% for all tests, except for one PENAP/test comparison, by introducing a constant coefficient of Coulomb friction of 0.1 at the penetrator/target interface. For penetrators with an ogival nose, a greater discrepancy was found between calculated and measured results, and
- (5) WONDY predictions were generally found to be in better agreement with the data than were the PENAP results.

It should be emphasized that the calculational methods employed to predict acceleration on the penetrators are approximate in nature employing simplifying assumptions and incomplete target material constitutive relations. Considering the difficulties associated with uncertainties in the experimental technique, variability in target sample preparation, errors associated with determination of target material properties, the unknown frictional effects and the approximations inherent in the computational methods, the agreement between calculated and observed penetrator accelerations is encouraging. Additional laboratory experiments, where conditions can be highly controlled and which largely avoid the difficulties involved with field penetration experiments in natural geologic environments, can be expected to provide additional data for critical assessment of penetration prediction methods. Further, the methods outlined represent one means of investigating the important and largely unexplored question of frictional effects between targets and penetrators over impact velocity ranges of interest. If target material properties are well known and accurately described in constitutive models then from a well-founded computational model and from carefully-conducted experiments the Coulomb friction coefficient may be deduced.

These first few preliminary experiments together with two approximate methods of prediction have indicated a direction for further study and more detailed, careful investigation of earth penetration phenomena.

REFERENCES

1. R. J. Lawrence and D. S. Mason, "WONDY IV - A Computer Program for One-Dimensional Wave Propagation with Rezoning," Report SC-RR-71 0284, Sandia Laboratories, Reprinted November 1975.
2. P. Yarrington and N. K. Ruiz, "PENAP: An Interactive Computer Program for Calculating Surface Loads on Conical- and Ogival-Nosed Earth Penetrators," Report SAND77-1359, Sandia Laboratories, February 1978.
3. P. H. Hadala and J. O. Ehgott, "Constitutive Property Tests on Foundry Core," U. S. Army Engineer Waterways Experiment Station, Report for Sandia Laboratories, November 1977.
4. G. R. Fowles, G. E. Duvall, J. Asay, P. Bellamy, F. Feistman, D. Grady, T. Michaels, and R. Mitchell, "Gas Gun for Impact Studies," Rev. Sci. Instr., Vol. 41, pp. 984-996, 1970.
5. L. M. Barker and R. E. Hollenback, "Interferometer Technique for Measuring the Dynamic Mechanical Properties of Materials," Rev. Sci. Instr., Vol. 36, pp. 1617-1620, 1965.
6. C. B. Bailey, M. K. Gordon and R. E. Jones, "Brief Instructions for Using the Sandia Numerical Mathematical Subroutine Library on the DEC POP-10," Report SLA-74-0331, Sandia Laboratories, June 1974.
7. F. R. Norwood, "Cylindrical Cavity Expansion in a Locking Soil," Report SLA-74-0201, Sandia Laboratories, July 1974.
8. R. S. Bernard and S. V. Hanagud, "Development of a Projectile Penetration Theory; Penetration Theory for Shallow to Moderate Depths," Technical Report S-75-9, U. S. Army Engineer Waterways Experiment Station, June 1975.

9. W. Herrmann, "Constitutive Equation for the Dynamic Compaction of Ductile Porous Materials," J. Appl. Phys., Vol. 40, pp. 2490-2499, May 1969.
10. H. S. Lauson and R. K. Byers, "The SLA Cap Models and the CAPMOD Code," Report SAND77-1364, Sandia Laboratories, March 1978.

DISTRIBUTION:

Picatinny Arsenal (4)
Dover, New Jersey 07081
Attn: P. Harris
E. Zimpo
A. Garcia
Technical Library

U. S. Army Advanced Ballistic
Missile Defense Agency (2)
Huntsville Office
P. O. Box 1500
Huntsville, Alabama 35807
Attn: CRDABH-S
CRDABH-X

University of California (3)
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, CA 94550
Attn: Technical Library
M. Wildings
G. L. Goudreau

Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, NM 87544
Attn: Reports Library

Department of Aerospace
Engineering and Engineering
Mechanics
University of Texas
Austin, TX 78712
Attn: Prof. C. H. Yew

Atomic Weapons Research
Establishment
Aldermaston
Berkshire, England
Attn: B. D. Lambourn

California Research and (2)
Technology, Inc.
6269 Variel Avenue, Suite 200
Woodland Hills, CA 91364
Attn: K. Kreyenhagen
Technical Library

RDA (6)
P. O. Box 9695
Marina del Rey, CA 90291
Attn: J. Lewis
W. Wright
Technical Library

Science Applications, Inc., (3)
1250 Prospect Street
La Jolla, CA 92037
Attn: D. Maxwell
D. Bernstein
Technical Library

U. S. Army Engineer Waterways
Experiment Station (5)
Soils and Pavements Laboratory
Vicksburg, MS 39180
Attn: G. Jackson
P. Hadala
B. Rohani
R. Bernard
Technical Library

Avco Corporation (4)
Research and Systems Group
201 Lowell Street
Wilmington, MA 01887
Attn: D. Henderson
J. Atanasoff
F. Lasher
Research Library-A830
Room 217

Martin Marietta Aerospace (4)
Orlando Division
P. O. Box 5837
Orlando, FL 32805
Attn: N. Singletory
A. Gowan
M. Anthony
Technical Library

Stanford Research Institute (3)
333 Ravenswood
Menlo Park, CA 94025
Attn: G. Abrahamson
SRI Library, Rm. G021
L. Seaman

DISTRIBUTION (cont'd):

Physics International
Company
2700 Merced Street
San Leandro, CA 94577
Attn: Technical Library

(4)

Pacifica Technology
P. O. Box 148
Del Mar, CA 92014
Attn: R. L. Bjork

Systems, Science, and
Software, Inc.
P. O. Box 1620
La Jolla, CA 92037
Attn: E. Gaffney
D. Grine
Technical Library

(3)

Northwestern University
Chicago, IL 60680
Attn: T. B. Belytscho

Terra Tek, Inc.
University Research Park
420 Wakara Way
Salt Lake City, UT 84108
Attn: S. Green
A. Jones
Technical Library

(3)

Defense Nuclear Agency (3)
Headquarters DNA
Washington, DC
Attn: STTL
DDST
SPSS

Texas A&M University
College Station, TX 77843
Attn: J. Handin

Naval Surface Weapons Center (4)
Dahlgren Laboratory
Dahlgren, VA 22448
Attn: M. Weiland
T. Williams
W. Wisherd
Technical Library

Washington State University
Department of Physics
Pullman, WA 99164
Attn: G. Duvall

U. S. Department of Energy
Division of Military
Application
Washington, DC 20545
Attn: Library

Weidlinger Associates,
Consulting Engineers
110 E. 59th Street
New York, NY 10022
Attn: J. Wright
M. Baron

(2)

University of New Mexico (2)
Albuquerque, NM 87106
Attn: G. Triandafilidis
H. Southward

Air Force Armament
Laboratory, AFSC
Eglin AFB, FL 32542
Attn: J. Collins
J. Osborne
Technical Library

(3)

U. S. Army Ballistic Res. (2)
Laboratory
Aberdeen Proving Ground,
Maryland 21005
Attn: Technical Library
E. Baicy

Air Force Weapons Laboratory,
AFSC
Albuquerque, NM
Attn: M. Plamondon
SUL

(2)

Massachusetts Institute of
Technology
Dept. of Earth and Planetary
Sciences
Cambridge, MA 02139
Attn: W. Brace

DISTRIBUTION (cont'd):

Penetrator Study Team	1760	W. F. Hartman	
Theoretical and Planetary	4000	A. Narath	
Studies Branch		Attn: G. Yonas, 4200	
Ames Research Center		R. Peurifoy, 4300	
Moffett Field, CA 94035		A. W. Snyder, 4400	
Attn: Maxwell B. Blanchard		E. H. Beckner, 4500	
		J. H. Scott, 4700	
Mail Stop 183B-365	4340	H. W. Schmitt	
Jet Propulsion Laboratory	4342	W. R. Reynolds	
4800 Oak Grove Drive	4342	M. J. Forrestal	
Pasadena, CA 91103	4342	W. J. Patterson	
Attn: Geoffrey Briggs	4360	J. A. Hood	
	4361	E. M. Austin	
California Institute of	4361	R. C. Hartwig	
Technology	4361	R. P. Kutarnia	
Division of Earth and	4362	J. M. Parvin	
Planetary Sciences	4443	P. Yarrington	(5)
Pasadena, CA 91025	4536	D. R. Anderson	
Attn: Dr. J. G. Wasserburg	4536	D. M. Talbert	
	5000	J. K. Galt	
Planetology Programs Manager		Attn: F. L. Vook, 5100	
NASA Headquarters		G. A. Samara, 5130	
Washington, DC 20546		J. Schirber, 5150	
Attn: D. H. Herman		R. S. Claassen, 5800	
Science Applications, Inc.	5500	O. E. Jones	
5005 Newport Dr., Suite 305	5510	D. B. Hayes	
Rolling Meadows, IL 60008	5520	T. B. Lane	
Attn: John Niehoff	5521	S. W. Key	
	5522	T. G. Priddy	
Space Systems Division	5523	R. C. Reuter	
P. O. Box 92960 World Postal	5523	D. B. Longcope	
Center	5524	R. T. Othmer	
Los Angeles, CA 90009	5524	P. P. Stirbis	
Attn: Maj. Phillip A. Terry	5530	W. Herrmann	
	5531	L. D. Bertholf	
Aerospace Corporation	5531	M. E. Kipp	
P. O. Box 92957	5532	B. M. Butcher	
Los Angeles, CA 90009	5532	D. E. Grady	
Attn: W. P. Thompson	5533	A. J. Chabal	
R. L. Strickler	5533	T. K. Bergstresser	
	5533	W. R. Davey	
University of Rhode Island	5533	F. R. Norwood	(30)
Dept. of Ocean Engineering	5541	W. C. Luth	
Kingston, RI 02881	5612	J. W. Keizur	
Attn: A. J. Silva	5620	M. M. Newsom	
	5621	C. E. Dalton	
	5621	M. M. Hightower	
	5621	A. D. Foster	
	5621	C. W. Young	
	5621	E. C. Rightley	
	5640	G. J. Simmons	

DISTRIBUTION (cont'd):

8110	J. F. Barham	
8120	W. E. Alzheimer	
8266	Technical Library	(2)
3141	T. L. Werner	(5)
3151	W. L. Garner	(3)
	for DOE/TIC Unlimited Release	
3154-3	R. P. Campbell (For DOE/TIC)	(25)

[illegible]

* Recipient must initial on classified documents.