PROJECTILE PENETRATION INTO EARTH MEDIA

AUGUST 31, 1972

PROJECT 827

BY J. D. MURFF
H. M. COYLE

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a TECHNICAL
report

from the Texas A&M
RESEARCH FOUNDATION

College Station, Texas

EARTH PENETRATION
AND
DYNAMIC SOIL MECHANICS

This work performed for
Sandia Laboratories
Albuquerque, New Mexico
Sandia Laboratories Purchase Contract No. 48-9880
Buyer E. G. Connelly 4371
Requestor J. L. Colp 5627

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A Technical Report

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PROJECTILE PENETRATION OF EARTH MEDIA
FINAL REPORT - JUNE 30, 1972 TO AUGUST 31, 1972

GENERAL

Introduction

On June 1, 1967, Texas A&M University was awarded a contract by Sandia Corporation to perform a laboratory investigation of projectile penetration into earth targets.

The first year of this work (1967-1968) was devoted to the development of a conceptual design for a laboratory in which this work could be performed. In addition a statistical design for the experiment was formulated.

The second year's work (1968-1969) entailed implementing a major portion of the conceptual design and performing several small scale penetration tests.

The third year's work (1969-1970) was concerned with developing a reliable electronics system and performing a number of penetration tests in accordance with the statistical design.

The fourth year's work (1970-1971) was devoted to performing several investigations concerning soil properties nose effects and mold effects and the continuation of penetration tests in accordance with the statistical design.

The fifth year's work (1971-1972) has been devoted to completion of the basic series of earth penetration tests in a variety of soil targets.

Purpose and Objectives of This Work

This report is concerned with penetration testing in accordance with the proposal submitted to Sandia for 1971-1972.

The specific objectives of this research are

1. To empirically devise means of predicting forces on a penetration projectile,
2. To generate methods of predicting the total depth and subsurface trajectory of a penetrating projectile,
3. To provide understanding and data for use in the formulation of a fundamental penetration equation, and
4. To delineate soil and projectile properties that effect penetration.

Accomplishments and Current Status

The contract year was spent completing a basic series of tests in several soil types. Considerable attention was also given to statistically analyzing the data collected over the several years of the project duration.

The project as outlined in the proposal for 1971-1972 was completed with a few minor exceptions. Exceptions will be discussed in the section containing the presentation of data.

EXPERIMENTAL PROCEDURES

The procedures developed in previous years for target construction, target testing, projectile delivery, data acquisition, and data reduction have been adhered to except where noted and/or amplified below. These procedures are described by Thompson, et al. (3), and Murff and Coyle (1,2).

Target Construction

Dry sand targets were constructed using the concrete vibrator technique described in earlier reports. Targets with cohesive strength were constructed using the pneumatic hammer also described in earlier reports.

Target Testing

In very stiff brittle targets a great deal of difficulty was encountered in taking undisturbed samples. During sampling and extruding the material had a decided tendency to crack and fall apart. For this reason it was decided to reconstruct the sample in the sampling tube from loose target material. This was done only where difficulty in sampling was encountered. The exact effect of this procedure cannot be known although it seems probable that the cohesion of these targets is over-estimated.

Data Acquisition

Data acquisition techniques were, for the most part, identical to those discussed in earlier reports. The need to test outside away from the laboratory created a requirement to develop a remote transmitting capability. This capability was developed during the year. Both deceleration-time and impact velocity data can be transmitted from the mobile air gun to the Terramechanics Laboratory for distances up to several miles. A series of penetration tests was successfully conducted at a field site during the year.

DYNAMIC VS STATIC PENETRATION TESTS

In order to compare the dynamic resistance with static resistance, a device has been developed which is capable of pushing a projectile into the soil and simultaneously measuring total force. The device consists of a screw type motor driven actuator which extends at a rate of 2 inches per second. A load cell is affixed to the actuator and the selected projectile is in turn affixed to the load cell. The actuator has a total throw of approximately one foot and is limited in capacity to 1500 lbs. Fig. 1 is a schematic diagram of the static test set up. Because the actuator is non-linear under load, a timer is connected directly to the "on" switch of the actuator. Photographs are taken of the projectile and timer at a rate of 2 frames/second so that the projectile location as a function of time is known. Load cell data is recorded on direct print visicorder paper with time marks superimposed so that load-time data is known. The two records can be cross plotted to give a load-depth curve for comparison with dynamic penetration data. Data comparing static and dynamic results is presented in the following discussion for (1) soft clay, (2) stiff clay, (3) dry ottawa sand, and (4) a mixture of concrete sand and kaolin clay.

Fig. 2 is a plot of resistance vs penetration depth for both the static and dynamic case in a soft kaolin clay. The static curve was obtained by measuring the load required to penetrate a projectile at

Fig. 1. - Schematic Diagram of Dynamic Penetration Test Set Up

Fig. 2 - Comparison of Static and Dynamic Resistance - Soft Kaolin Clay

a slow rate (approximately 2 inches per second) using the static test device discussed previously. The dynamic curve is derived from the deceleration vs time record. The dynamic resistance is approximately twice the static resistance at the point the projectile nose is totally embedded (.13 feet). The slope of the dynamic resistance - depth curve is also approximately twice the slope of the static curve. This difference might be attributed to the effects of inertia and/or dynamic strength of the soil.

Similar tests were conducted in a stiff kaolin clay target as shown in Fig. 3. In this case the dynamic resistance is on the order of 1.2 times the static resistance. The ratios of dynamic to static resistance for the two tests in soft and stiff kaolin clay, 2.0 and 1.2, are approximately equal to the strain rate sensitivity values suggested by Whitman (4) for similar soils. It should be borne in mind however that Whitman's values are ratios of failure strengths at strain rates of .03%/second (static) to 1000%/second (dynamic). In this case velocity fields are unknown and consequently strain rates are also unknown. If, however, the strains for the static and dynamic cases are the same then the ratios of strain rates are equal to the ratio of "static" and dynamic velocities. Whitman's data covers approximately five decades. This indicates that kaolin clay is slightly more sensitive than the corresponding general categories of soil described by Whitman, but still well within a "reasonable" range of accuracy. Since the soils described herein increase in strength 1.2 to two times over three to five

Fig. 3 - Comparison of Static and Dynamic Resistance - Stiff Kaolin Clay

decades of time it seems reasonable to assume that the rate effects will not be large in the velocity range 30-300 fps. These data indicate that the increased strength is not primarily due to inertia since the dynamic resistance increased more in the slower test.

A comparison of force vs depth for static and dynamic test in dry ottawa sand is shown in Fig. 4. The static resistance is almost a perfect quadratic function of depth. The dynamic resistance for this test appears to remain almost constant until near the end of the event where the deceleration rises and then falls as the projectile stops. For higher velocities there is a peak at the beginning of the event, which is often followed by a second smaller peak of approximately the same time duration.

A comparison of static and dynamic penetration tests in a stiff sand-clay mixture is shown in Fig. 5. The difference in magnitude between the forces can be attributed to an increase in strength due to dynamic loading and/or the apparent confining pressure due to inertial forces. It appears from the data that the resistance encountered in sand-clay mixtures has some characteristics seen in both sand and clay tests.

Fig. 4 - Comparison of Static and Dynamic Resistance - Dense Ottawa Sand

Fig. 5 - Comparison of Static and Dynamic Resistance - Dense Sand Clay Mixture

PRESENTATION OF DATA

A total of 108 penetration tests have been conducted during the year. Of these, a full set of data (deceleration record and soils data) was obtained for 93 tests. This amounts to a total of 83% successful tests.

Although a few tests were conducted as a part of the comparison of static and dynamic penetration, the majority of tests were conducted in accordance with the proposal for 1971-1972. The proposal calls for 12 tests for each type of soil tested. This number was exceeded in almost every case by repeating one or more tests for statistical evaluation.

It was found that the results of tests in saturated dense ottawa sand were for all practical purposes identical to those in dry dense ottawa sand. For this reason a complete series of tests in saturated ottawa sand was not conducted. Instead, an additional sand was used for one series of tests (concrete sand).

Table I is a summary of penetration tests conducted during the year. Table II is a summary of target properties. In the test series, abbreviations are as follows: CS = concrete sand, OS = ottawa sand, SS = silty sand, KC = kaolin clay, SC = sand-clay mixture, SSC = silt-sand-clay mixture, and NC = natural clay (the stiff in-situ clay in the vicinity of the Terramechanics Laboratory).

Multiple tests were conducted in all targets except CS 1 thru CS 5, OS 15, and SS4.

TABLE I
SUMMARY OF PENETRATION DATA

Test No.	Proj. Length (in)	Proj. Weight (lb)	Proj. Diameter (in)	Proj. W/A (psi)	Impact Velocity (FPS)	Time Duration (MS)	Penetration Depth (in)	Proj. Nose
CS 1-1	22.25	7.34	1.56	3.83	113.	25	17.6	Short Ogive
CS 1-2	22.25	7.34	1.56	3.83	113.5	26	16.7	Short Ogive
CS 1-3	22.25	7.34	1.56	3.83	112.5	28	18.7	Short Ogive
CS 1-4	24.25	7.38	1.56	3.85	115.0	31	25.6	Long Cone
CS 1-5	21.75	7.39	1.56	3.85	117.0	31.5	17.5	Blunt
CS 1-6	22.75	7.35	1.56	3.83	119.0	29.0	20.8	Short Cone
CS 1-7	23.37	7.33	1.56	3.82	119.0	27.0	23.2	Long Ogive
CS 1-8	24.25	7.38	1.56	3.85	115.0	31.5	25.9	Long Cone
CS 1-9	21.75	7.39	1.56	3.85	118.5	33.5	16.2	Blunt
CS 1-10	22.75	7.35	1.56	3.83	114.5	36.0	22.9	Short Cone
CS 1-11	23.37	7.33	1.56	3.82	115.0	28.0	24.5	Long Ogive
CS 1-12	36.62	14.70	1.56	7.67	118.5	33.0	25.7	Short Ogive
CS 1-13	64.75	29.85	1.56	15.57	102.5	38.0	29.8	Short Ogive
CS 1-14	20.87	3.62	1.56	1.89	116.0	29.5	13.9	Short Ogive
CS 1-15	22.25	7.34	1.56	3.83	154.0	27.5	25.0	Short Ogive
CS 1-16	22.25	7.34	1.56	3.83	60.0	36.0	13.6	Short Ogive
CS 1-17	22.25	7.34	1.56	3.83	81.5	38.5	20.5	Short Ogive ¹
CS 1-18	22.25	7.34	1.56	3.83	130.0	38.5	31.0	Short Ogive ¹
CS 1-19	22.25	7.34	1.562	3.83	158	--	32.2	Short Ogive
CS 1-20	22.25	7.34	1.562	3.83	113.5	--	28.2	Short Ogive
CS 1-21	22.25	7.34	1.562	3.83	190	22	25.7	Short Ogive
CS 1-22	22.25	7.34	1.562	3.83	161	25	23.7	Short Ogive
CS 1-23	22.25	7.34	1.562	3.83	131	26	22.2	Short Ogive

TABLE I CONTINUED

Test No.	Proj. Length (in)	Proj. Weight (lb)	Proj. Diameter (in)	Proj. W/A (psi)	Impact Velocity (FPS)	Time Duration (MS)	Penetration Depth (in)	Proj. Nose
CS 1-24	22.25	7.34	1.562	3.83	145	26	22.7	Short Ogive
CS 1-25	22.25	7.34	1.562	3.83	108	31	20.5	Short Ogive
CS 1-26	24.37	15.31	2.187	4.075	103.5	31	18.1	Short Ogive
CS 1-27	24.37	15.31	2.187	4.075	103.0	30	18.5	Short Ogive
CS 1-28	24.00	31.03	3.062	4.213	88.5	43	19.2	Short Ogive
CS 2-1	22.25	7.34	1.562	3.83	57.3	--	40.5	Short Ogive
CS 3-1	22.25	7.34	1.562	3.83	53.8	61	23.2	Short Ogive
CS 4-1	22.25	7.34	1.56	3.83	51.4	47	16.5	Short Ogive
CS 5-1	22.25	7.34	1.56	3.83	51.4	41	14.5	Short Ogive
CS 5-2	22.25	7.34	1.562	3.83	51.5	46.0	16.7	Short Ogive
OS 15-1	22.25	7.34	1.562	3.83	113	--	42+	Short Ogive ²
OS 15-2	22.25	7.34	1.562	3.83	114.5	29.0	22.0	Short Ogive
OS 15-3	24.25	7.38	1.562	3.85	110.0	32.0	26.0	Long Cone
OS 15-4	22.75	7.35	1.562	3.83	113	--	35.75	Short Cone ³
OS 15-5	22.75	7.35	1.562	3.83	113	--	25.0	Short Cone
OS 15-6	23.75	7.33	1.562	3.82	116.0	27.0	23.8	Long Ogive
OS 15-7	21.75	7.39	1.562	3.85	119.0	27.0	20.6	Blunt
OS 15-8	36.62	14.70	1.562	7.67	117.6	35.0	30.2	Short Ogive
OS 15-9	20.87	3.64	1.562	1.89	111.0	20.0	14.5	Short Ogive
SC 11-1	42.5	7.83	1.56	4.08	110.0	12	9.4	Short Ogive
KC 27-1	22.25	7.34	1.56	3.83	115.0	16	12.38	Short Ogive
KC 28-1	22.25	7.34	1.56	3.83	50.0	28	8.25	Short Ogive
KC 28-2	22.25	7.34	1.56	3.83	115.0	32	21.9	Short Ogive
KC 28-3	42.5	7.83	1.56	4.08	67.0	30	11.75	Short Ogive

TABLE I CONTINUED

Test No.	Proj. Length (in)	Proj. Weight (lb)	Proj. Diameter (in)	Proj. W/A (psi)	Impact Velocity (FPS)	Time Duration (MS)	Penetration Depth (in)	Proj. Nose
SS 1-1	42.50	7.83	1.56	4.08	111.5	14	9.3	Short Ogive
SS 1-2	44.37	7.83	1.56	4.08	114.5	--	11.6	Long Cone
SS 1-3	41.87	7.83	1.56	4.08	113.0	14	8.6	Blunt
SS 1-4	42.50	7.83	1.56	4.08	112.0	14	9.4	Short Ogive
SS 2-1	43.50	7.83	1.56	4.08	113.0	--	10.5	Long Ogive
SS 2-2	42.87	7.83	1.56	4.08	110.0	15	10.6	Short Cone
SS 2-3	42.50	7.83	1.56	1.90	161.0	10	8.6	Short Ogive
SS 2-4	36.62	14.70	1.56	4.08	110 (EST)	--	14.0	Short Ogive ⁴
SS 2-5	64.75	29.85	1.56	15.57	100.0	24	17.63	Short Ogive
SS 2-6	20.87	3.64	1.56	1.90	117.0	10	7.12	Short Ogive
SS 2-7	36.62	14.70	1.56	7.67	117.0	20	15.50	Short Ogive
SS 2-8	22.25	7.34	1.56	3.83	116.5	14	10.13	Short Ogive
SS 3-1	22.25	7.34	1.56	3.83	117.0	14	8.50	Short Ogive
SS 3-2	22.25	7.34	1.56	3.83	155.0	13	11.75	Short Ogive
SS 3-3	22.25	7.34	1.56	3.83	198.0	13	14.75	Short Ogive
SS 3-4	22.25	7.34	1.56	3.83	72.0	15	6.75	Short Ogive
SS 3-5	24.37	15.31	2.18	4.07	101.0	16	9.37	Short Ogive
SS 3-6	24.00	31.03	3.06	4.21	116.0	18	12.25	Short Ogive
SS 4-1	22.25	7.34	1.56	3.83	55.5	--	14.5	Short Ogive
SS 4-2	22.25	7.34	1.56	3.83	57.0	38	14.25	Short Ogive
SS 4-3	22.25	7.34	1.56	3.83	80.0	44	22.25	Short Ogive
SS 4-4	22.25	7.34	1.56	3.83	112.5	43	27.50	Short Ogive
SS 4-5	22.37	7.38	1.56	3.85	115.0	43	25.25	Blunt

TABLE I CONTINUED

Test No.	Proj. Length (in)	Proj. Weight (lb)	Proj. Diameter (in)	Proj. W/A (psi)	Impact Velocity (FPS)	Time Duration (MS)	Penetration Depth (in)	Proj. Nose
SS 4-6	24.25	7.38	1.56	3.85	112.0	48	36.12	Long Cone
SS 4-7	23.37	7.33	1.56	3.82	114.0	41	30.7	Long Ogive
SS 4-8	22.75	7.39	1.56	3.85	115.0	43	27.7	Short Cone
SS 4-9	36.62	14.7	1.56	7.67	117.0	60	45.39	Short Ogive
SS 4-10	24.25	7.38	1.56	3.85	117.0	47	36.00	Long Cone
SS 4-11	64.75	29.8	1.56	15.57	98.5	89	57.75	Short Ogive
SS 4-12	22.25	7.34	1.56	3.83	159.0	37	33.12	Short Ogive
SS 4-13	24.37	15.3	2.187	4.07	102.0	43	26.5	Short Ogive
SS 4-14	24.00	31	3.06	4.21	92.4	--	23.25	Short Ogive
SS 4-15	25.12	17.62	3.062	2.39	86.5	30	13.90	Short Ogive
SSC 1-1	25.12	17.63	3.062	2.39	92.0	10	4.87	Short Ogive
SSC 1-2	22.25	7.34	1.562	3.83	113.0	9	6.75	Short Ogive
SSC 1-3	22.75	7.39	1.562	3.85	112.0	10	7.25	Short Cone
SSC 1-4	23.37	7.33	1.562	3.82	115.0	11	9.0	Long Ogive
SSC 1-5	24.25	7.38	1.562	3.85	110.0	11	10.12	Long Cone
SSC 1-6	21.75	7.39	1.562	3.85	117.0	9	5.0	Blunt
SSC 1-7	22.25	7.34	1.562	3.85	65.3	--	3.125	Short Ogive
SSC 1-8	22.25	7.34	1.562	3.85	190	--	11.25	Short Ogive
SSC 1-9	20.87	3.64	1.562	1.90	116.0	6	4.12	Short Ogive
SSC 1-10	22.25	7.34	1.562	3.83	65.0	10	4.0	Short Ogive
SSC 1-11	22.25	7.34	1.562	3.83	193	--	11.5	Short Ogive
SSC 1-12	36.62	14.7	1.562	7.67	115.0	13	10.25	Short Ogive
SSC 1-13	64.75	29.85	1.562	15.57	99.0	19	13.25	Short Ogive
SSC 1-14	24.37	15.31	1.562	4.07	99.5	11	6.75	Short Ogive

TABLE I CONTINUED

Test No.	Proj. Length (in)	Proj. Weight (lb)	Proj. Diameter (in)	Proj. W/A (psi)	Impact Velocity (FPS)	Time Duration (MS)	Penetration Depth (in)	Proj. Nose
NC 1-1	22.25	7.34	1.562	3.83	127	23	17.2	Short Ogive
NC 1-2	24.25	7.38	1.562	3.85	134	21	17.7	Long Cone
NC 1-3	23.37	7.33	1.562	3.82	136	14	11.9	Long Ogive
NC 1-4	22.75	7.39	1.562	3.86	130	--	21.0	Short Cone
NC 1-5	21.75	7.39	1.562	3.86	127	24	19.85	Blunt
NC 1-6	22.75	7.39	1.562	3.86	113	--	20.75	Short Cone
NC 1-7	24.25	7.38	1.562	3.85	125	26	22.7	Long Cone
NC 1-8	22.25	7.34	1.562	3.83	134	23	18.6	Short Ogive
NC 1-9	22.25	7.34	1.562	3.83	178	--	29.25	Short Ogive
NC 1-10	22.25	7.34	1.562	3.83	192	--	29.25	Short Ogive
NC 1-11	23.37	7.33	1.562	3.82	131	--	19.37	Long Ogive
NC 1-12	36.62	14.70	1.562	7.66q	114	33	24	Short Ogive
NC 1-13	64.75	29.85	1.562	15.57	119	43	34.6	Short Ogive
NC 1-14	20.87	3.64	1.562	1.90	118	17	14.1	Short Ogive
NC 1-15	22.25	7.34	1.562	3.83	66	21	13.7	Short Ogive
NC 1-16	24.00	31.03	3.06	4.21	114	27	24	Short Ogive
NC 1-17	24.37	15.24	2.18	4.07	131	29	22.37	Short Ogive
NC 1-18	24.37	15.24	2.18	4.07	115	30	22.37	Short Ogive

¹ Attempted to use rubber lined target. Test Invalid.

² Attempted to construct target with wet sand.

³ Target disturbed when water added.

⁴ Gun misfired.

TABLE II
SUMMARY OF SOIL PROPERTIES

Target Number	Bulk Density (Lb/Ft ³)	Dry Density (Lb/Ft ³)	Moisture Content (%)	Degree of Saturation (%)	Void Ratio (-)	Unconfined Compression Strength (psi)	Angle of Internal Friction (Degrees)
CS 1	112.5	112.5	0	0	.47	0	39
CS 2	103.5	103.5	0	0	.60	0	33.5
CS 3	107.5	107.5	0	0	.54	0	35°*
CS 4	109.5	109.5	0	0	.51	0	37°*
CS 5	112.5	112.5	0	0	.47	0	39
OS 15	131	110	18.9	100	.50	0	34
SC 11	119	114.5	4.1	25	.44	59	37.5
KC 27	114	91.	25.5	86.5	.78	94	24.6
KC 28	114	87.5	30.2	94	.85	10	9.5
SS 1,2,3	108	100.5	7.4	31	.64	26	38.7
SS 4	100	100.	Trace	Nil	.65	0	43°
SSC 1	123	118.0	4.3	28.5	.40	29	38.0
NC 1	131	115.0	13.9	82	.46	29 - 125	Varies

*Estimated

ANALYSIS OF PENETRATION DATA

Low velocity penetration data is now available for a wide range of soil types. This analysis will encompass all previously reported data (reports for 1968-69, 69-70, 70-71) as well as data given in this report.

The primary means of penetration analysis has been to assume a resisting force which is a function of instantaneous velocity and depth, i.e.

$$m \frac{d^2x}{dt^2} = f(x, \frac{dx}{dt}) \quad (1)$$

If a solution to this differential equation is known, the coefficients preceding the velocity and depth terms can be evaluated in terms of soil and projectile properties. This can be done by performing several tests varying one parameter of interest at a time and observing how each parameter changes with changing conditions. Most previous analyses have included two terms on the right side of Eq. 1. There are several dangers inherent in this technique. Paramount is the assumption that Eq. 1 is in fact true. Secondly is the inability of such a technique to weigh large amounts of data i.e. two tests determine two coefficients.

Eq. 1 implies that the force on a projectile is dependent on the instantaneous values of velocity and depth, given a fixed set of soil and projectile variables. Whether or not this force depends on the history of the projectile's motion is not known.

Development of experimental techniques to measure deceleration-time histories of penetrating projectiles has provided a first hand look at what occurs during penetration. Observation of such records indicates that many previously assumed forms of Eq. 1 may be in error in predicting deceleration behavior. The use of such equations for depth prediction are often adequate for all the wrong reasons. By forcing agreement at certain points the depth prediction techniques can be made reasonably accurate as long as large deviations of important parameters do not occur.

Many investigators have tried to attach some fundamental significance to Eq. 1 but in reality there is no evidence to indicate any exists. This equation is at most intuitively appealing. The end product of solving Eq. 1 in any of its forms is a limited depth prediction equation. Since the existing equations offer little help in predicting deceleration-time behavior it is far simpler to assume a depth function, i.e.

$$x_0 = f(s, p) \quad (2)$$

where x_0 = final penetration depth, s = soil properties, and p = projectile properties. There seems to be as much basis for starting with Eq. 2 as with Eq. 1. Additionally, Eq. 2 can be developed statistically and does not require integration. This technique has been used by Young (5) and has to date provided probably the best correlation with experimental data.

Thompson proposed still another empirical analysis procedure. He proposed to delineate all variables felt to be important in the

penetration process. The resisting force is then considered to be a generalized power series in all these variables. Since force, velocity, and depth can be determined as continuous functions of time, each test theoretically provides an infinite set of data points. As a practical matter one or two points per millisecond are selected. By performing tests over a wide range of variables the least squares procedure can be used to evaluate coefficients. This technique should provide realistic deceleration-time predictions as well as total depth predictions. If the form devised produces an integrable equation, then a simple expression for velocity-time and depth-time follows. If the form is not integrable, then numerical approximations can be made.

This technique was used by Murff and Coyle (1) with reasonable success for penetration tests in clay and sand-clay mixtures. It was found that the equation

$$m \frac{d^2x}{dt^2} = A \frac{dx}{dt} + B x \quad \dots \dots \dots (3)$$

fit the data quite well and provided accurate predictions for the time dependent behavior of the projectile. This equation has the added advantage of being readily integrable.

During the past year a large number of functions of velocity and depth were investigated. In the search for one form of an equation which fits all the data, one soil type and one projectile geometry are considered at a time. Because of assumptions already made, i.e. the force is independent of motion history, various impact velocities and projectile weights can be considered in

seeking the equation form.

It has been found that Eq. 3 provides an excellent fit for all soil types considered i.e. clay, sand, and sand-clay mixtures although the coefficients vary considerably. For the initial investigation the projectile geometry considered was a 1.56 inch diameter, short ogive projectile. Table III shows typical Eq. 3 coefficients for this projectile for a variety of soil types.

TABLE III
COEFFICIENTS - FIRST FIT

Soil Type	Coefficients	
	$\frac{A}{lb - sec}$ Ft	$\frac{B}{lb}$ Ft
Uniform Dense Dry Sand (OS 11)	2.1	600
Well Graded Dense Dry Sand (ES 1)	3.1	784
Med. Dense Dry Silty Sand (SS 4)	2.4	286
Uniform Very Loose Dry Sand (OS 12)	.5	12.5
Stiff Sand-Clay Mixture (SC 8)	7.6	6567
Soft Sand-Clay Mixture (SC 7)	10.3	500
Stiff Kaolin Clay (KC 17)	20.3	2571

Coefficients A and B are considered to be functions of both soil and projectile properties. The technique used for determining appropriate functions is explained by Murff and Coyle (1). Briefly this technique consists of changing one variable at a time and observing how the coefficients change. The first attempts were made to identify the role of projectile properties in the A and B coefficients.

A large number of trials were made in developing a general equation that fits all laboratory data. This equation incorporates the projectile properties but does not include soil properties. The form of the equation selected is

$$F = A_1 D^2 \left(\frac{NL}{D} \right) V + A_2 D^2 V + A_3 D \cdot d + A_4 D^2 \dots (4)$$

where F = force in lbs, D = projectile diameter in inches, $\overline{NL}$ = projectile nose length in inches, V = velocity in FPS, d = depth in Ft, and A_1 thru A_4 are functions of soil properties.

Some physical significance might be attached to this equation although caution should be exercised in using it. It is not generally considered good practice to extrapolate from regression equations such as Eq. 4 unless the equation does have a fundamental basis. It is also important to avoid high order terms in such equations if extrapolation is desired.

The first two terms might be considered as damping resistance. The third term could be considered as side frictional resistance and the last term as end bearing. Fig. 6 depicts the resistance according to this interpretation.

Fig. 6 - Physical Interpretation of Regression Model

As mentioned this equation fits all data well. Table IV is a summary of curve fits for various soil types. Included in Table IV are multiple correlation coefficients for Eq. 4 for the different soil types.

TABLE IV
COEFFICIENTS - SECOND FIT

Soil Target		A ₁	A ₂	A ₃	A ₄	Multiple Correlation, r
Clay {	KC 20	.020	3.21	2113	-577	.997
	NC 1	.843	-1.01	563	216	.962
Dry Sand {	OS 11	-.565	3.51	402	- 67	.937
	CS 1	-1.86	6.16	497	-133	.946
	SS 4	- .73	2.45	120	69	.985
Mixtures {	SC 2,3,4,8,9					
	SSC 1	-3.01	5.63	1319	548	.939
	SC 1,7,10	-2.53	5.68	248	129	.898
	SS 1,2,3	-1.27	7.7	2081	-109	.977

It can be seen that the correlation coefficients are quite high indicating high correlation between the set of independent variables and the dependent variable. A value of 1 indicates perfect correlation.

In the curve fitting procedure force is considered as positive whereas it is actually opposite in sense to the depth and velocity. In order to solve the differential equation (Eq. 4) all coefficients shown must be reversed in sign. Table IV shows that dry sands and

mixtures indicate a nose effect in the expected direction, i.e. as the nose length to diameter ratio increases the resisting force decreases. The two clays however show an inverse nose effect. This occurrence has been observed and reported by Murff and Coyle (2). For some materials A_4 is negative suggesting a negative end bearing. This is of course physically unreasonable and must be attributed to interaction with A_1 and A_2 (all terms contain the variable D^2).

Attempts to tie the coefficients together with soil properties such as friction angle or cohesion have not been successful. Using the classification shown analyses can be made of the three groups, i.e. clay, dry sand, and mixtures.

Clay

Regression analyses were conducted on tests into five different kaolin clay targets (KC 18,20,22,23,26). Unconfined strengths for these targets ranged from 9 psi to 80 psi. The target material has a ductile character unlike the brittle fissured material of the natural clay targets. Tests in which separation was felt to occur were not considered in this analysis. Further investigation as to the effects of cohesive strength on soil projectile separation should be conducted in order to develop equations which are valid at higher velocities.

It was found that A_3 and A_4 varied with cohesive strength while A_1 and A_2 exhibited almost random fluctuations. Thus the

equation developed for clay penetration is

$$F = .44 D^2 \left(\frac{NL}{D}\right) V - 1.94 D^2 V + (6.86 u + 5.91) Dd + 10.27 u D^2 \dots (5)$$

where u = unconfined compression strength in psi and the other variables are as previously defined. This equation has a multiple correlation coefficient of .983, indicating a very excellent equation for the data considered.

Dry Sand

A complete set of data is available in three dry sands. Experimentation with Eq. 4 indicates that both relative density and gradation are important in this problem. The coefficients can be expanded as functions of soil properties as follows:

$$F = -1.15(D^2)\left(\frac{NL}{D}\right)\left(\frac{C_u}{C_c}\right)(D_r) V + 3.92(D^2)(D_r) V + 288(D)(D_r) d + 35.3(D^2)(D_r) \dots (6)$$

where D_r = relative density, C_u = coefficient of uniformity, C_c = coefficient of curvature and the remaining terms are as previously defined. The coefficient of correlation is .929, again an excellent value.

Mixtures

The authors were unable to develop an equation showing a simple relationship among the coefficients of Eq. 4 and standard

soil properties for soil mixtures. It is possible that a relationship could be developed along the lines previously described; however, it is the authors opinion that such an equation might be misleading. It is quite easy to statistically show relationships where none exist. The coefficients given in Table II for mixtures provide at least a set of bounds for estimating forces and depths for various mixtures. It should be noted that the unconfined strength of targets SC 2,3,4,8,9 and SSC 1 vary considerably (as much as a factor of 5); however, it was possible to obtain an excellent data fit lumping all of these targets together. This is an indication that the unconfined strength in the range of 10 psi - 60 psi may not be too significant. (Obviously this strength will become significant as the material approaches rock.) Targets SC 1,7 and 10 were similarly insensitive to changes in unconfined strength. Factors which are felt to be significant are gradation, compressibility, and moisture content in relation to clay content and activity of clay. As mentioned no simple way to relate these factors has been developed and Table IV is presented as a guide or bound for materials with both cohesive strength and frictional strength.

Solution of the Equation of Motion

Since the forces on a projectile oppose the motion, Eq. 4 can be written as

$$F = m \frac{d^2 x}{dt^2} = - A_1 D^2 \left(\frac{NL}{D} \right) \frac{dx}{dt} - A_2 D^2 \frac{dx}{dt} - A_3 D x - A_4 D^2 \dots (7)$$

or

$$m \frac{d^2 x}{dt^2} + B_1 \frac{dx}{dt} + B_2 x + B_3 = 0 \dots (8)$$

where:

$$B_1 = - A_1 D^2 \left(\frac{NL}{D} \right) - A_2 D^2$$

$$B_2 = A_3 D$$

$$B_3 = A_4 D^2$$

The solution to this Eq. is straight forward. It has been discussed by Murff and Coyle (1) but is briefly reviewed here. Two solutions are possible depending on the relationship among coefficients. For

$$\left(\frac{B_1}{2m} \right)^2 > \left(\frac{B_2}{m} \right) \dots (9)$$

it can be shown that

$$x(t) = e^{-\frac{B_1 t}{2m}} \left[E e^{\left[\left(\frac{B_1}{2m} \right)^2 - \left(\frac{B_2}{m} \right) \right]^{1/2} t} + F e^{-\left[\left(\frac{B_1}{2m} \right)^2 - \left(\frac{B_2}{m} \right) \right]^{1/2} t} \right] - \frac{B_3}{B_2} \dots (10)$$

where E and F are constants of integration. For

$$\left(\frac{B_1}{2m} \right)^2 < \left(\frac{B_2}{m} \right) \dots (11)$$

it can be shown that

$$x(t) = e^{-\frac{B_1 t}{2m}} \left[E \cos \left[\left(\frac{B_2}{m} \right) - \left(\frac{B_1}{2m} \right)^{1/2} t \right] + F \sin \left[\left(\frac{B_2}{m} \right) - \left(\frac{B_1}{2m} \right)^{1/2} t \right] - \frac{B_3}{B_2} \right] \dots \dots \dots (12)$$

The initial conditions are

$$\text{at } t = 0, \frac{dx}{dt} = V_0, x = 0$$

where V_0 = impact velocity. To determine the total depth of penetration the applicable equation (10 or 12) is differentiated once and set equal to zero (i.e. $\frac{dx}{dt} = 0$ or velocity = 0). A value of t is determined giving the time at which the velocity is zero or the time at which depth is maximum. Multiple roots exist but the correct root is the smallest value i.e. the first time at which $\frac{dx}{dt} = 0$. This value of time is substituted into the appropriate equation (10 or 12) and an equation for total penetration depth results.

For Eq. 10,

$$E = \frac{V_0 + \frac{B_1 B_3}{2B_2}}{2 \left[\left(\frac{B_1}{2m} \right)^2 - \left(\frac{B_2}{m} \right) \right]^{1/2}} + \frac{B_3 m}{2B_2} \dots \dots \dots (13)$$

$$F = \frac{-(V_0 + \frac{B_1 B_3}{2B_2})}{2 \left[\left(\frac{B_1}{2m} \right)^2 - \left(\frac{B_2}{m} \right) \right]^{1/2}} + \frac{B_3 m}{2B_2} \dots \dots \dots (14)$$

$$t^* = \frac{1}{2[(\frac{B_1}{2m})^2 - (\frac{B_2}{m})]^{1/2}} \left[\ln \left(- \frac{E(\frac{B_1}{2m} - [(\frac{B_1}{2m})^2 - (\frac{B_2}{m})]^{1/2})}{F(\frac{B_1}{2m} + [(\frac{B_1}{2m})^2 - (\frac{B_2}{m})]^{1/2})} \right) \right]$$

where t^* = penetration time.

For Eq. 12,

$$E = \frac{B_3}{B_2}$$

$$F = (V_0 + \frac{B_1 B_3}{2B_2}) / [(\frac{B_1}{2m})^2 - (\frac{B_2}{m})]^{1/2}$$

and

$$t^* = \frac{1}{[(\frac{B_2}{m}) - (\frac{B_1}{2m})^2]^{1/2}} \text{Arc tan} \left(\frac{\frac{B_1}{2m} E - F[(\frac{B_2}{m}) - (\frac{B_1}{2m})^2]^{1/2}}{-\frac{B_1}{2m} F - E[(\frac{B_2}{m}) - (\frac{B_1}{2m})^2]^{1/2}} \right)$$

Comparison with Experiment

Comparison of the statistical equations with experimental data can be made in two ways. Since the equations themselves were derived from the data, the statistical parameters and tests are a measure of how well the equations fit. Additionally the equations can be tested on data not used in the curve fitting procedure.

Table IV includes multiple correlation coefficients for the various soil types. These values (.89 - .99) are indications that the selected equation is an excellent fit. In addition to these parameters the "F" statistics based on analysis of variance for the tests fitted, range from 500 to 4000. These values are

considerably larger than the value of 3.02 required for concluding at a .01 level of significance the terms in the regression equation do affect the resisting force. In addition each term in the regression equation has been tested at a .005 level of significance using the "t" test. Thus, statistically, the equations given offer an excellent fit of the laboratory data.

The purpose of the experiment is, of course, to enhance the ability to predict projectile behavior in natural soils. Within the range of variables tested it is felt that the equations provided will yield good correlation with field data. When extrapolating out of the range from which the data was derived, care should be exercised. In general it is not good practice to extrapolate from regression equations except where a fundamental relationship has been established.

Comparisons are not included for clay and sand penetration equations due to lack of applicable field data. Some data at very high impact velocities is available in sands; however, this falls far beyond the range of applicability. Likewise some data for very low strength clays (approximately 1/10 of the minimum strength tested) is available but has been found to be out of the range of the regression equations presented here. The impact velocity range and soil property range are apparently the most sensitive parameters in the regression equations.

The bulk of available field data is taken from tests at Tonopah Test Range. Although the soil properties vary somewhat

it is in general a stiff mixture of sand, silt, and clay similar to SC and SSC targets constructed in the laboratory but having a higher clay content. As previously mentioned a wide range of cohesive strengths were included in the curve fitting for this material. It is thus desirable to see to what degree the regression equation fits the TTR data. Fig. 7 shows a comparison of experimental and predicted deceleration vs time records for tests 279-1 and 279-59. Parameters for both tests fall into the range of laboratory parameters except for diameters. It is encouraging that larger diameters were used in field tests yet the predictions are quite good.

Data is also available for tests conducted in loess. This material is highly compressible and composed primarily of silt. Sufficient moisture exists to give the material a slight cohesive strength. It was reasoned that the resistance to penetration for this material should be bounded by the dry silty sand (SS 4) and the moist compacted silty sand (SS 1-3). Fig. 8 shows that this is in fact the case.

Other comparisons with field data can be made however only through using the equations can on become familiar with their range of applicability. It is felt that the primary strengths of the equations herein developed are to:

- (1) Provide bounds and/or approximations to the resisting force.

Fig. 7 - Comparison of Actual and Predicted G-T Records

(a) 279-1 (b) 279-59

Fig. 8 - Comparison of Actual and Predicted G-T Records 339-19

- (2) Indicate the influence of various projectile and soil properties on the resisting force.

Any regression equation can be improved by considering more and more data in its development. Certainly the equations provided herein are not exceptions to this rule.

SUMMARY AND CONCLUSIONS

Regression analysis of over 300 low velocity penetration tests has shown that the equation

$$F = A V + B d$$

provides an excellent fit. Further comparison shows that the equations developed provide good correlation with much existing field data. In summary the force prediction equations are:

- (1) Non-brittle clay with unconfined compression strengths between 10 and 100 psi

$$F = .44(D^2)\left(\frac{NL}{D}\right) V - 1.94 D^2 V + 6.86 D u d + 592. Dd + 10.3 u D^2$$

- (2) Dry sands with $D_r > .5$

$$F = -1.15(D^2)\left(\frac{NL}{D}\right)(D_r)\left(\frac{C_u}{C_c}\right) V + 3.92 D^2 D_r V + 289 D D_r d + 35.4 D^2 D_r$$

- (3) Dense sand-silt mixture with sufficient moisture to provide some cohesion (compressible material)

$$F = -1.27 D^2 \left(\frac{NL}{D}\right) V + 7.76 D^2 V + 2081 Dd - 109. D^2$$

- (4) Stiff sand-clay or sand-silt-clay with low moisture content (unconfined compression strength of 10 to 60 psi)

$$F = -3.01 D^2 \left(\frac{NL}{D} \right) V + 5.63 D^2 V + 1319 Dd + 549 D^2$$

- (5) Soft sand-clay or sand-silt-clay with high moisture content (unconfined compression strength of 2 to 10 psi)

$$F = -2.53 D^2 \left(\frac{NL}{D} \right) V + 5.68 D^2 V + 249 Dd + 129 D^2$$

Although these equations do not cover every possible situation, they provide a basis for predictions for many cases and at least upper and lower bounds for many more.

The regression equations presented effectively summarize the laboratory penetration data. Previous reports have specifically pointed out the effects of soil and projectile properties observed during laboratory testing.

The conclusions reached during this study are

- (1) The regression equations presented are useful in predicting field behavior.
- (2) Laboratory penetration testing is a valid means for obtaining experimental data.
- (3) In order to develop empirical prediction equations data covering the entire variable range of interest is desired.
- (4) Laboratory data has been obtained which includes a wide range of variables and will be useful in future testing of empirical and theoretical analyses.

The following recommendations are presented for consideration:

- (1) That the experimental program be continued in those specific areas previously recommended i.e. (a) impact studies (b) layered soils (c) separation and (d) high velocity.
- (2) That future research emphasis be placed on development of a projectile penetration theory.
- (3) That the field data available to Sandia Corporation be subjected to regression analysis using a model similar to the one proposed herein.
- (4) That the three previous recommendations be meshed and directed toward the common goal of predicting the behavior of a projectile penetrating a soil target.

APPENDIX I

REFERENCES

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APPENDIX II

NOTATION

A, A_n, B, B_n, E, F = Coefficients

CS = Concrete sand

C_c = Coefficient of curvature

C_u = Coefficient of uniformity

d, X = Instantaneous depth, ft.

D_r = Relative density

D = Projectile diameter

F = Force

$f()$ = Function

KC = Kaolin clay

m = Projectile mass, slugs

NC = Natural clay

$\overline{NL}$ = Projectile nose length, inches

OS = Ottawa sand

r = Multiple correlation coefficient

SC = Sand-clay

SS = Silt-sand

SSC = Silt-sand-clay

t = Time

$V, dx/dt$ = Instantaneous velocity, fps

V_0 = Impact velocity

X_0 = Total penetration depth

APPENDIX III

PENETRATION RECORDS

The penetration records presented in this section are computed plots of digital information. The deceleration records were read into the computer as scaled ordinates at one millisecond time intervals. The computer performed a numerical integration on this data to produce velocity vs. time and depth vs. time plots. It should be pointed out that the records presented consist of separate data points joined by straight lines. As a result some of the plots appear to have many sharp peaks. This, of course, is a somewhat erroneous impression since the true curves have smooth transitions. The plots presented do conform in general to the true data with this exception. Figures III-1 thru III-93 are deceleration, velocity, and depth vs. time plots for all tests in which deceleration data was obtained.

FIG. III-1

RESULTS OF TEST CS 1-1

FIG. III-2
RESULTS OF TEST CS 1-2

FIG. III-3

RESULTS OF TEST CS 1-3

FIG. III-4

RESULTS OF TEST CS 1-4

FIG. III-5

RESULTS OF TEST CS 1-5

FIG. III-6

RESULTS OF TEST CS 1-6

FIG. III-7

RESULTS OF TEST CS 1-7

FIG. III-8

RESULTS OF TEST CS 1-8

FIG. III-9

RESULTS OF TEST CS 1-9

FIG. III-10

RESULTS OF TEST CS 1-10

FIG. III-11

RESULTS OF TEST CS 1-11

FIG. III-12

RESULTS OF TEST CS 1-12

FIG. III-13

RESULTS OF TEST CS 1-13

FIG. III-14

RESULTS OF TEST CS 1-14

FIG. III-15

RESULTS OF TEST CS 1-15

FIG. III-16

RESULTS OF TEST CS 1-16

FIG. III-17

RESULTS OF TEST CS 1-17

FIG. III-18
RESULTS OF TEST CS 1-18

FIG. III-19

RESULTS OF TEST CS 1-21

FIG. III-20

RESULTS OF TEST CS 1-22

FIG. III-21

RESULTS OF TEST CS 1-23

FIG. III-22

RESULTS OF TEST CS 1-24

FIG. III-23

RESULTS OF TEST CS 1-25

FIG. III-24

RESULTS OF TEST CS 1-26

FIG. III-25

RESULTS OF TEST CS 1-27

FIG. III-26

RESULTS OF TEST CS 1-28

FIG. III-27

RESULTS OF TEST CS 3-1

FIG. III-28

RESULTS OF TEST CS 4-1

FIG. III-29

RESULTS OF TEST CS 5-1

FIG. III-30

RESULTS OF TEST CS 5-2

FIG. III-31

RESULTS OF TEST OS 15-2

FIG. III-32

RESULTS OF TEST OS 15-3

FIG. III-33

RESULTS OF TEST OS 15-6

FIG. III-34

RESULTS OF TEST OS 15-7

FIG. III-35

RESULTS OF TEST OS 15-8

FIG. III-36

RESULTS OF TEST OS 15-9

FIG. III-37

RESULTS OF TEST SC 11-1

FIG. III-38

RESULTS OF TEST KC 27-1

FIG. III-39

RESULTS OF TEST KC 28-1

FIG. III-40

RESULTS OF TEST KC 28-2

FIG. III-41

RESULTS OF TEST KC 28-3

FIG. III-42

RESULTS OF TEST SS 1-1

FIG. III - 43

RESULTS OF TEST SS 1-3

FIG. III-44

RESULTS OF TEST SS 1-4

FIG. III-45

RESULTS OF TEST SS 2-2

FIG. III-46

RESULTS OF TEST SS 2-3

FIG. III-47

RESULTS OF TEST SS 2-5

FIG. III-48

RESULTS OF TEST SS 2-6

FIG. III-49

RESULTS OF TEST SS 2-7

FIG. III-50

RESULTS OF TEST SS 2-8

FIG. III-51

RESULTS OF TEST SS3-1

FIG. III-52

RESULTS OF TEST SS3-2

FIG. III-53

RESULTS OF TEST SS 3-3

FIG. III-54

RESULTS OF TEST SS 3-4

FIG. III-55

RESULTS OF TEST SS 3-5

100

FIG. III-56

RESULTS OF TEST SS 3-6

101

FIG. III-57

RESULTS OF TEST SS4-2

FIG. III-58

RESULTS OF TEST SS4-3

FIG. III-59

RESULTS OF TEST SS4-4

104

FIG. III-60

RESULTS OF TEST SS 4-5

FIG. III-61

RESULTS OF TEST SS 4-6

FIG. III-62

RESULTS OF TEST SS 4-7

FIG. III-63

RESULTS OF TEST SS 4-8

FIG. III-64

RESULTS OF TEST SS 4-9

FIG. III-65

RESULTS OF TEST SS 4-10

FIG. III-66

RESULTS OF TEST SS 4-11

FIG. III-67

RESULTS OF TEST SS 4-12

FIG. III-68

RESULTS OF TEST SS 4-13

FIG. III-69

RESULTS OF TEST SS 4-15

FIG. III-70

RESULTS OF TEST SSC 1-1

FIG. III-71

RESULTS OF TEST SSC 1-2

FIG. III-72

RESULTS OF TEST SSC 1-3

FIG. III-73

RESULTS OF TEST SSC 1-4

FIG. III-74

RESULTS OF TEST SSC 1-5

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FIG. III-75
RESULTS OF TEST SSC 1-6

FIG. III-76

RESULTS OF TEST SSC 1-9

FIG. III-77

RESULTS OF TEST SSC 1-10

FIG. III-78

RESULTS OF TEST SSC 1-12

FIG. III-79

RESULTS OF TEST SSC 1-13

FIG. III-80

RESULTS OF TEST SSC 1-14

FIG. III-21

RESULTS OF TEST NC 1-1

FIG. III- 82

RESULTS OF TEST NC1-2

FIG. III-83

RESULTS OF TEST NC 1-3

FIG. III-84

RESULTS OF TEST NC 1-5

FIG. III-85

RESULTS OF TEST NC 1-7

FIG. III-86

RESULTS OF TEST NC 1-8

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FIG. III-87
RESULTS OF TEST NC 1-12

FIG. III-88

RESULTS OF TEST NC 1-13

FIG. III-89

RESULTS OF TEST NC 1-14

FIG. III-90

RESULTS OF TEST NC 1-15

FIG. III-91

RESULTS OF TEST NC 1-16

FIG. III-92

RESULTS OF TEST NC 1-17

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FIG. III-93

RESULTS OF TEST NC 1-18

APPENDIX IV

TARGET PROPERTIES

The purpose of this appendix is to give a narrative description of each target constructed to supplement the data given in Table II. Additionally grain size analysis curves for CS and SS targets and stress strain curves and Mohr Coulomb Failure Envelopes for all targets are given in Figs. IV-1 thru IV-19.

Concrete Sand Targets (CS)

Five targets were constructed of air dry concrete sand. Two of these targets, CS 1 and CS 5, were very dense and were identical for practical purposes. These two targets were constructed using a concrete vibrator to densify the material. The remaining targets were constructed by manually rodding a specified amount of material in varying degrees.

Densities were measured by determining the gross weight of material and the gross volume of the mold. The maximum density range was determined to be 11 lb/ft.³ from 103.5 lb/ft.³ to 114.5 lb/ft.³ Triaxial tests were performed on samples prepared in the laboratory. Attempts were made to prepare samples at both minimum and maximum relative density i.e. to approximate CS 2 (loosest) and CS 1 and 5 (densest). It is felt that linear interpolation of these results provides sufficient accuracy for determination of properties of other targets (CS 3 and 4).

Ottawa Sand (OS)

The procedure for constructing ottawa sand targets is explained in detail by Murff and Coyle (2) and is similar to that for concrete sand. The series of targets covered in this report were saturated.

The targets were constructed dry in the normal manner. Once constructed, water was forced into the bottom of the target mold at a slow rate. This allowed the water to rise from the bottom and hence minimized air bubbles trapped in the voids. This technique worked well with dense sand but did not work with loose sand. In every case attempts to saturate loose sand also resulted in densification.

Sand Clay Mixtures (SC)

One target, SC 11, was constructed of a mixture of 15% kaolin clay and 85% concrete sand. This target was very similar to targets SC 8 and 9 reported previously by Murff and Coyle (2). The unconfined compression strength of this target is several times higher (about 4) than that of targets SC 8 and 9 reported in 1971. The angle of internal friction however is only about 1 degree higher. This apparent difference may not actually exist. The previous tests were conducted on 3 inch samples extracted from the target by sampling tube. The most recent tests were conducted on 1 1/2 inch samples prepared in the laboratory attempting to match

the density of the target. It is well known that larger samples as well as disturbed samples tend to be weaker. These effects are felt to account for the difference in measurements rather than an actual difference in properties. It is the authors' opinion that the properties presented in the 1971 report more nearly represent the properties of the SC targets. It was considered important however to point out this discrepancy as an indication of the difficulties and pitfalls of determining in situ properties. The problem here was accentuated because of the stiff brittle nature of the target medium.

Kaolin Clay (KC)

Two targets, KC 27 and KC 28, were constructed of pure kaolin clay. These targets are constructed in a manner discussed in earlier reports by Murff and Coyle (2). They were constructed to provide data for comparison of static and dynamic penetration tests.

Silty Sand (SS)

The silty sand used was excavated from a local site. It was manually screened to remove significant organic matter only. Two types of targets, wet and dry, were constructed.

SS 1, 2, and 3 were wet silty sand targets. Sufficient water was added to enable optimum compaction with the pneumatic compaction hammer. SS 4 targets were dry silty sand targets compacted with a concrete vibrator.

The procedures for construction and testing of wet silty sand targets were similar to those for kaolin clay. The procedures for the dry material were similar to those for ottawa sand.

The dry density range for the silty sand was 88 to 108. Because of the small particles and the resulting interaction among grains, it was not practical to approximate maximum density for the dry material. The densest arrangement that was achieved with the concrete vibrator was 100 lb/ft.³

Sand-Silt-Clay Mixture (SSC)

A mixture of 71% concrete sand, 15% silty sand, 10% kaolin clay and 4% water was determined to give a very stiff target material. Two targets were used for the SSC 1 test series but the differences in measured properties was negligible. The construction and testing procedures were identical to those previously used for kaolin clay.

Natural Clay (NC)

A test series was conducted in an in-situ clay near the Terramechanics Laboratory. The top 3 - 4 inches of organic material was removed from the soil over a large area. This exposed a thick deposit of heavily over-consolidated clay. The density and moisture content of the clay remained reasonably consistent; however, as seen in Fig. IV-19, the strength properties of the material varied widely with small changes (on the order of inches) in location.

Fig. IV-1 - Grain Size Distribution - CS Targets

Fig. IV-2 - Grain Size Distribution - SS Targets

Fig. IV - 3 - Stress Strain Curves, Dense Concrete Sand

Fig. IV - 4 - Mohr Coulomb Failure Envelope, Dense Concrete Sand

Fig. IV - 5 - Stress Strain Curves, Loose Concrete Sand

Fig. IV - 6 - Mohr Coulomb Failure Envelope, Loose Concrete Sand

Fig. IV - 7 - Stress Strain Curves, SC 11

Fig. IV - 8 - Mohr Coulomb Failure Envelope, SC 11

Fig. IV - 9 - Stress Strain Curves, KC 27

Fig. IV - 10 - Mohr Coulomb Failure Envelope, KC 27

Fig. IV - 11 - Stress Strain Curves, KC 28

Fig. IV - 12 - Mohr Coulomb Failure Envelope, KC 28

Fig. IV - 13 - Stress Strain Curves, SS 1, 2, and 3

Fig. IV - 14 - Mohr Coulomb Failure Envelope, SS 1, 2 and 3

Fig. IV - 15 - Stress Strain Curves, SS 4

Fig. IV - 16 - Mohr Coulomb Failure Envelope, SS 4

Fig. IV - 17 - Stress Strain Curves, SSC 1

Fig. IV - 18 - Mohr Coulomb Failure Envelope, SSC 1

Fig. IV - 19 - Unconfined Compression Tests Natural Clay Soil