A Laboratory Investigation of Projectile Penetration

by

Umesh Dayal

Introduction

The problem of projectile penetration into earth target has been studied for several hundred years and an immense amount of literature has been published which are reviewed in literature (Dayal 1974, Fuchs et al 1963, Hakala 1965, Schimd 1969, Thomson 1966, Wang 1971). Historically, interest in projectile penetration has stemmed from militery applications. Recent work has highlighted many possible avenues of engineering applications; among those are a remote site investigation of inacessible locations such as lunar surface, ocean bottom, swamps and jungles (Caudle 1967, Dayal et al 1975, McNeil 1972, Schmid 1969).

In more recent years, several studies have been carried out both theoretical and experimental. to study the projectile penetration phenomenon. Most of those investigations are concerned with projectile striking a relatively hard target of soils at considerably high velocity. Various theoretical relationships have been proposed for estimating the velocity profile, maximum penetration depth and total force (Hakala 1965, Schmid 1969, Thomson 1966, Wang 1971). However, those invesigations are hamperedbecause of inadequate knowledge of failure mechanism of projectile penetration and complex condition of soil in situ. In general, the target material has been assumed to be homogenous isotropic half space, either compressible elastic, incompressible plastic, or viscoplastic. Unfortunately, soil deposits generally do not satisfy most of thr above properties. This results in adding a number of variables to already complicated problem.

With the advancement of electronics the present day projectiles are instrumented with accelerometer and are useful tools in tracing the velocity profile, depth of penetration and total soil resistive force offered to the projectile. The acceleration signature alone is inadequate in explaining the penetration mechanism and estimating the target strength. To overcome these difficulties a modiffcation in the projectile instrumentation was proposed (Dayal et al 1973) which, in addition to accelerometer, was instrumented with cone thrust and local side friction (sleeve friction) measuring devices. It has been shown in earlier papers (Dayal et al 1973, 1974a 1974b) that the proposed instrumentation system provides a useful tool for measuring insitu strength properties of soft soil targets.

In order to understand the penetration mechanism laboratory tests were carried out with the instrumented projectile under fully controlled conditions. The purpose of this paper is to present those results and to

---

* Assistant Profsser, Department of Civil Engneening, Indian Institute of Technology, Kanpur 208016, India

This paper was received in August 1980 and is open for disussion till the end of May 1981.

explain penetration mechanism applicable to low velocity projectile penetration of clay.

Test Program

The laboratory test programs in this investigation were of the following three types:

(*i*) Two-dimensional constant velocity penetration tests

(*ii*) Constant velocity penetration tests, and

(*iii*) Projectile penetration tests

The objectives of the first two types of experiments were to study the mechanism of soil displacement during penetration and the influence of penetration rate effects on shear strength, so that, realistic assumptions concerning the velocity and stress fields can be made in theoretical analysis.

The two-dimensional constant velocity penetration test results (Dayal et al 1974 a) indicated that under low velocity the failure mode is basically of a 'static' nature (the soil resistance is distributed over the base and shaft of the projectile). From the experimental results of constant velocity penetration tests (Dayal 1974, Dayal et al 1974a) it is established that in clay soils an increase in penetration velocity increases both cone and sleeve friction resistances and this increase in apparent cohesion is directly proportional to the logarithm of the velocity ratio.

A series of projectile penetration tests were conducted, on partially saturated cohesive targets. The influence of the following selected para. meters on penetration mechanism were studied:

(1) Weight of projectile.

(2) Impact velocity

(3) Nose shape, and

(4) Target strength

Test Apparatus

The basic dimensions of the projectile selected for this experimental program are the same as those generally used for the static cone penetration tests to enable the utilization of available knowledge or static penetration tests for evaluating test results. The projectile was a 60° cone-tipped right-circular cylinder of area 1.55 sq. in. (10 cm^2), diameter of the friction sleeve was 1.405 in. (35.6 mm) and the surface area was 23.25 sq. in. (150 cm^2). The overall height of the projectile was 3.5 ft. (1.07 m). It It was designed to provide a varying weight system ranging from 15 1b. (6.8 kg) to 45 1b. (20.4 kg) so that a pre-selected weight can be used in particular tests and the noses of the projectile were interchangeable. In the present investigations four nose shapes were studied-30°, 60°, 90° and blunt nose. The impact velocity used ranged from 10 fps (3 m/s) to 20 fps (6.1 m/s) controlled by the free fall height of the projectile. The instrumentation consisted on an accelerometer, a cone load cell, and a friction sleeve load cell to measure acceleration/deceleration, cone thrust and local side friction respectively. The signals were amplified and recorded on a four channel high speed instrumentation tape recorder. The detailed descriptions of the design of transducers, projectile and recording equipment have been presented in earlier papers (Dayal 1974, Dayal et al 1973)

Target Material and Construction

The target material was pottery clay (readily available in large quantities) which provided a uniform target materail. The mineral analysis of this material indicated its composition to be mainly of illite and chlorite minerals withsome persentages of quartz, feldspar, and kaolinite. According to the M.I.T. system of soil classifications, it is classified as clayey slit. The physical properties of the modeling clay used are given in Table 1.

TABLE 1

Physical Properties

Liquid Limit = 37%
Plastic Limit = 21%
Plasticity Index = 16%
Specific Gravity = 2.615
All material psses # 200 sieve

The test material was thoroughly dried and pulverized. It was placed in a large concrete mixer and mixed with a measured amount of water to obtain a specific moisture content. The material was recycled until the mixture was homogeneous and was then removed from the mixer. Targets were constructed in cylindrical steel molds of 18 in. (45.72 cm) diameter and 30 in. (76.20 cm) high. The soil mixture was placed in the mold in layers (normally 4 to 8 in., 10.16 to 20.32 cm) and compacted with modified AASHO hand hammer. The desired density was controlled by the number of blows per layer of soil. During the target construction, the samples were collected at 6 in. (15.24 cm) intervales for moisture content determination. After construction of the target up to approximately mid-dpeth, the in-situ vane shear tests were performed at 6 in. (15.24 cm) intervals. The vane shear tests for the remaining upper half were performed either before or immediately after the test at 6 in, (15.24 cm) intervals. The average density was calculated from the total weight of the target.

Test Results

In all the tests acceleration/decelaration, cone thrust, and local side friction (sleave friction) were recorded which, as described in earlier papers (Dayal 1974, Dayal etal 1974a, 1974b) can be related directly to the strength governing parameters of the target materials. In cohesive soils, 'static' strength profile can be obtained from the measured 'dynamic' strength profile by applying the correction for strain/peneration rate sensitivity. In addition, the proposed instrument has been shown to be an effective device for estimating the depth, strength, and the soil type of different layers. It will now be shown that the measured cone and sleeve friction resistances provide a rational approach for explaining the penetration mechanism and quantifying the various previously reported qualitative observations.

Figure 1 is a typical output record for medium stiff clay. Target and projectile properties are given with penetration test resuls where they occur. The salient recorded features of the event, as indicated from accelerometer cone thrust, and friction sleeve records, include :

(*a*) From the accelermeter record

(1) acceleration of the projectile for a while after impact, then

(2) a steady increase in deceleration, and finally

(3) an abrupt drop in declaration level with an acceleration pulse or 'dip' towards the end of the penetration event.

(*b*) From the cone thrust record

(1) an abrupt rise in cone thrust at the beginning of the event, then

(2) a steady decrease in cone thrust (attributed to penetration velocity effect), and finally

(3) a sudden drop at the end of the event.

(*c*) From the friction sleeve record

(1) a steady increase in friction at the beginning of the event (due to continuously increasing area of the sleeve), then

(2) a steady friction, and finally

(3) a gradual increase in friction with negative friction towards the end of the penetration event.

It appears that the 'dip' on the acclerometer record is the result of the rebounding of the projectile caused by elastic energy stored in the soil during penetration. The friction record, which at the end of the penetration event shows a substantial negative friction on the sleeve, confirms the occurrence of rebounding phenomena. Although the 'dip' at the end of the event may be important to the understanding of the complete mechanism, its influence on the penetration depth is normally insignificant. Consequently, this aspect will not be considered in this investigation.

Weight of Projectile

To study the effects of the weight of the projectile on penetration mechanism, tests were conducted on two different types of targets having shear strengths of 1066 psf (51 kN/m^2) and 204 psf (9.8 kN/m^2). The test results are plotted in Figures 2, 3, 4 and 5. These results indicate that an increase it the projectile weight yields an increase in total penetration, an increase in the total time of the penetration event and a decrease in measured deceleration. The measured cone thrust and sleeve friction records indicate that an increase in the weight of the projectile does not make any significant difference to their magnitudes.

Impact Velocity

The effect of impact velocity on the penetration mechanism was studied and the results for impact velocities of 20.01 fps (6.1 m/s), 18.84 fps

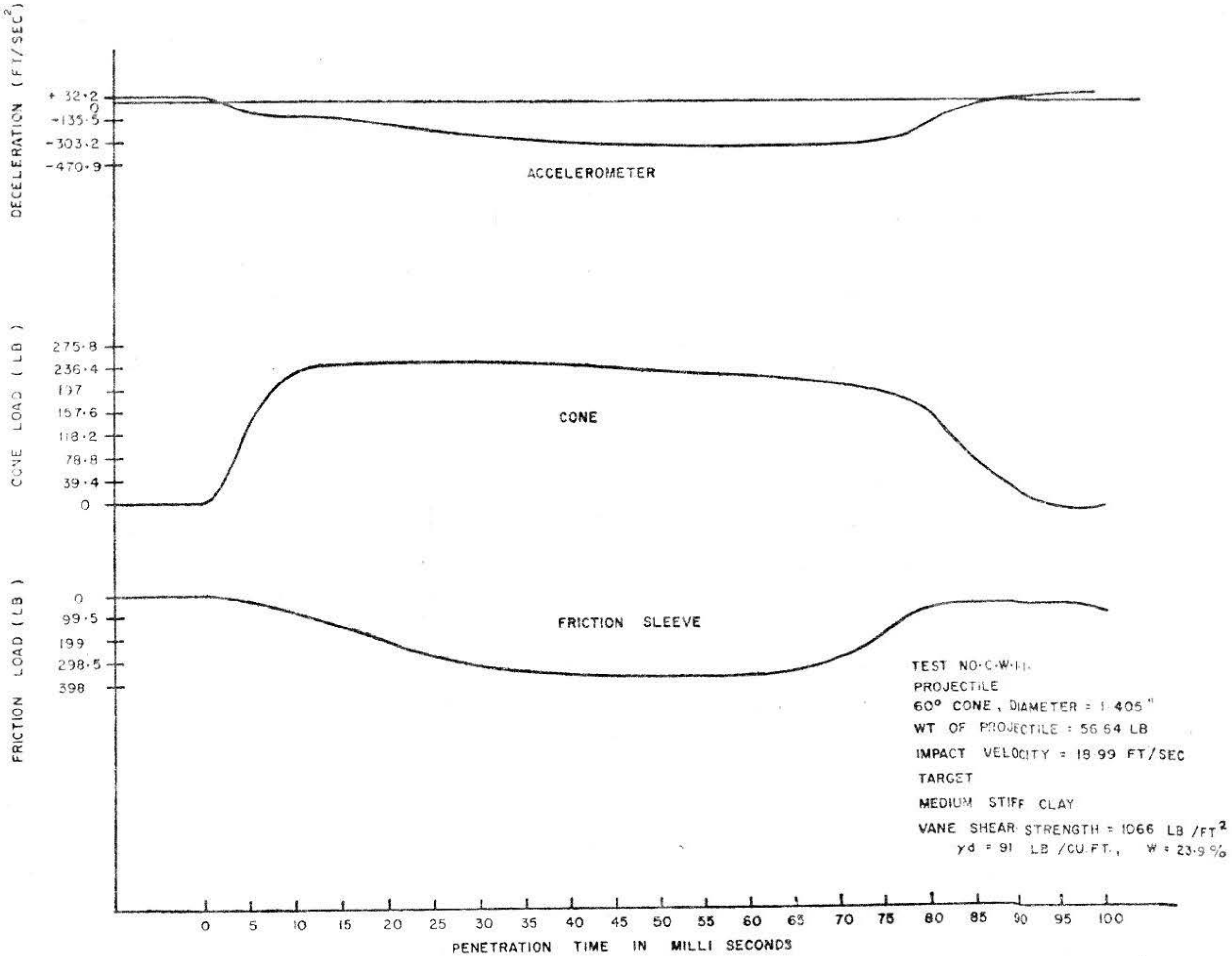

FIGURE 1. Typical impact penetration test records for medium stiff clay (1 L B = 0453 kg, 1FT/SEC² = 0.305 M/SEC²)

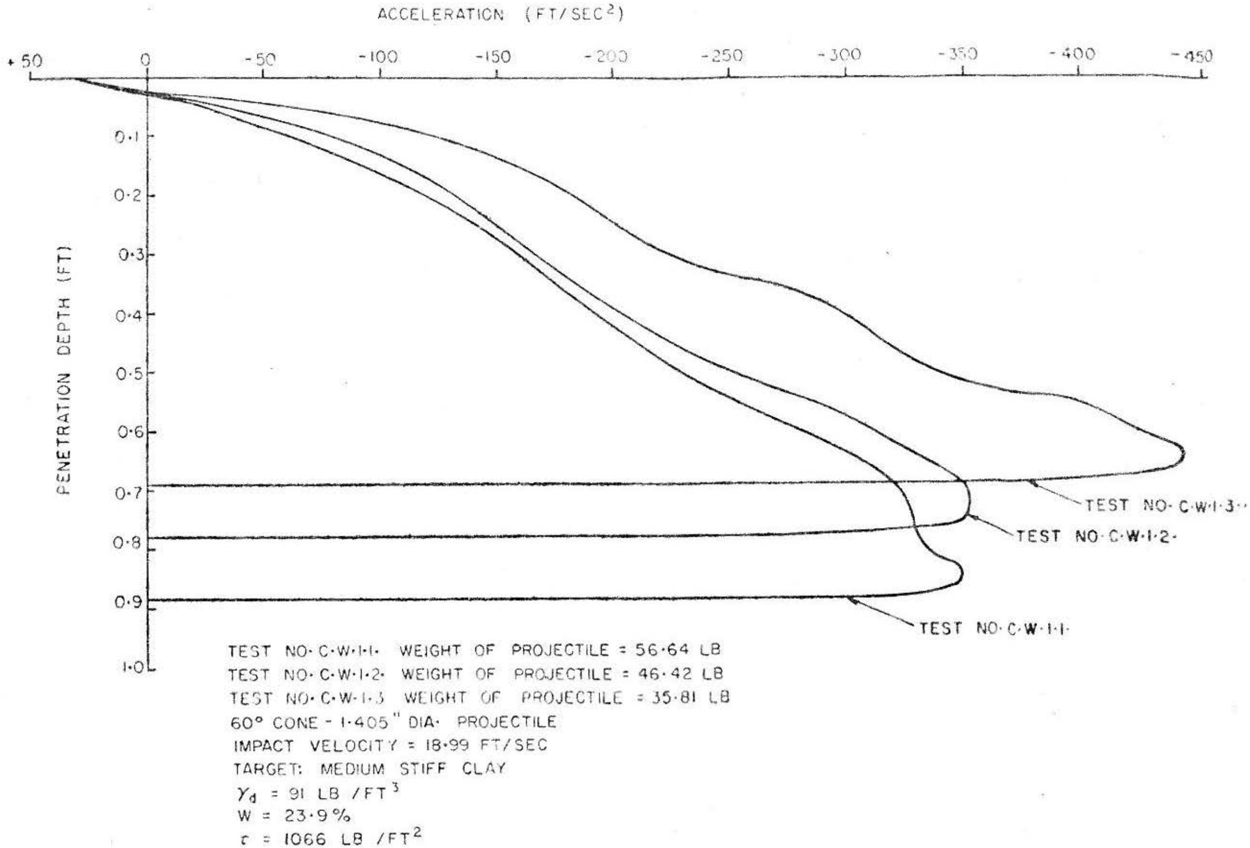

FIGURE 2 **Plot of Penetration depth vs acceleration for different weights (1 FT = 0.305; 1 FT/SEC² = 0.305 M/SEC²)**

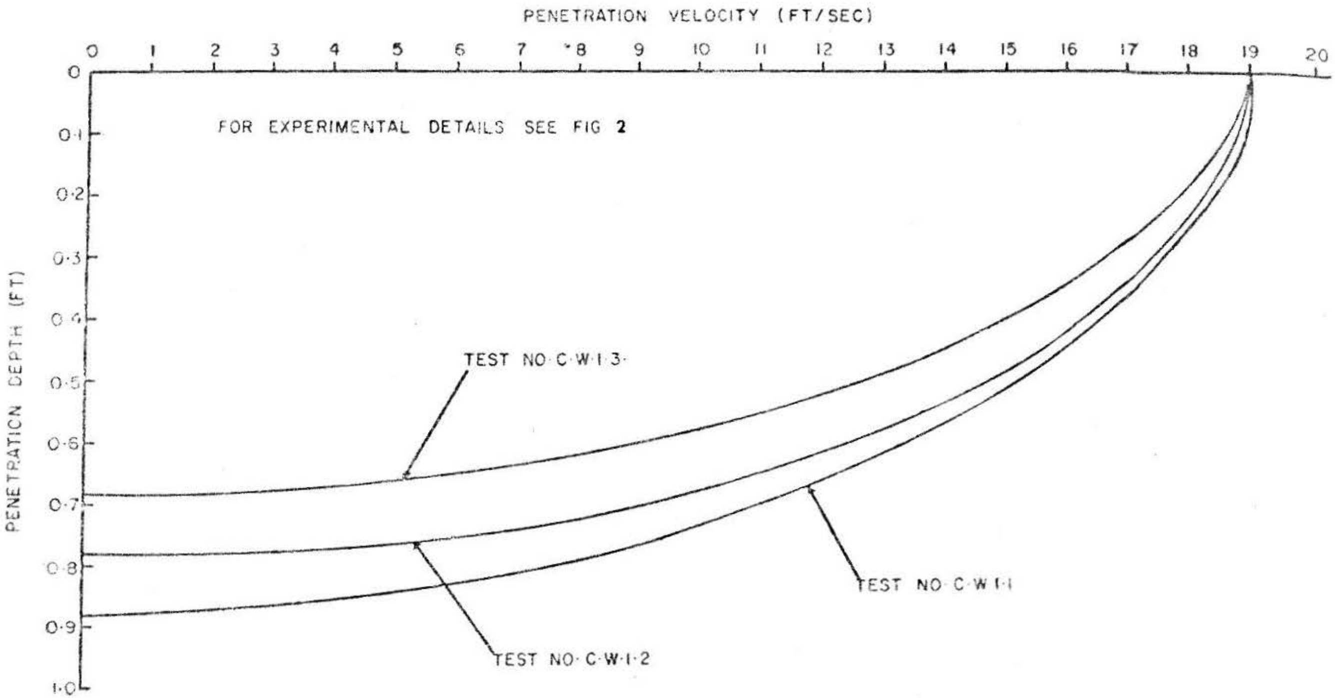

FIGURE 3 Plot of Penetration depth vs. velocity for different weights (1 FT = 0.305 M; 1 FT/SEC = 0.305 M/SEC)

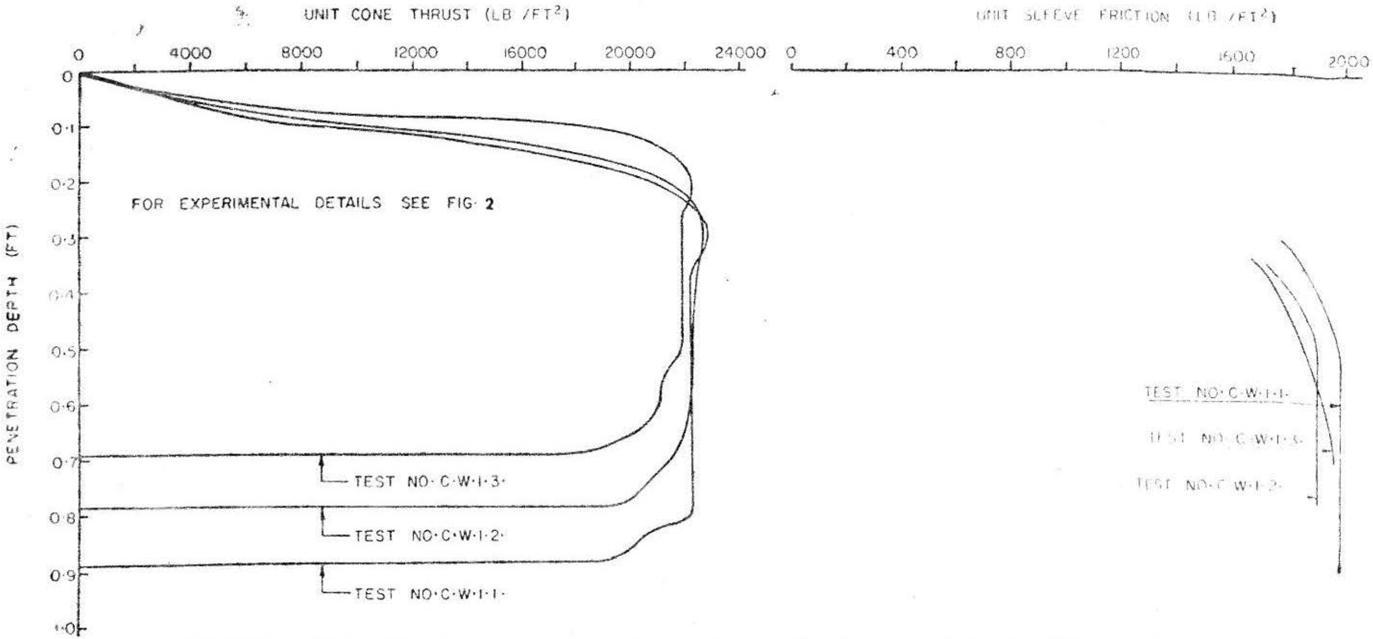

FIGURE 4 Plot of Penetration depth vs. unit cone thrust and unit sleeve friction for different weights (1 FT = 0.305 M; 1 LB/FT² = 47.9 N/M²)

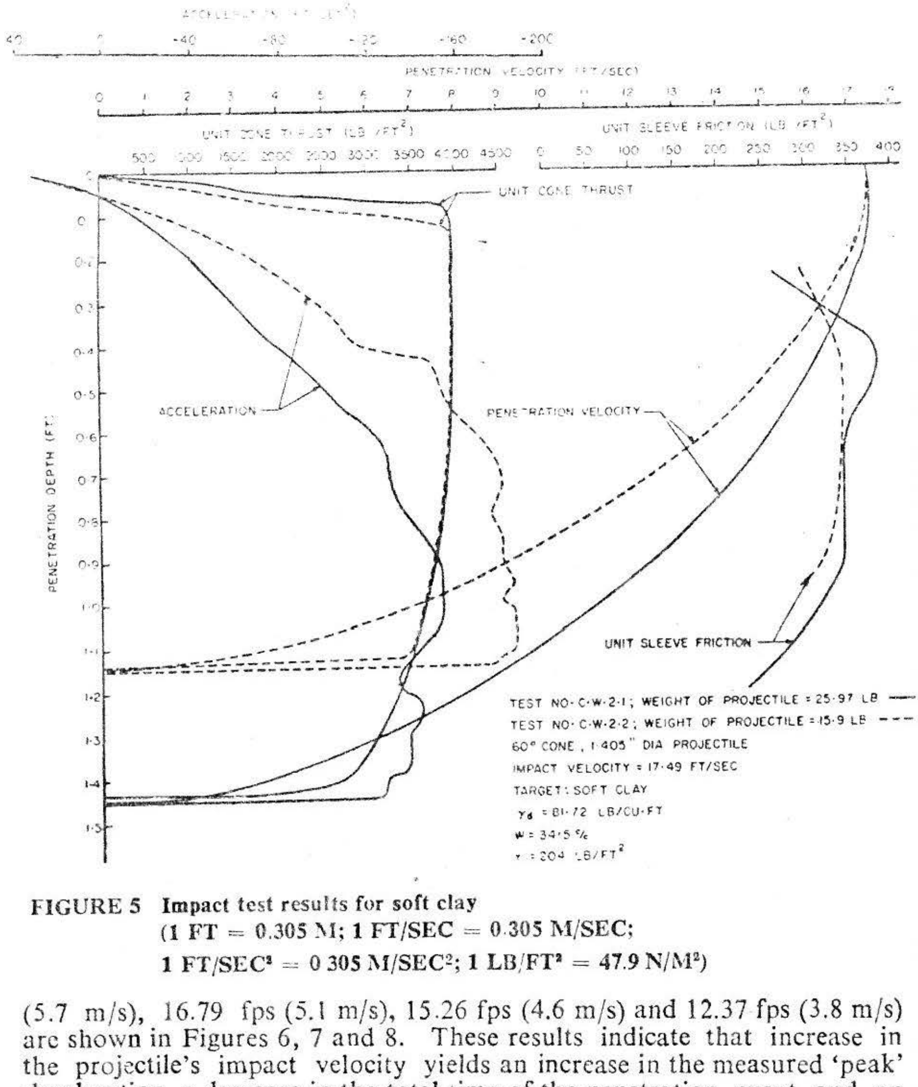

FIGURE 5 Impact test results for soft clay
(1 FT = 0.305 M; 1 FT/SEC = 0.305 M/SEC;
1 FT/SEC² = 0.305 M/SEC²; 1 LB/FT² = 47.9 N/M²)

(5.7 m/s), 16.79 fps (5.1 m/s), 15.26 fps (4.6 m/s) and 12.37 fps (3.8 m/s) are shown in Figures 6, 7 and 8. These results indicate that increase in the projectile's impact velocity yields an increase in the measured 'peak' deceleration, a decrease in the total time of the penetration event and an increase in total penetration. For approximately up to 60 per cent of the total penetration depth, the rate of gradually increasing deceleration and its magnitude are more or less the same for the tested velocity range. Furthermore, the increase in impact velocity generally yields an increase cone thrust and sleeve friction values. This is attributed to velocity effects on cone and sleeve friction resistance (Dayal et al 1974*a*).

The effects of impact velocity and the weight of projectile on the penetration mechanism have been studied by several investigators. In contrast to the present investigations of low velocity impact and high frontal loading, their studies were mostly on high velocity impact and low frontal loading, but their results show qualitative agreement with the above mentioned conclusions.

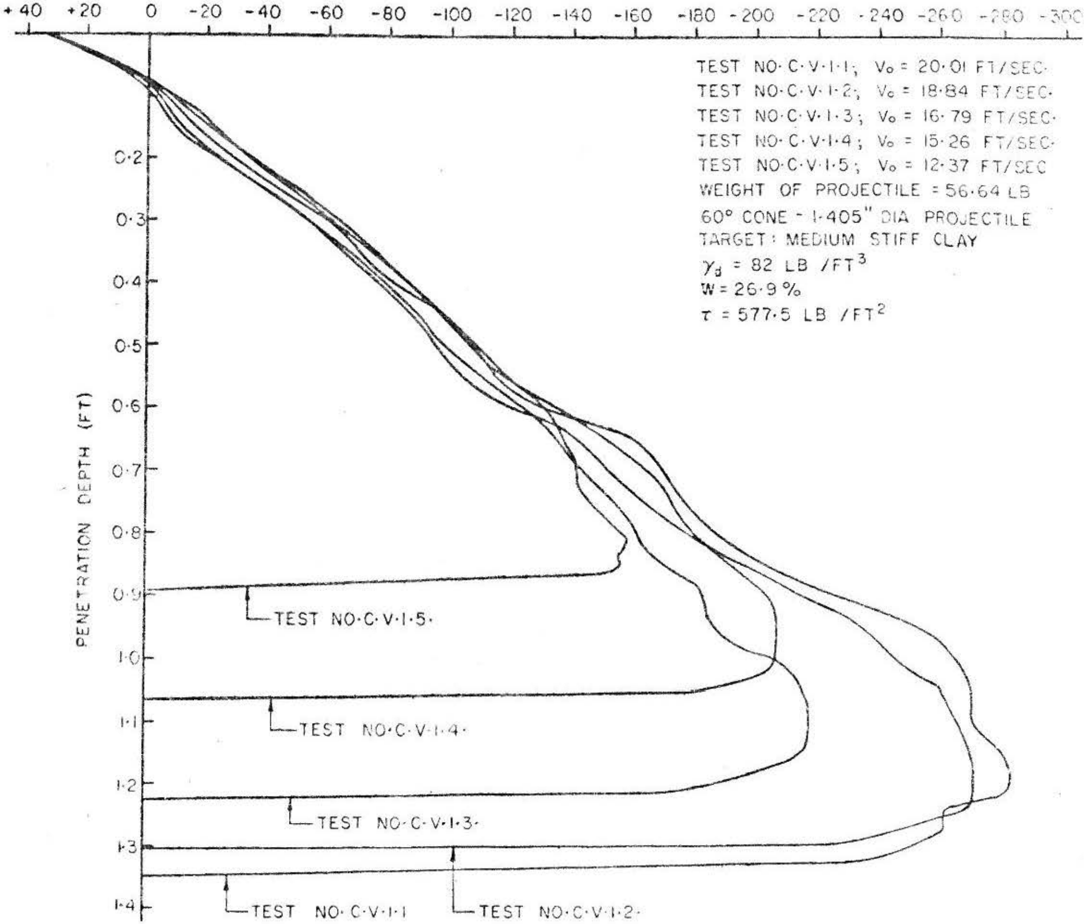

FIGURE 6 Plot of penetration depth vs. acceleration for different impact velocities
(1 FT = 0,305 M; 1 FT/SEC² = 0.305 M/SEC²)

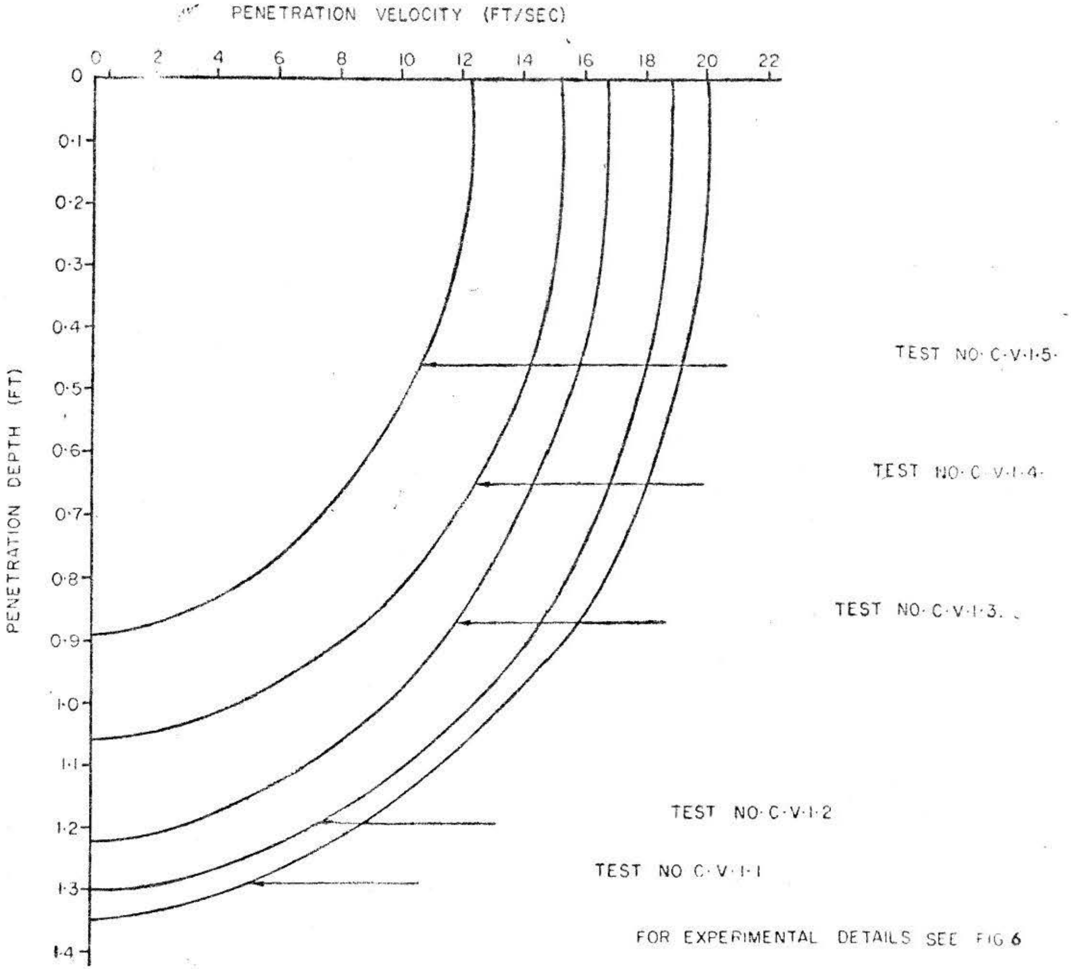

FIGURE 7 Plot of Penetration depth vs. velocity profile for different impact velocities (1 FT = 0.305 M; 1 FT/SEC = 0.305 M/SEC)

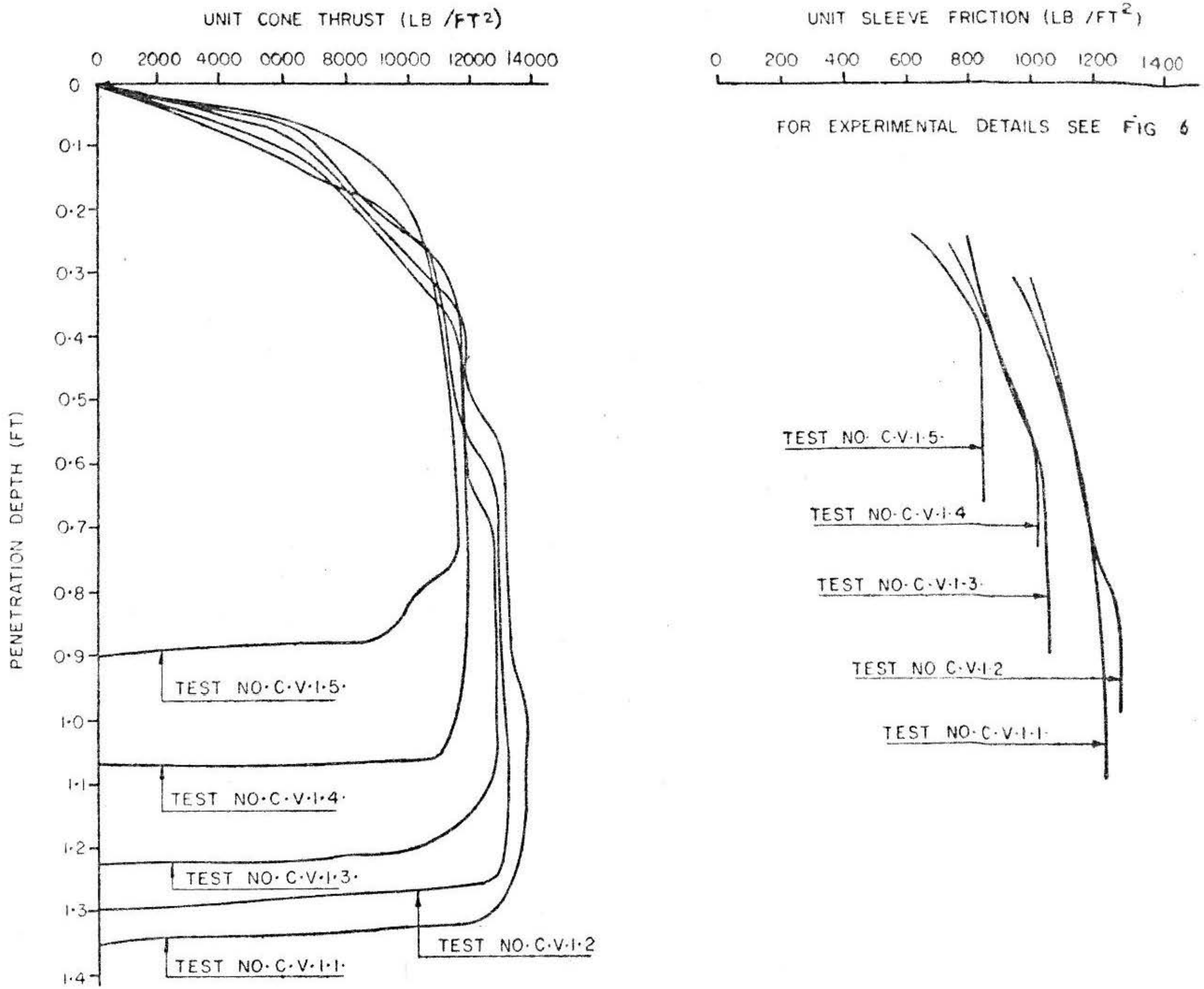

FIGURE 8 Plot of Penetration depth vs. unit cone thrust and unit sleeve friction profile for different impact velocities (1 FT = 0.305 M; 1 LB/FT² = 47.9 N/M²)

Nose Shape

Test results for four nose shapes (30°, 60°, 90° and blunt nose) are plotted in Figures 9, 10 and 11. Those results confirm the intuitively obvious findings of previous investigators (Murff et al 1972, Thompson 1966, young 1969) that the increase in nose sharpness yields an increase in the total penetration. The blunt nose projectile experiences a very high deceleration at impact (several attempts were made in the present investigations to measure the peak deceleration at impact, but it was much higher than that of the rated range of the accelerometer) but after that deceleration trace is similar to that of other end shapes.

Table 2 shows the average cone thrust and sleeve friction obtained from impact tests for different end shapes. An examination of Table 2 reveals that the maximum and minimum cone resistances are offered to the blunt and 60° cone, respectively. Contrary to the general belief (Thomson 1966, young 1969), it is seen that the 30° cone encounters more resistance than the 60° cone. The cone resistance ratio is given in column 5 of Table 2 for different cone angles with respect to 60° cone. Similarly, column 6 of Table 2 shows the ratio of Meyerhof's (1961) bearing capacity factor (N_{cr}) for a different cone angle to the 60° cone angle. The trend of the experimentally observed values is similar to that for Meyerhof's theoretical ratios calculated for the 'static' condition.

The sleeve friction records indicate that the increase in cone angle causes a decrease in sleeve friction resistance. The sleeve friction resistance for a blunt shape is approximately 35 per cent lower than the 30° cone. However, the combined effects of cone and friction resistance produce little difference and thus a small difference is observed in the total penetration depth. It is noted that, in spite of the higher cone and friction resistances for a 30° cone, a 60° cone yields lower penetration depths than a 30° cone. This is because of the geometrical shape viz., 30° cone provides a lesser surface area than a 60° cone for the same height.

TABLE 2

Cone and Sleeve friction resistances for different nose shapes

Test No.	End Shape	Cone Thrust in (psf)	Sleeve Friction (in psf)	Penetration depth in ft	Ratio of cone pressure w.r.t. 60° cone	
					Experiment	Meyerhof's theoretical
	1	2	3	4	5	6
C.S.1.1.	30°	32600	2110	0.82	1.2	1.02
C.S.1.2.	60°	27000	2075	0.803	1	1
C.S.1.3.	90°	33200	1825	0.745	1.23	1.04
C.S.1.4.	Blunt end	42000	1550	0.7	1.55	1.2

Note : 1 psf = 47.9 N/m², 1 ft = 0.305 m.

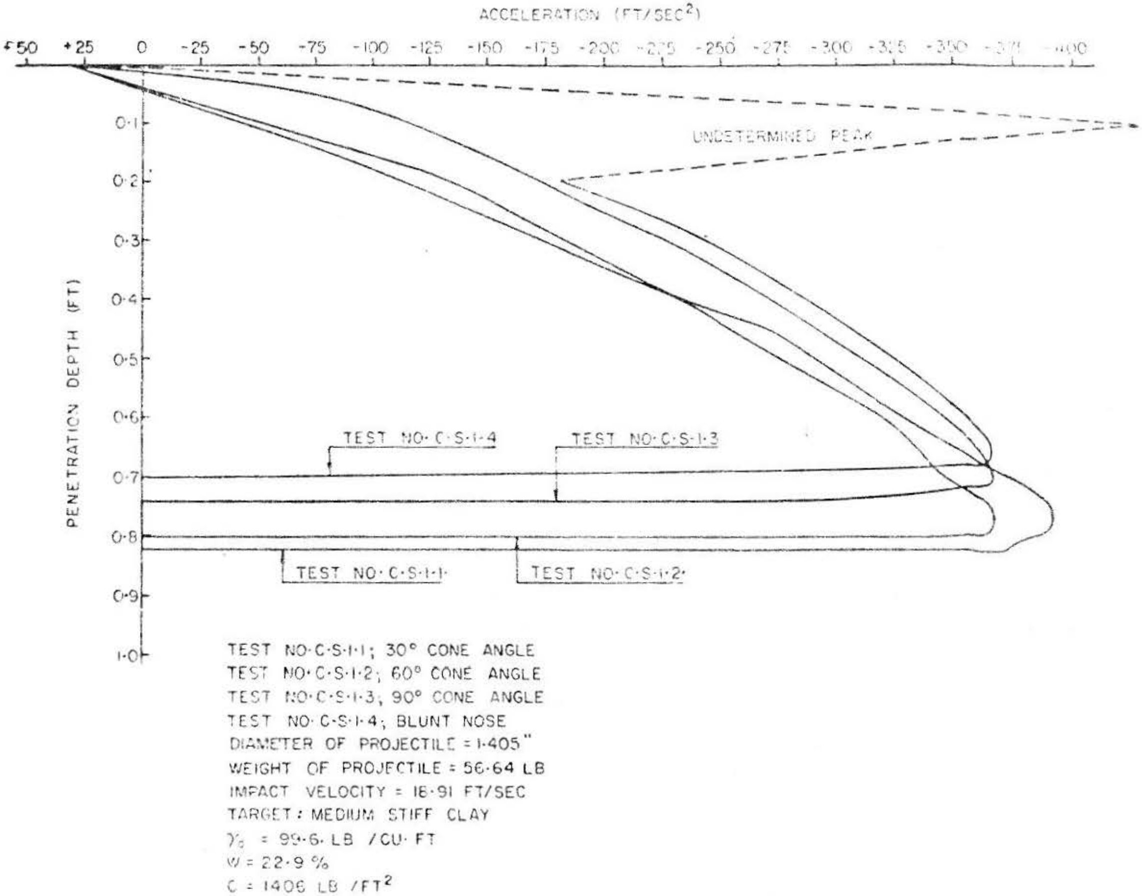

FIGURE 9 Plot of Penetration depth vs. acceleration for different nose shapes (1 FT = 0.305 M; 1 FT/SEC² = 0.305 M/SEC²)

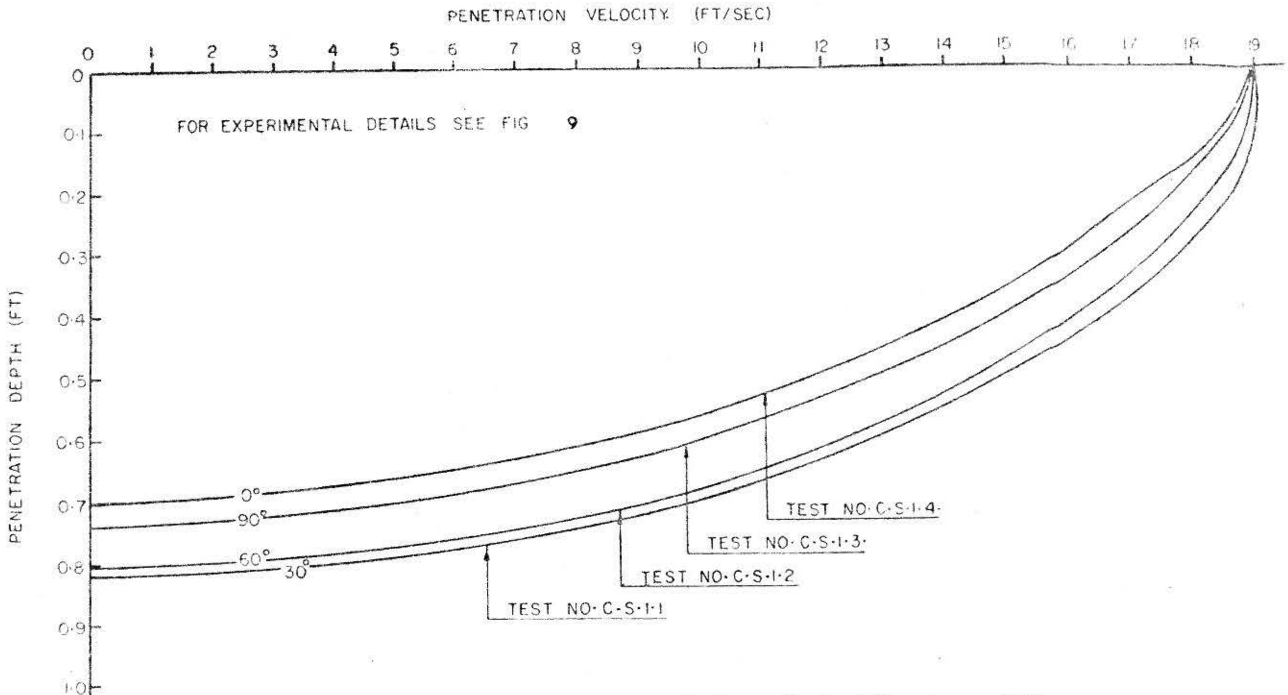

FIGURE 10 Plot of penetration depth vs. velocity profile for different nose shapes 1 FT = 0.305 M; 1 FT/SEC = 0.305 M/SEC)

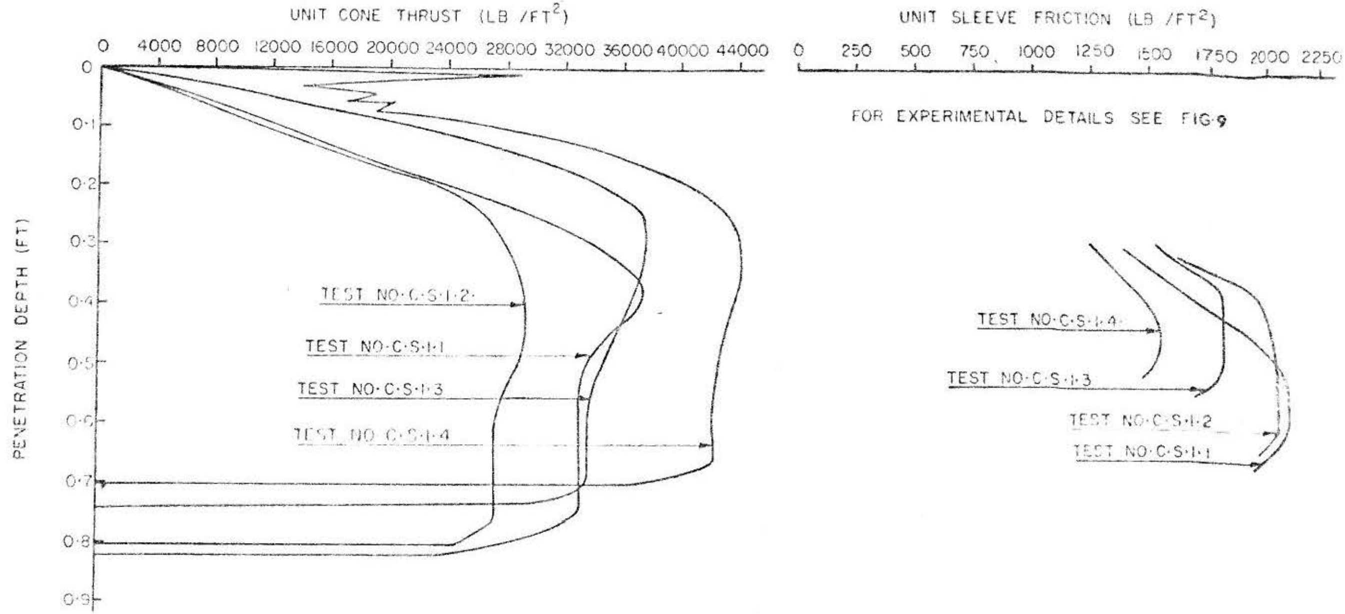

FIGURE 11 Plot of penetration depth vs. unit cone thrust and unit sleeve friction for different nose shapes (1 FT = 0.305 M; 1 LB/FT² = 47.9 N/M²)

TABLE 3

Test Results For Different Target Strengths

Test No.	Wt. of Projectile in lb	Impact Velocity in fps	Taget Strength (τ) in psf	Dry Unit wt. in lb/cu ft	Moisture Content %	Peak deceleration in ft/sec²	Cone Thrust in psf	Sleeve Friction in psf	Penetration Depth in ft.
C.V.1.2.	56.64	18.84	577.5	82	26.9	268	12800	1250	1.3
C.W.1.1.	56.64	18.89	1066	91	23.9	357	22000	1990	0.886
C.S.1.2.	56.64	18.89	1410	89.6	22.92	365	27000	2075	0.803

Note: 1 lb = 0.453 kg; 1 ft = 0.305 m; 1fps = 0.305 m/s; 1 ft/sec² = 0.305 m/sec²; 1 psf = 47.9 N/m².

Target Strength

Three test results are abstracted in Table 3 to show the effect of target strength on penetration event. As expected, these results indicate that an increase in target strength yields an increase in 'peak' deceleration, a decrease in total penetration, and an increase in cone and sleeve friction resistances.

Conclusions

Low velocity projectile penetration tests were performed on clay targets under controlled conditions with a projectile instrumented with accelerometer, cone thrust and sleeve friction measuring devices. This instrument provided a rational approach for explaining the penetration mechanism and quantifying the various previously reported qualitative observations.

The total resistance on a projectile is made up of two parts, resistance on the nose and resistance along the side. Those resistances are found to be more or less depth invariant (beyond the depth of 2D) but increasing with velocity.

The penetration is found to increase as the weight of projectile increases and also with impact velocity. The magnitude of cone and sleeve friction resistances are not influenced by the weight of the projectile. However, these resistances are highly influenced by the strength of target and end shapes of the projectile. It is found that the 60° cone-shaped projectile offers the minimum resistance and the blunt one the maximum.

References

CARDEN, H.D., "Experimental Study of the Application of the Penetrometer Technique to the Lunar Surveying Staff Concept", *Langley Research Center*, Langley Station, Hampton, Virginia, NASS TND—3937,1967.

CAUDLE W.N., (1967), "et al", "The Feasibility of Rapid Soil Investigation Using High Speed Earth Penetrating Projectiles", *Proc. Int. Symp. Wave Propag. Dyn. Prop Earth Mater., ASCE*, Albuquerque, N.M., pp. 945-955.

CLARK, L.V., and McCarty, J.L., (1963), "The Effect of Vacuum on the Penetration Characteristics of Projectile into Fine Particles", *Langley Research Center*, Langley Station, Hampton, Virginia, NASA TND—1519.

DAYAL, U-, (1974), "Instrumented Impact Cone Penetrometer", *Ph. D Thesis*, Memorial University of Newfoundland, St. John's, Newfoundland.

DAYAL. U. and ALLEN, J.H., (1973), "Instrumented Impact Cone Penetrometer", *Canadian Geotechnical Journal*, Vol. 10 No. 3, pp. 397-409.

DAYAL, U. and ALLEN, J.H., (1974 a), "Penetration Rate Effect on Soil Strength", *Proc. 27th. Canadian Geotechnical* Conference. Edmonton.

DAYAL, U. and ALLEN, J.H., (1974 b), "Discussion on "Low Velocity Penetration of Kaoline Clay", *Journ. of the Geotechnical Engineering Division*, ASCE, Vol. 100, GT 1, pp. 85-86.

DAYAL, U., ALLEN, J.H., and JONES, J.M., (1975), "Use of an Impact Cone Penetrometer for the Evaluation of the In-Situ Strength of Marine Sediments", *Marine Geotechnology*, Vol. 1, No. 2, pp. 73-89.

FUCHS, OTTO, P., (1963), "Impact Phenomena", *AIAA Journal*, Vol. 1, No. 9, pp. 2124-2126.

HAKALA, W.W., (1965), "Resistance of Granular Medium to Normal Impact of a Rigid Projectile", *Ph. D Thesis, Virginia Polytechnic Institute*, Blacksburg, Va.

HANKS, B.P., and McCart Y, J.L., (1966), "Investigation of the Use of Penetrometers to Determine the Capability of Dast Materials to Support Bearing Load", *Langley Research Center*, Langley Station, Hampton, Virginia, NASA TND-3200.

McCART Y, J.L., and CARDEN, H.D., (1968), "Response Characteristics of Impacting Penetrometers Appropriate to Lunar and Planetary Mission.,' *Langley Research Center*, Langley Station, Hampton, Virginia, NASA TND-4454.

McNEILL, R.L., (1972), "Rapid Penetration of Terrestrial Materials—The State of The Art", *Proc. Conf. on Rapid Penetration Terr. Mater.*, Texas A & M Univ., Texas, pp. 11-126.

MEYERHOF, G.G., (1967), "The Ultimate Bearing Capacity of Wedge Shaped Foundations", *Proc. Fifth Int. Conf. Soil Mech. Found. Eng.*, Paris, Vol. 2, pp. 105-109.

MITCHELL, J.K. QUIGLEY, D.W., And SMITH, S.S., (1969), "Impact Records as a Source of Lunar Surface Material Property Data", Final Report, 1, NASA contract NASR 05-003-189, Space Science Lab., Series 10, Issue 28.

MOORE, H.J., (1967), "The Use of Ejected Blocks and Secondary Impact Craters as Penetrometer on the Lunar Surface", Appendix A of Preliminary Geological Evaluation and Apollo Landing Analysis of Area Photographed by Lunar Orbiter III—NASA Report.

MURFF, J.D., and COYLE, H.M., (1972), "A Laboratory Investigation of Low Velocity Penetration", *Proc. Conf. on Rapid Penetration Terr. Mater.*, Texas A & M Univ., College Station, Texas, pp. 319-359.

—— "Low Velocfty Penetration of Kaoline Clay", *Journ. of Soil Mech. Found. Div., ASCE*, 99, No. SM 5, 1973, pp. 375-389.

SCHMID, W.E., (1969), "Penetration of Object Into the Ocean Bottom", *Civil Eng. in the Ocean-II, ASCE*, Miami Beach, Florida, pp. 167-208.

THOMPSON L.J., (1966), "Dynamic Penetration of Selected Projectile Into Particulate Media", Sandia Lab. Rep. SC-R-R-66-376, Albuquerque, N.M.

WANG, L.W., (1971), "Low Velocity Projectile Penetration", *Journ. of Soil Mech. Found. Div.. ASCE*, 97, No. SM 12, pp. 1635-1653.

YOUNG, C.W., (1969), "Depth Prediction for Earth-Penetrating Projectiles", *Journ. of Soil Mech. Found. Div. ASCE*, 95, No. SM 3, pp. 803-817.