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THE MECHANICS OF PENETRATION EQUIPMENT

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This study was undertaken to develope and test the mechanics of penetration equipment for predicting soil resistance under different conditions. Penetration tests were carried out in clay loam soil at different moistures and densities with a penetrometer of 0.115 inch diameter and a cone angle of 60 degrees. The resistance of soil was found to increase linearly with the density of soil at different moistures and decreased with the moisture of soil generally following a quadratic relationship at various densities under nondrying conditions.

The prediction equation for the penetration resistance of soil, derived from the analysis of forces acting on the penetrometer, was found to be a function of depth of penetration, soil density, cohesion (c), angle of internal friction ø, soil to metal friction (μ), and penetrometer diameter. The soil strength parameters (c, ø and μ) were determined with the help of the shear box. The parameters were substituted in the prediction equation to predict the resistance of soil. The mean value of the percentage differences between the measured and predicted values of resistance was computed as −27.88 per cent, the negative sign indicating over-prediction by the prediction equation. One of the major reasons for the differences was that the soil strength values were not determined under the same stress conditions as induced by the penetration equipment.

INTRODUCTION

The importance of developing the mechanics of mechanical equipment used to penetrate soil for predicting soil resistance has long been recognised by engineers. The resistance or physical impedance of soil is greatly affected by tillage and other agricultural operations. Tillage is generally performed to reduce soil resistance, and allow free movement of air and water. Traffic over agricultural land, on the other hand, by tractors, men and animals cause soil compaction which increases the resistance of soil and reduces its permeability to water and aeration. All of these factors greatly affect the quality and quantity of crops grown on the soil. Accurate prediction of soil resistance will, therefore, greatly help the engineers in the careful operation of suitable machines at proper times for increasing plant production.

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In this study, an effort was made to develope and test a theoretical equation for predicting soil resistance offered to a vertical penetrating device operating under different soil conditions.

MATERIALS AND METHODS

(a) *Description of soil.* The soil used for determining the penetration resistance of soil had the following mechanical composition by weight :

Sand	25.9 per cent	(0.050 to 2.00 mm)
Silt	41.3 per cent	(0.002 to 0.40 mm)
Clay	32.8 per cent	(0.002 mm)

The above air dried soil passed through a nine mesh (0.078-inch opening) sieve was weighed and mixed with the necessary amount of moisture by means of an electric sprayer. It was then transferred to plastic boxes ($3\frac{1}{16}$ inch diameter and $5\frac{1}{2}$ inch deep) and compacted to a height of 2 inches.

(b) *Measurement of soil parameters.* The following soil parameters were experimentally determined :

1. Cohesion and angle of internal friction (c, $\varnothing$)
2. Soil-metal friction (μ)

The cohesion and angle of internal friction of soil were determined with the help of Shear Box used by Schafer (1961) employing a shear cylinder with an internal diameter of three inches. Boxes of soil at 12, 16, 20, and 24 per cent moisture contents were compacted to different bulk densities. The maximum torque (M_1) at the moment of failure of each soil was recorded on the dynograph. From this maximum torque, the shear stress was computed from the formula $S = 3\ M_1/2 \wedge r^3_1$, where r_1 is the internal radius of the shear cylinder. The normal stress was obtained by dividing the weight applied on the cylinder by its inner cross sectional area. Four levels of normal stress were considered at each soil moisture and density condition. The linear regression for these values of normal and shear stresses at each soil condition provided the values for cohesion and angle of internal friction corresponding to the intercept and slope of the regression line.

Soil-metal friction was measured in a similar fashion using the procedure demonstrated by Row (1959). A flat steel circular plate having a diameter of 2.5 inches was attached to the shear box. The circular plate was pressed into soil under a vertical pressure. The maximum torque applied through the handle of the box was recorded on the dynograph. Maximum frictional stress (S_f) was calculated from the equation $S_f = 3\ M_2/2 \wedge r^3_2$, where r_2 is the radius of the plate. Five levels of normal stress were considered at each soil moisture and density conditions. The linear regression for these values of normal and shear stresses at each soil condition provided the value for adhesion as intercept and soil-metal friction as slope of the regression line.

The values of cohesion (c), angle of internal friction ($\varnothing$) and soil-metal friction (u) for different soil moistures and densities have been shown in Table 1.

(c) *Measurement of soil resistance.* The resistance of soil was measured with the help of a conical shaped penetrometer which could be moved vertically up or down manually or by means of an electric motor and gearing arrangement. The penetrating tool was attached to a proving ring employing a four strain gage bridge circuit for sensing the resistance of soil. The bridge circuit was connected by means of an input coupler to Offner dynograph fitted with amplifiers, writer element, recording paper operated by a revolving drum, and a regulated power supply unit. The resistance of the soil experienced by the penetrometer when moved through the soil box could be measured with the help of the dynograph at a desired amplifier sensitivity.

The maximum values of force (soil resistance), measured by a conical shaped penetrometer having a diameter of 0.115 inch when moved through a two-inch depth of nondried soil kept in a constant temperature room of 20°C, have been shown in Table 1 for different soil moistures and densities. Each value of the force recorded in the Table is the average of three values obtained on each of the three soil boxes (replications).

(d) *Development of mechanics.* The equation for predicting soil resistance was developed with the help of the principles of mechanics.

Figure 1a represents a round shaped steel penetrometer actuated by a vertical force F, for entering the soil surface. Consider a small slice of the cylinderical body of the penetrometer situated at a depth h from the soil surface. It is laterally subjected to the earth pressure (passive) as shown in Figure 1b. A small segment of the slice subtending an angle $d\varnothing$ at the center of the penetrometer and having a circular arc $r\,d\varnothing$ is shown in the figure.

Frictional force between the segment of the slice and the soil is given by

$$dF = u\,p\,r\,d\Theta$$

Where :

dF = frictional force between the segment of slice and soil

μ = coefficient of friction between soil and metal surface
r = radius of penetrometer
p = passive earth pressure
= 2 c tan $(45^\circ + \varnothing/2)$ + w h $\tan^2 (45^\circ + \varnothing/2)$ from Lambe and Whitman (1969)

c = cohesion of soil
$\varnothing$ = angle of internal friction of soil (degress)
w = unit weight of soil
r $d\theta$ = dh = surface area of the segment of slice

Total frictional force between the penetrometer and soil is given as follows :

$$\text{Total frictional force} = u\, r \int_0^L \int_0^{2\pi} p\, dh\, d\theta$$

$$= 2\pi u r \int_0^L p\, dh$$

$$= 2\pi u r \int_0^L [2 c \tan (45^\circ + \varnothing/2) + w h \tan^2 (45^\circ + \varnothing/2)]\, dh$$

$$= D u \pi [2 c L \tan (45^\circ + \varnothing/2) + \frac{w L^2}{2} \tan^2 (45^\circ + \varnothing/2)$$

Where :

D = diameter of penetrometer

RESULTS AND DISCUSSION

(a) *Prediction of soil resistance.* The equation developed above with the help of the principles of mechanics was used in an attempt to predict the force (soil resistance) experienced by the penetrometer. In order to use this equation, the data on cohesion (c) and angle of internal friction ($\varnothing$) of soil, as recorded in Table I, were employed for calculating the soil resistance (force) at different moistures and densities. The values predicted from the equation for a penetrometer diameter of 0.115 inch and soil depth of 2 inches are shown in the last column of the Table. Sample values for 12 per cent moisture and 70 lb/cft density of soil are given below :

w = 70 lb/cft = 0.0405 lb/in^3, c = 0.87 psi, $\varnothing$ = 22.5°,

μ = 0.362, D = 0.115 in, and L = 2 in.

Substitution of these values in the equation gave the calculated value of force (soil resistance) as 0.706 pound.

TABLE 1. *Values of measured and predicted force for nondrying conditions.*

Moisture %	Density	c	ø	μ	Measured force (Lb)	Force predicted from equation
12	70	0.87	22.5	0.364	0.534	0.706
				0.373	0.600	0.747
				0.383	0.634	0.727
	80	1.50	28.0	0.373	1.800	1.382
				0.373	1.834	1.534
				0.414	2.867	1.522
	90	1.31	42.0	0.092	4.133	1.299
				0.331	4.267	1.573
				0.342	4.267	1.522
	100	1.274	46.264	0.290	4.767	2.140
		2.280	45.40	0.300	4.800	2.490
		2.960	42.633	0.290	4.933	2.096
16	70	1.60	13.0	0.269	0.600	0.800
				0.311	0.600	0.925
				0.311	0.633	0.925
	80	1.95	27.5	0.533	1.067	2.480
				0.549	1.133	2.603
				0.549	1.334	2.603
	90	1.08	46.0	0.559	2.133	2.290
				0.590	2.133	2.419
				0.590	2.133	2.419
	100	1.009	47.1	0.455	2.533	1.772
		0.833	47.1	0.538	2.634	1.797
		1.02	45.833	0.466	2.667	1.859
20	70	1.32	2.0	0.414	0.500	0.942
				0.545	0.533	1.013
				0.486	0.567	1.106
	80	2.10	15.0	0.497	1.000	2.015
				0.497	1.067	2.015
				0.497	1.067	2.015
	90	2.30	25.0	0.383	1.467	2.036
				0.404	1.533	2.148
				0.424	1.567	2.254
	100	1.25	43.3	0.466	1.600	9.058
		1.513	41.334	0.476	1.633	2.403
		1.667	40.0	0.507	1.667	2.721
24	70	1.320	8.5	0.197	0.433	0.197
				0.197	0.433	0.197
				0.238	0.467	.537
	80	1.97	16.0	0.311	0.867	1.195
				0.362	0.900	0.591
				0.373	0.933	1.433
	90	1.89	35.0	0.352	0.200	1.899
				0.373	0.233	2.012
				0.404	1.233	2.179
	100	2.138	32.9	0.238	1.233	1.387
		2.719	29.633	0.217	1.300	1.495
		2.862	28.066	0.269	1.367	1.888

(b) *Comparison.* A comparison of the values of measured force (soil resistance) and those calculated from the prediction equation was made in order to test the mechanics of the penetration equipment. Both the measured and calculated (predicted) values of force have been shown in the table. For making statistical analysis and graphical comparisons, it was decided to study the effect of the density of soil on force. Since the range of soil density in the experiments varied from 70 lb/cft to 100 lb/cft, a variable $r' = w - 62.4$ (where w = unit weight of soil, 62.4 = unit weight of water in lb/cft, and w = submerged unit weight of soil) was selected so as to draw the data close to the origin and facilitate its statistical regression analysis. The coefficient of variation for force (F) and r' was computed as a first step towards the regression analysis. It was decided to perform the regression of force (F) on r', where the coefficient of variation for the former was greater or equal to that of the latter. The regression of F on r' and vice versa was carried out when the coefficient of variation for the former was found lower.

Figures 2 and 3 show some of the results, indicating the effect of soil density (r') on force (measured and calculated) at 12 and 20 per cent moisture contents. The confidence bands on the regression lines at 95 per cent level of significance have been shown in the figures. In figure 2, referring to 12 per cent moisture content of soil, the regression lines have been erected through the origin, since their intercepts were detected non-significant. Figure 3 shows the regression of F on r' and vice versa alongwith their final confidence bands, as the coefficient of variation for F was found lower than that of r'. Although the confidence bands for the regression lines did not contain one another, as indicated by the figures, the mean value of the percentage differences, however, between the measured and predicted values of force (as reported in the table) was computed as -27.88 per cent, the negative sign indicating over prediction by the prediction equation. The differences were referred to the following :

(i) The soil strength parameters (c, ϕ and μ) were not determined under the same stress conditions as induced by the penetrometer.

(ii) The force was calculated from the prediction equation, using a maximum soil depth of two inches, whereas the measured force became almost constant beyond a certain depth.

(iii) The soil resistance at the tip of the penetrometer was ignored in the prediction equation.

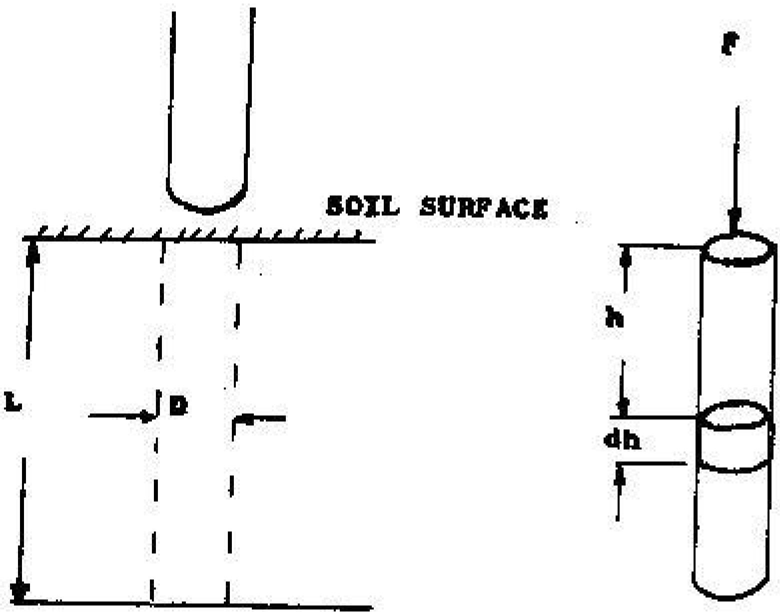

FIGURE 1a. PENETROMETER MOVING VERTICALLY IN SOIL

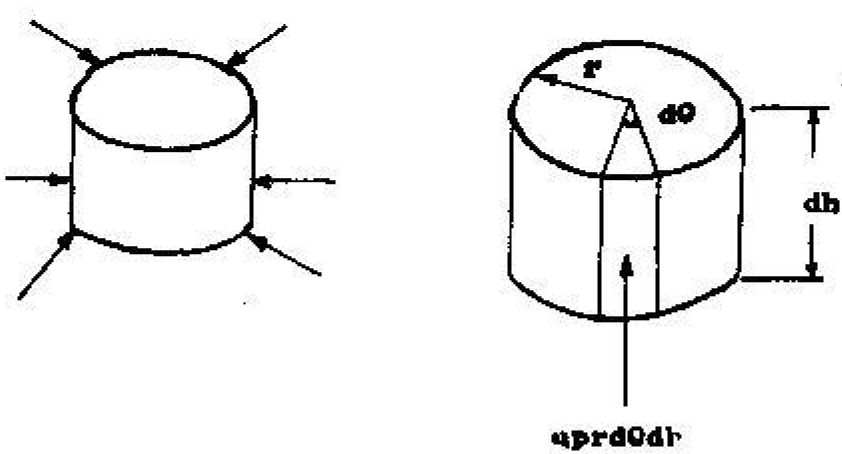

FIGURE 1b. FREE BODY DIAGRAM

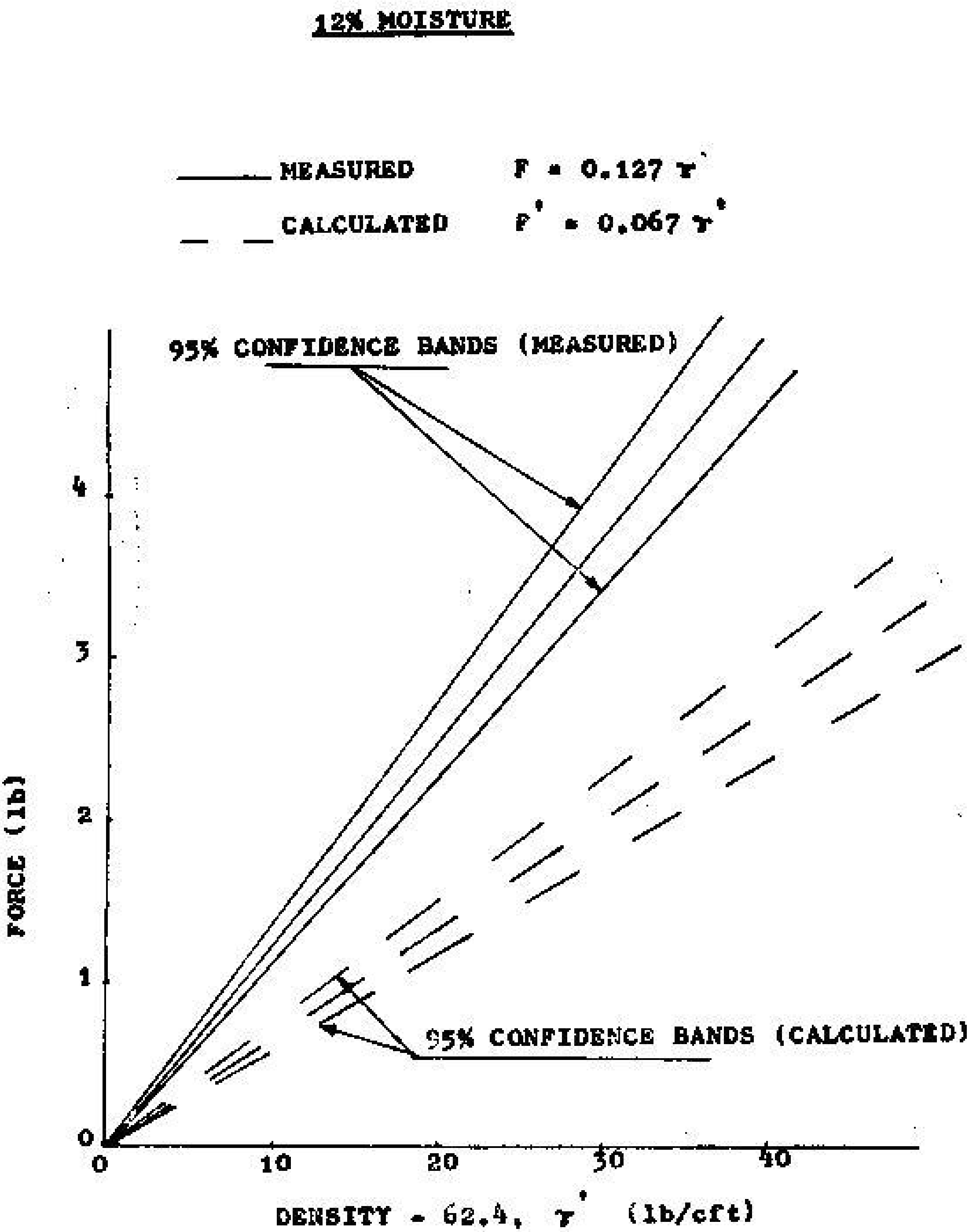

FIGURE 3. COMPARISON OF MEASURED AND CALCULATED FORCES AT 12% MOISTURE CONTENT

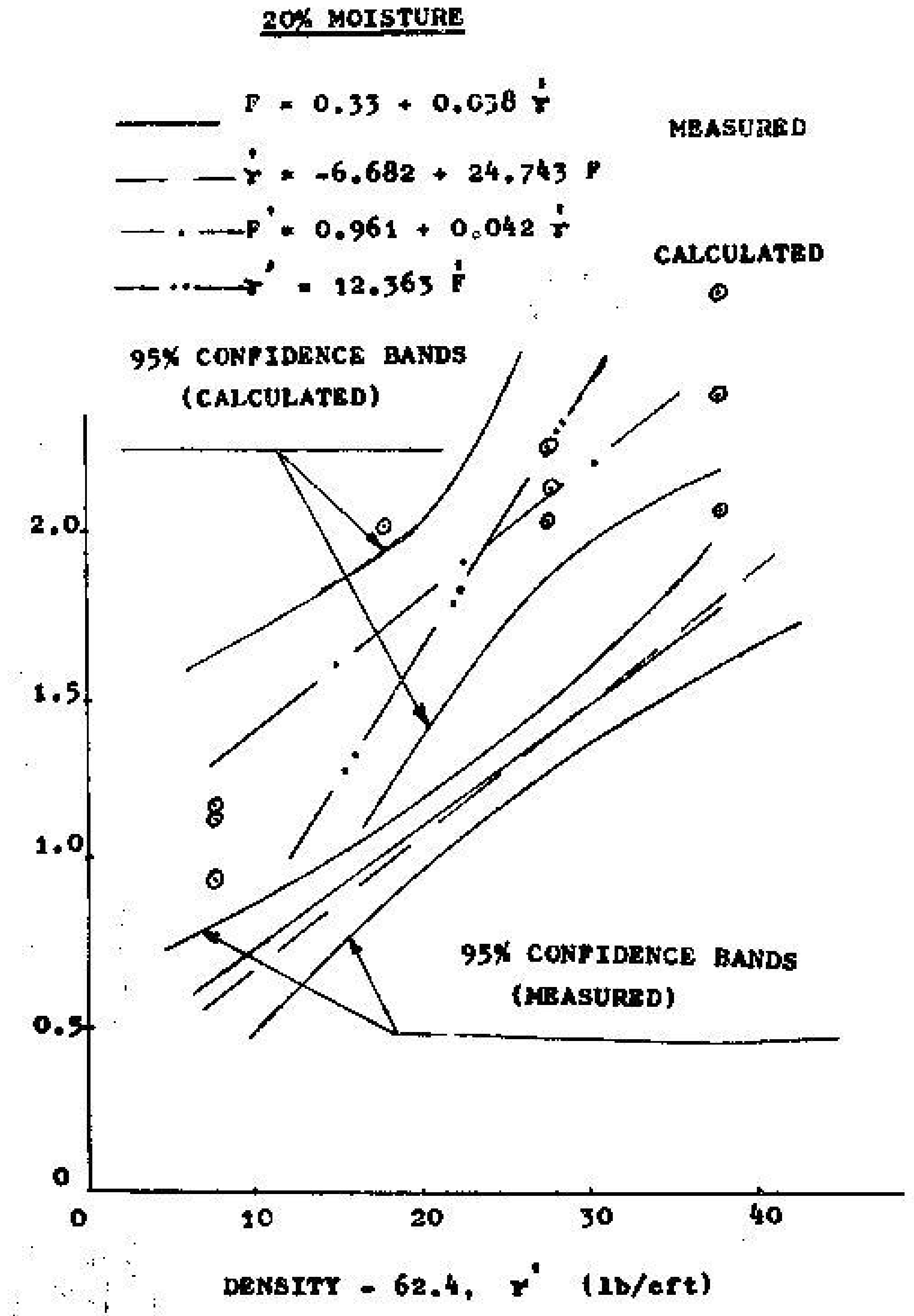

FIGURE 3. COMPARISON OF MEASURED AND CALCULATED FORCES AT 20% MOISTURE CONTENT.

Further, the effect of soil initial moisture on its resistance, under nondrying conditions, was studied. It was interesting to conclude from the statistical analysis of the measured data that the penetration resistance of soil decreased with moisture generally following a quadratic relationship at various densities. This resistance, however, increased linearly with the density of soil at different moistures, as indicated by Figures 2 and 3.

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