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EVALUATION OF PENETROMETERS FOR MEASURING SOIL STRENGTH

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Summary—Cone index, as determined by a cone penetrometer, is frequently used as a measure of soil strength. The index is a compound parameter involving components of shear, compressive and tensile strength and soil metal friction. In order to assess the effect of soil type and condition on the relative contributions of these components to penetration resistance, the forces required to push blunt and sharp probes into two soils under a range of moisture contents and bulk densities were investigated. The maximum penetration force in homogeneous soil was not uniquely related to dry bulk density or cohesion, but varied with soil moisture content.

At high and low moisture contents, the soil tended to interact with the shaft of the penetrometer thus increasing the resistance to penetration. At low moisture content, bodies of compressed soil formed in front of the probe, effectively changing the probe geometry.

It was concluded that interpretation of cone index in typical layered field soils is difficult. Even in homogeneous soils, the proportion of shear, compressive and tensile components that the cone index reflects varies with soil condition.

INTRODUCTION

PENETROMETERS have been widely used in soil studies related to off-the-road traffic and soil cultivation [1, 2]. To facilitate comparisons, 30° right circular cones of base area 323 mm^2 are commonly used. Despite their widespread use and acknowledged value in providing an empirical index for traction studies, relatively little is known about how cone index is affected by soil mechanical properties [3, 4]. The index is clearly a measure of soil strength but to be of fundamental value to traction and cultivation research the relative contributions of shear, compressive and tensile strengths and friction to the index must be known. Hence, experiments have been conducted in sandy and clay soils with blunt and sharp penetrometer probes to relate penetration resistance to bulk density and cohesion over a range of moisture contents.

BACKGROUND

In the constant rate of penetration penetrometer the force required to maintain a steady rate of penetration is considered to be a measure of the consistency of a soil [3]. Results from the Waterways Experiment Station (WES) show little effect of angle or size of cone on penetration pressure in plastic cohesive soil [5]. Dexter and Tanner [6], using steel spheres also found that the maximum penetration pressure on four soils did not vary with sphere diameter except at very small diameters where edge effects became important. Resistance to penetration of soil may be completely altered by the formation of soil bodies on the leading edges of tools. Soil bodies are liable to form on blunt tools such as spheres as mentioned by Gill [4].

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Gill [4] found a minimum value of the cone index at tip angles of 30°–45° in three soils, two of which were approximately saturated. He does not mention the structural condition of the soils. Freitag [3] found that a 30° cone had 10% more penetration resistance than a 90° cone (with the same base area) in clay while in sand the 90° cone had slightly greater resistance. Freitag also found that peak penetration resistance for a lean clay depended on the structural condition of the clay. In a study of over-compaction on lean clay, he found that the peak resistance when the soil was prepared by compacting each layer with 320 blows was only 75% of the value obtained when 50 blows per layer were used.

Richardson [7] found that the force on steel spheres being pushed through soil rises to a maximum limiting value and that the relationship between force and penetration could be approximated by the exponential:

$$F = F_{\max} (1 - k_1 \, e^{-k_2 \, (L/R)}) \tag{1}$$

where F = the force on the steel sphere
$F_{\max}$ = the maximum limiting force on the sphere
L = penetration depth into soil
R = radius of sphere
k_1 and k_2 are constants.

Values of k_1 varied from 0.7 to 0.8 and of k_2 from 0.3 to 1.1. Values of k_2 were lowest for a sand soil at a gravimetric moisture content (θ_w) of 11.9%. In two successive years, k_2 varied from 0.597 to 1.29 on the same site. Later, Dexter and Tanner [6] extended Richardson's work.

It is apparent from the published work that considerable difficulty exists in the interpretation of penetrometer results in terms of soil properties. The performance of penetrometers must be elucidated in controlled experiments.

EXPERIMENTAL PROCEDURE

Controlled experiments with two probes on two soils at a constant rate of penetration of 20 mm/s were carried out using the N.I.A.E. recording soil penetrometer described in [8]. The two probes were (i) a blunt probe consisting of a hardened steel sphere of radius 10.0 mm, (ii) a sharp probe consisting of a hardened steel 30° right circular cone with base radius 10.1 mm. The probes were mounted on shafts of 15.94 mm diameter.

The properties of the sandy clay loam and clay loam soils (subsequently referred to as sandy loam and clay) are shown in Table 1. Both soils were procured by sampling

TABLE 1. PHYSICAL DATA FOR SANDY CLAY LOAM AND CLAY LOAM

Soil	Sand (%)	Silt (%)	Clay (%)	Org. matter (%)	$CaCO_3$ (%)	Particle density (kg/m^3)	Plastic limit (% H_2O)	Liquid limit (% H_2O)
Sandy clay loam	60.4	13.0	26.6	3.5	2.2	2540	21	30
Clay loam	23.0	17.0	60.0	11.0	18.0	2320	39	78

the plough layer to a depth of approximately 230 mm from two regularly cultivated fields. Both soils were allowed to air dry in the laboratory and structural aggregates were broken down. In the case of the clay, an impact hammer was used to break down the drying clods. Each soil was sieved through a 6.35 mm screen and retained stones removed. Each soil was then wetted to pre-determined moisture contents by adding measured quantities of distilled water in a concrete mixer. The soils were then stored in air tight bins and the moisture conditions allowed to equilibrate. Both soils were packed by (i) compression to achieve low densities and (ii) impact hammers to achieve high densities and structural breakdown. The soils were packed in layers of 10 kg of soil in rigid cylindrical steel bins of about 0.04 m^3 with approximate dimensions 380 mm diameter and 380 mm high. The exact volume of each bin was measured by filling with water to overflow. Compression was achieved by loading a rigid lid which just fitted into the bin. Two hammers were used (i) 6.4 kg, 190 mm diameter hammer with a deadweight pressure of 2.2 kPa, (ii) 15.1 kg, 140 mm diameter hammer with a deadweight pressure of 6.9 kPa. These were manually dropped a predetermined height 30 times (6.4 kg) and 40 times (15.1 kg).

The bulk densities and moisture contents of both soils used are shown in Tables 2 and 3. Dry bulk densities (ρ_b) of the sandy loam varied from about 1200 to 1860 kg/m^3 and porosities varied from 52% down to 25%. Saturation ratios varied from 27% to saturation. For the clay the ranges were: bulk density 580–1340 kg/m^3, porosity 75–44%, saturation ratio 26% to saturation.

TABLE 2. BULK DENSITIES AND MOISTURE CONTENTS OF SANDY CLAY LOAM

% H_2O	Bulk Density (kg/m^3)									
6.8	1500									
11.6	1216	1393	1409	1494	1502	1606	1630	1650	1756	1759
14.5	1295	1358	1434	1572	1667	1861				
16.5	1338	1555	1756							

TABLE 3. BULK DENSITIES AND MOISTURE CONTENTS OF CLAY LOAM

% H_2O	Bulk Density (kg/m^3)									
8.2	1343									
12.9	1180	1275	1312							
20.3	1025	1068	1106	1228						
25.9	813	918	983	1038	1129	1257				
29.5	726	866	958	1085	1297					
34.6	678	801	908	1107	1308					
43.5	584	768	892	1179	1187					

Soil strength was measured in two top layers in the packed bins by the N.I.A.E. torsional shear box [9]. Three or four boxes were driven into the soil and the surrounding soil excavated away in the surface 0–50 mm layer. After measurements were completed on the top 50 mm, measurements were then made in the 50–100 mm layer by the same procedure. Sometimes shear took place between two packings despite keying and these results were discarded. Angle of internal friction could not be satisfactorily derived for loosely packed soils because of slip sinkage of the shear box.

After the strength measurements were completed, soil penetrations were made at two levels viz. at 100 mm and about 230 mm below the top of the bin. The stroke of the penetrometer was about 125 mm. Two penetrations of each probe were made at each level on the dry soils and three penetrations with each probe at each level in wet soft soils.

RESULTS

Limit values

The penetration force increased with penetration depth to a limit value as shown by Richardson [7]. Limit values were obtained in all the sandy loam packings and in the clay packings with a moisture content (θ_w) of 20.3 % or greater. Results for the sphere in the sandy loam are shown in Fig. 1 and for the cone in the clay in Fig. 2. They show that with increase in moisture content the relationship between limit force and bulk density changes from a rapidly increasing curvilinear form to a linear relationship when the soil is near and above the plastic limit. Also the standard errors in general decreased with increasing moisture content. Similar relationships held for the sphere in the clay and the cone in the sandy loam although in the latter case the curvi-

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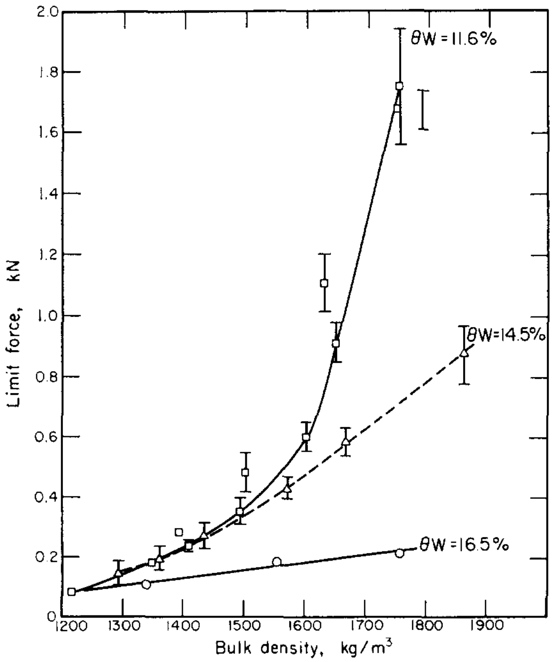

FIG. 1. Limit force for sphere penetrating sandy loam.

linear effect was less evident. It is worth noting that the limit values for both the sphere and the cone in the clay at ρ_b = 1187 kg/m^3, θ_w = 43.5% differed significantly at the 0.1% level from those at ρ_b = 1179 kg/m^3, conforming to the results of Freitag for compaction of a lean clay [3]. In the clay, the lines crossed over each other indicating that the same limit value may be obtained for the clay at the same bulk density with widely differing moisture contents. In the case of the cone (Fig. 2), the lines for θ_w = 20.3%, 25.9%, 29.5% and 34.6% virtually coincided at about ρ_b = 975 kg/m^3. In the sandy loam at low bulk densities (below about 1575 kg/m^3) the lines for the limit values at θ_w = 11.6% and 14.5% were not significantly different.

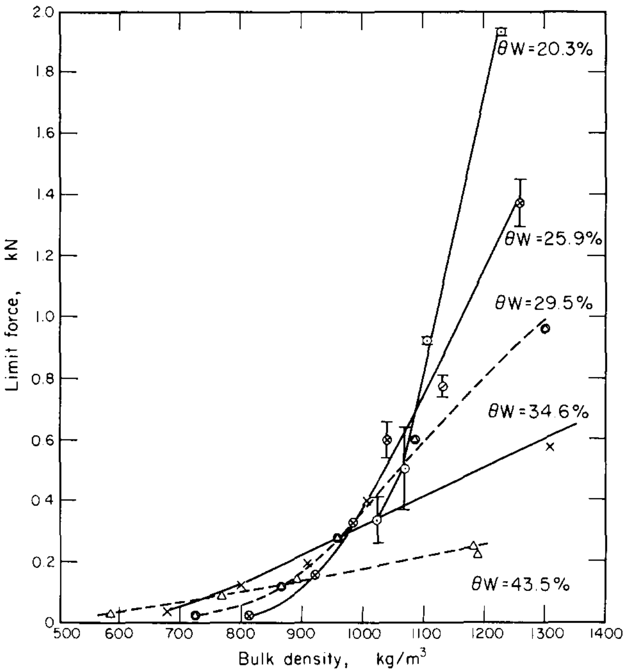

FIG. 2. Limit force for cone penetrating clay.

Limit forces can therefore be used to detect changes of density in highly packed soils only if the moisture content is already known.

Ratio of the limit force on the sphere and cone

In the non-plastic state and at low packing densities the limit force on the blunt sphere was significantly higher than that on the sharp cone (Tables 4 and 5).* In many cases the difference was significant at the 1% level. In the sandy loam, the differences were not significant at bulk densities greater than 1550 kg/m^3 for θ_w = 14.5% and greater than 1350 for θ_w = 16.5%. In the clay, the ratio of limit forces approached unity at high packing densities and intermediate moisture contents (Table 5). Taking the data at θ_w = 34.6% as example, the limit values for the sphere exceeded those for the cone at the 5%, 2% and 1% levels for ρ_b = 700, 800 and

*Densities in this section in Tables 4 and 5 have been rounded to the nearest 50 kg/m^3 for purpose of comparison.

TABLE 4. RATIO OF LIMIT FORCE ON SPHERE AND CONE IN SANDY CLAY LOAM

Density (nearest 50 kg/m^3)	% H_2O		
	11.6	14.5	16.5
1200	1.25	-	-
1300	1.51	1.43	-
1350	-	1.33	1.17
1400	1.28	-	-
1450	-	1.22	-
1500*	1.06, 1.33	-	-
1550	-	1.13	1.04
1600	1.18	-	-
1650	1.25	1.05	-
1700	-	-	-
1750*	1.11, 1.10	-	0.99
1850	-	1.00	-

* two densities near these values

TABLE 5. RATIO OF LIMIT FORCE ON SPHERE AND CONE IN CLAY LOAM

Density (nearest 50 kg/m^3)	% H_2O				
	20.3	25.9	29.5	34.6	43.5
600	-	-	-	-	0.99
700	-	-	-	1.41	-
750	-	-	1.32	-	0.97
800	-	1.29	-	1.41	-
850	-	-	1.62	-	-
900	-	1.44	-	1.22	0.97
950	-	-	1.35	-	-
1000	1.25	1.42	-	-	-
1050	1.21	1.18	-	-	-
1100	1.30	-	0.98	0.95	-
1150	-	1.10	-	-	-
1200*	-	-	-	-	1.00, 1.00
1250	1.03	0.91	0.92	-	-
1300	-	-	-	0.94	-

* two packing densities nearest 1200 viz. 1179 and 1187

900 kg/m^3 respectively. At the bulk densities 1100 and 1300 kg/m^3 there was no significant difference; this coincided with a change from the light to the heavy impact hammer and suggested that the change-over was associated with structural change in the soil. This had already been suggested in the sandy loam where the change from ratio 1.17 at $\theta_w = 16.5\%$ to 1.04 and 0.99 coincided with a change from compression packing to packing with the impact hammers. A change in the structural

state of both soils from crumb/clod to a structureless mass was noted during excavation of the soils from the bins. There was no difference in limit values between the sphere and cone in the plastic clay at $\theta_w = 43.5\%$.

Penetration depth and maximum limit force

Force and penetration data were fitted by computer to equation (1) for the sandy loam and some of the clay penetrations ($\theta_w = 20.3\%$). The value of k_1 in equation (1) varied about 1.0 for the sphere and about 1.6 for the cone in both the sandy loam at all moisture contents and for the only clay analysed ($\theta_w = 20.3\%$). In the sandy loam, the value of k_2 was about 0.3 for both sphere and cone for $\theta_w = 6.8$, 11.6 and 14.5%. In the clay at $\theta_w = 20.3\%$, the mean value of k_2 varied from 0.48 through 1.12 to 1.40 for the bulk densities 1338, 1555 and 1756 kg/m^3 respectively.

Actual data for single penetrations in the clay are shown in Fig. 3 with the force

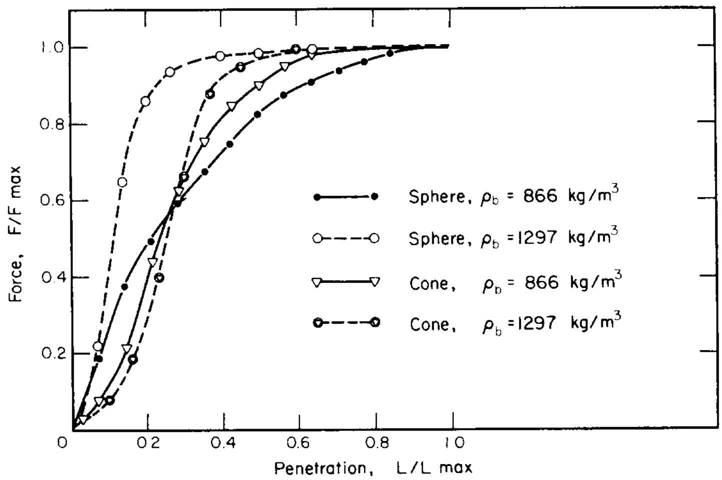

FIG. 3. Normalized force/penetration curves.
Clay: $\theta_w = 29.5\%$.

normalized to the limit force. Bulk density of 866 kg/m^3 was obtained by compression while bulk density 1297 kg/m^3 was obtained by 40 drops of the 15.1 kg hammer through a height of 300 mm. The structural difference in the two packings is shown in Fig. 4. There is a substantial difference in shape between the curves for the sphere but less so for the cone. Both cone curves show a point of inflexion which was always obtained as the cone approached full immersion.

When clay at $\theta_w = 43.5\%$ and $\rho_b = 1187$ kg/m^3 was formed into "puddle" clay by dropping the 15.1 kg hammer 380 mm the limit force was reached very quickly. Ninety per cent of the limit force was reached at 16 mm penetration for the sphere and at 38 mm in the case of the cone.

Failure to reach limit force

No limit force was reached in the case of the clay at $\theta_w = 8.2$ and 12.9% or at $\theta_w = 43.5\%$ for densities of 584, 768 and 892 kg/m^3. In the latter case, the limit could

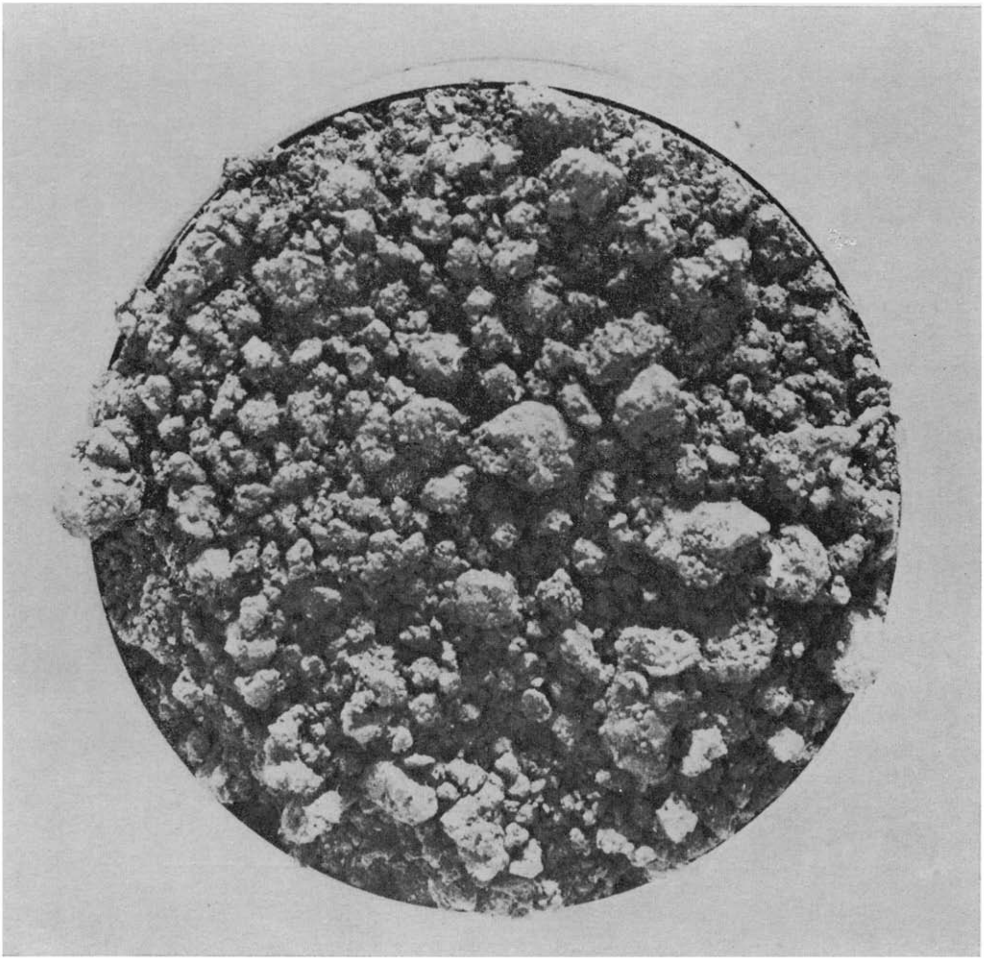

FIG. 4. The structure of the clay. $\theta_w = 29.5\%$. (a) $\rho_b = 866$ kg/cm³.

be deduced by extrapolation and a typical curve is shown in Fig. 5. Failure to reach a limit force was associated with engagement of soil by the shank of the probe except in the case of the soft plastic clay at $\theta_w = 584$ kg/m³.

Soil bodies and limit force

Soil bodies were easily found on excavation of the low moisture clays viz. $\theta_w = 12.9\%$ and 20.3%. The interface surface of the body was shiny and smooth as shown in Fig. 6 and the soil just around the body was of a browner colour than the soil matrix. Bulk density measurements were made of soil bodies under the sphere in the clay at $\theta_w = 20.3\%$ and $\theta_b = 1228$ kg/m³. The result for bodies about 5 mm thick was $\rho_b = 1740$ kg/m³ with a standard error of 10 kg/m³. This is an increase of 42% in bulk density and corresponds to a porosity of 25%. Under the microscope, the clods were observed to be crushed and, at the interface, the whole surface looked

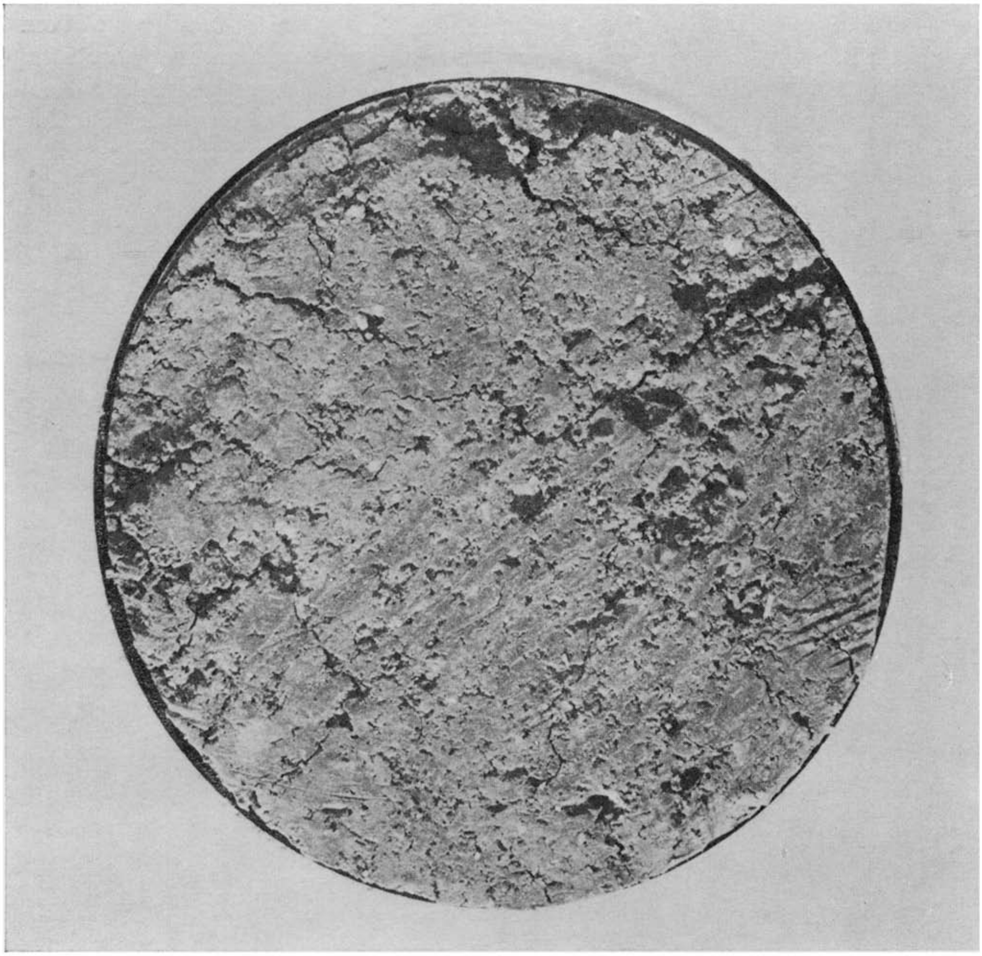

FIG. 4. The structure of the clay. (b) ρ_b = 1297 kg/m^3.

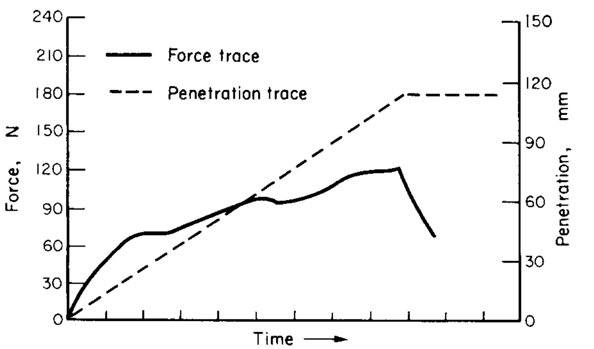

FIG. 5. Effect of soil engaging with the shank of the penetrometer on the shape of the force/penetration curve.
Sphere in clay: θ_w = 43.5%, ρ_b = 768 kg/m^3.

cemented together. In the case of clay at $\theta_w = 8.2\%$, the soil body was only about 1 mm thick. Soil bodies were not easily found in the sandy loam nor in the clay after the cone. It was realized too late that the techniques of excavation used were not sensitive enough to locate soil bodies. For example soil bodies were missed in the top layer of the 8.2% clay and were only detected in the second layer by tilting the bin when the soil flowed and the soil body remained.

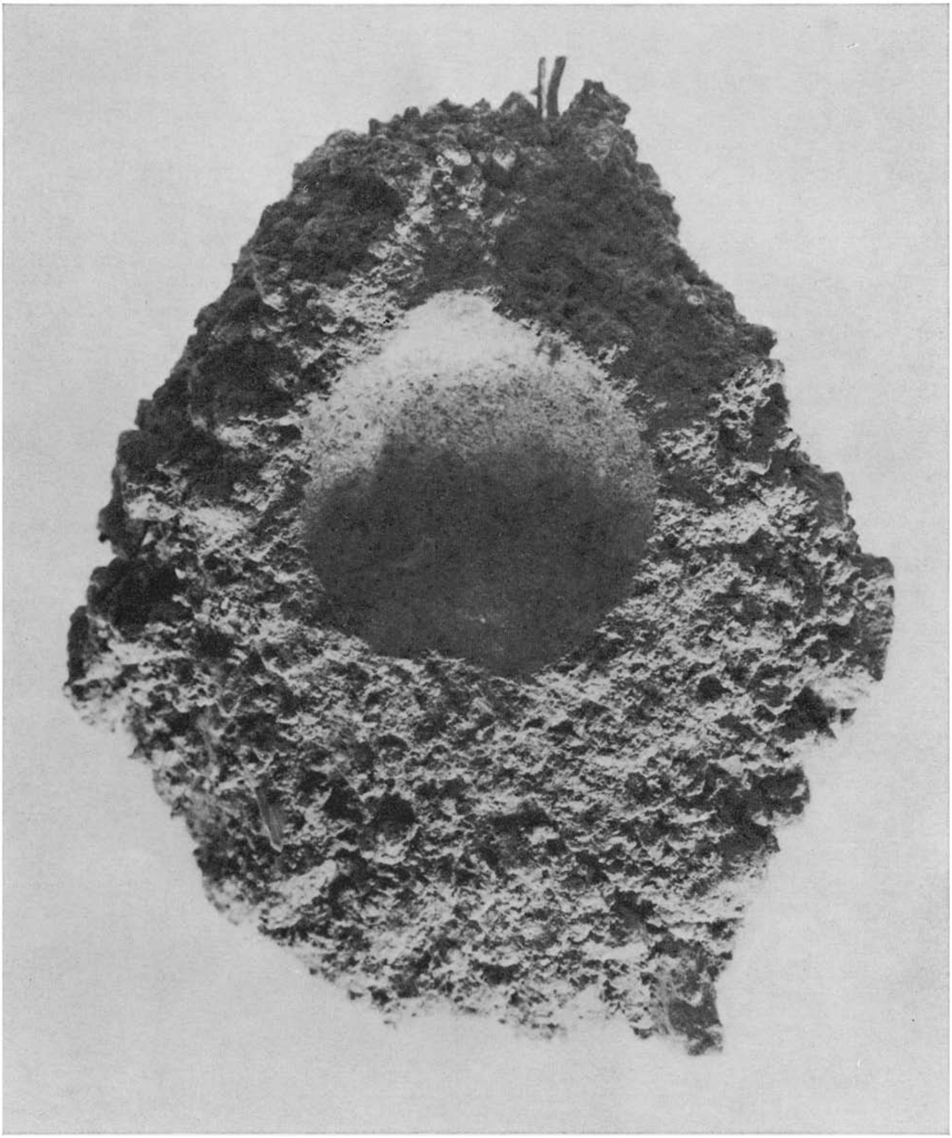

FIG. 6. A soil body recovered after penetration of the clay by the sphere. $\theta_w = 12.9\%$, $\rho_b = 1312$ kg/m^3.

Soil cohesion and limit force

Soil cohesion in the sandy loam (Fig. 7) did not show much dependence on moisture content at lower densities. There was a general tendency for cohesion to increase slowly with bulk density. There was no unique relationship between cohesion and limit values for cone or sphere in the sandy loam (Fig. 8).

In the clay, cohesion increased with bulk density in a curvilinear manner and peak cohesion was obtained at intermediate moisture contents (Fig. 9). Limit forces for the sphere plotted against cohesion in the clay gave a family of curves showing that limit force was again not uniquely related to cohesion (Fig. 10). Similar trends to those of Fig. 10 were also obtained for the cone. The rapid increase in cohesion with bulk density explains the tendency for soil body formation with compaction under the sphere at intermediate moisture contents.

DISCUSSION

Limit values were not uniquely related to density and soil cohesion for either sphere or cone. Limit values plotted against density (Figs. 1 and 2) or cohesion (Figs. 8 and 10) gave rise to a family of curves for each soil.

As the moisture content increased, limit values became less dependent on bulk density. It may be inferred that at high moisture content the penetration force would be independent of soil density. A comparison may be drawn with viscous materials where the resisting force on a body moving through the material depends on the viscosity and not on the density. As the soil becomes drier, compression under and around the probe becomes more important and the penetration force is very dependent on soil density. At intermediate moisture contents, both compression and shear appear to be important.

The hypothesis for the penetration characteristics at high moisture content is substantiated by:

(i) the absence of differences in the limit force between blunt and sharp probes in the plastic state (see Tables 4 and 5),

(ii) the low value of limit force at high moisture contents (Figs. 1 and 2), and

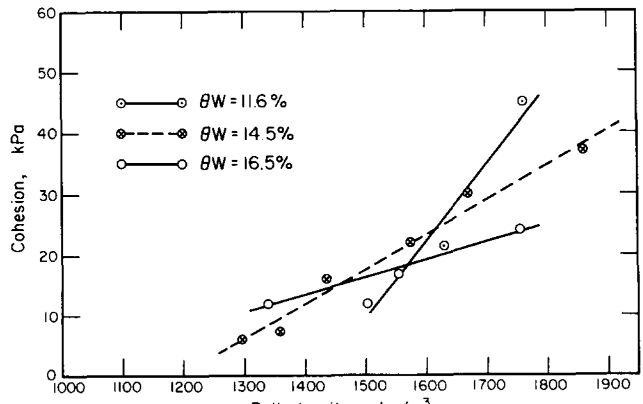

FIG. 7. Cohesion/density relationship for sandy loam.

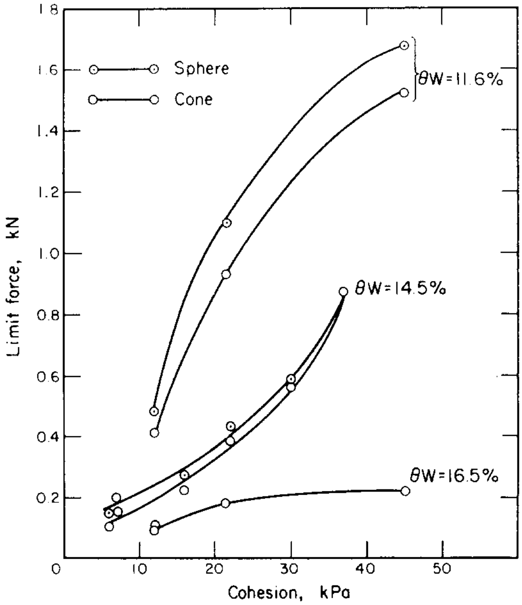

FIG. 8. Limit force/cohesion relationship for sandy loam.

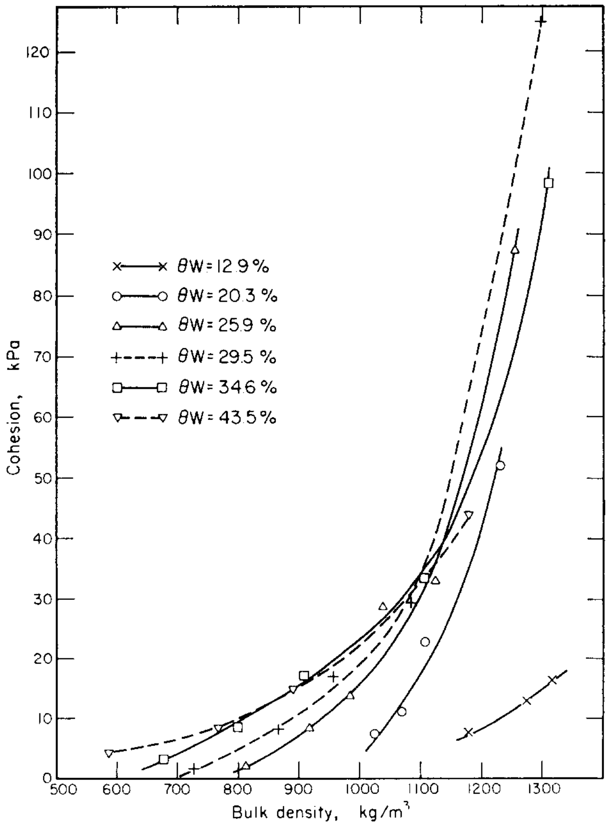

FIG. 9. Cohesion/density relationship for clay.

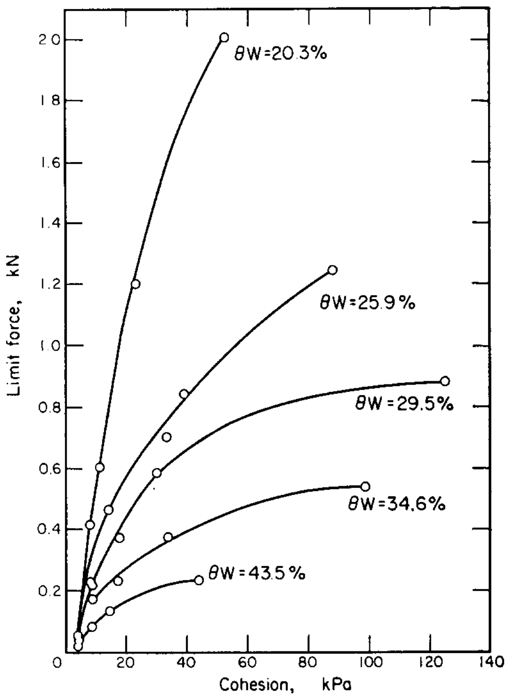

FIG. 10. Limit force/cohesion relationship for sphere in clay.

(iii) the relative insensitivity of limit force to density.

The hypothesis for the penetration characteristics at low moisture content is supported by:

(i) the substantial soil bodies of high bulk density found ahead of the probe at low moisture content, and

(ii) the observed tendency for the angle of internal friction to increase with decreasing moisture content, indicating higher soil strength at lower moisture contents.

In addition, radial cracking of the denser dry soils was observed, indicating that the penetration force reflected a tensile strength component under these conditions. An example of the cracking is illustrated in Fig. 11. The cracking presumably occurred to accommodate compressed soil at depth around the probe.

The relative amount of compression and shear can be altered by the structural condition of the soil; breakdown of the structural aggregates by heavy ramming apparently facilitated shear as illustrated by comparing limit forces for the cone and the sphere in clay at $\theta_w = 29.5\%$ and 34.6% and in the sandy loam at $\theta_w = 14.5\%$ and 16.5% (Tables 4 and 5). The effect of the structural state of the soil is also reflected in the shape of the force penetration curves (Fig. 3).

CONCLUSIONS

The value of the penetrometer in assessing the relative strengths of soils has been questioned by the work reported in this paper. A number of limitations which seriously restrict the usefulness of the instrument have been brought to light; these have not

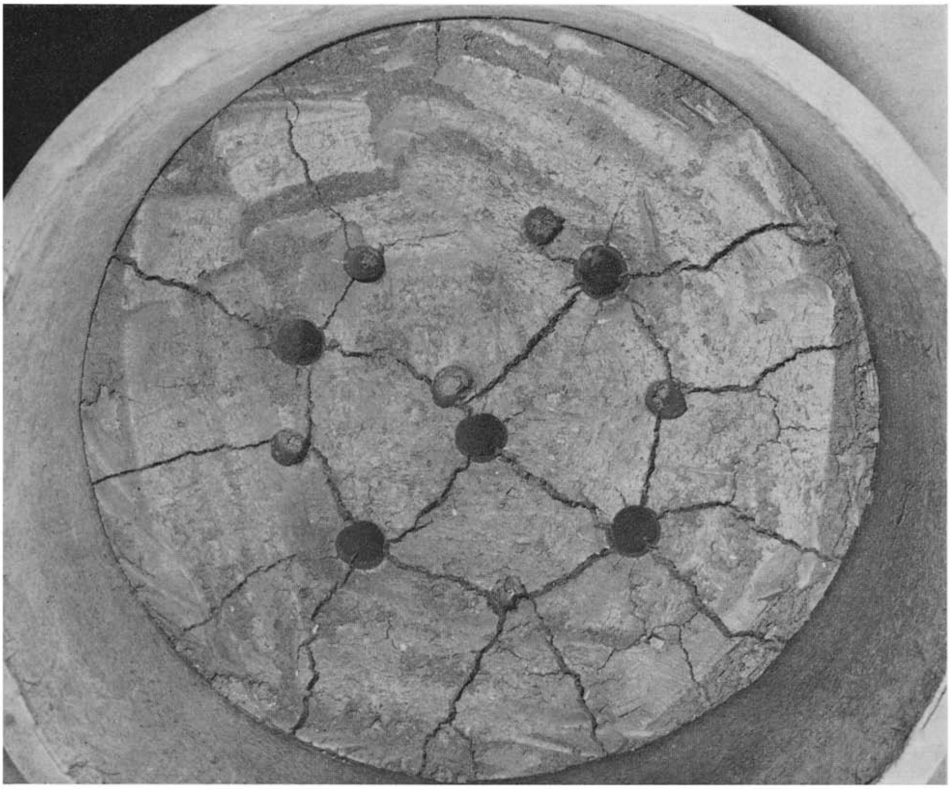

FIG. 11. Radial cracking due to penetration by sphere and cone in clay. $\theta_w = 29.5\%$, $\rho_b = 1297$ kg/m^3.

always been recognized by the users of penetrometers. The following limitations have been observed:

(i) the relative proportions of shear, compressive and tensile strengths reflected by cone index vary with soil moisture content,

(ii) as soil moisture content increases, cone index becomes increasingly insensitive to shear strength or compressive strength changes,

(iii) the formation of soil bodies and compaction zones ahead of the probe effectively change the probe geometry and so penetration force no longer reflects the the original properties of the soil,

(iv) engagement of the shaft of the penetrometer by soil sometimes prevents attainment of the limit force as well as modifying the penetration force/depth curve.

The limitations listed above apply to penetration characteristics in homogeneous remoulded soils. In field soils, where moisture content, bulk density, shear strength and structural state vary rapidly with depth, the interpretation of penetrometer data is subject to far greater ambiguity. In particular, the effects of compaction ahead of the probe and shank engagement cause the cone index measured at a particular depth to be at variance with the true cone index at that depth.

It is concluded that the penetrometer is useful (as it gives results quickly and easily) for comparing the relative strengths of soils under conditions of similar moisture content and structural state. In other cases, supplementary measurements (such as moisture content) must be made. Where a particular strength component (shear, compressive, etc.) is required then it must be obtained by direct measurement (shear box, density determination, etc.).

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