Cone Penetrometer Applications — A Review

J. V. Perumpral
MEMBER
ASAE

ABSTRACT

THIS report provides a history of cone penetrometers, a description of the various types, an explanation of the factors affecting the penetration resistance, and a discussion of possible applications of cone penetrometers.

INTRODUCTION

Cone penetrometers, devices used to sense the penetration resistance of soils, have been in use for many years, and have varied applications in many fields because of their easy, rapid and economical operation. Applications include site exploration, soil strength assessment, trafficability predicitons, and assessment of impedance to root penetration and soil compaction. Major factors affecting the penetration resistance are moisture content, density soil type, penetration resistance, soil strength and base diameter, apex angle and surface roughness of the cone.

History, description of various types of penetrometers used, effect of different factors on penetration resistance and a discussion of possible applications for cone penetrometers are discussed in this paper.

HISTORY OF PENETROMETERS

Even though it is not well documented, there are indications that penetrometers have been in use as early as 1846. A needle-type penetrometer of 1 mm diameter and a mass of one kg was used to estimate the cohesion of different types of clay of various consistencies. In the thirties, penetrometers with 90 deg cones were used to determine the penetration resistance as a function of depth and the strength of clay. During the same period, a pocket penetrometer with a cone tip was developed by Danish Railroads for estimating the cohesion of soil and to determine allowable bearing pressure.

As the instrument became more popular, many versions of hand or machine operated static cone penetrometers of different capacity (up to 10,000 kg) have been developed (Schmertmann, 1975). The wide variety of penetrometers and test procedures resulted in considerable variation in the data collected, and scientists found it difficult to interpret these data correctly. This inconsistency in data prompted the standardization of both the penetrometers and the test procedures.

Considering the simplicity involved in the construction and use of penetrometers for successful evaluation of soil properties, the U.S. Army Corps of Engineers at the Waterways Experiment Station in Mississippi (WES) developed a cone penetrometer in 1948 for predicting the trafficability of vehicles (WES, 1948). This static penetrometer is hand operated and has a maximum penetration of 15 cm. The WES cone penetrometer and its modified versions have seen a number of other applications since then.

TYPES OF CONE PENETROMETERS

Penetrometers have been widely used in many varied applications. Their popularity could be attributed to the following reasons: (a) they are quick, easy, and economical; (b) they provide test data that can be analyzed easily; and (c) they are good tools for investigating sands where undisturbed sampling is difficult. One disadvantage, however, is that they provide no samples for direct observation. Depending upon the problems being studied and the soil conditions, engineers have developed a great variety of both test equipment and test procedures.

CONE PENETROMETERS FOR CIVIL ENGINEERING APPLICATIONS

A comprehensive review of the variety of penetrometers and their use for in-situ measurements is available in Sanglerat (1972) and ESOPT (1974). Based on the procedure employed for the penetration of the tip, and the rate of penetration, Schmertmann (1975) classified penetrometers as shown in Table 1. Among the various types of penetrometers, the quasi-static and dynamic methods of penetration are used most commonly, although the quasi-static method is considered superior because of the usefulness of data that can be collected using this procedure (ESOPT, 1974). This superiority over the dynamic method and the lack of standardization for the testing method has resulted in the development of a tentative test method for deep, quasi-static, cone and friction-cone penetration tests of soil by the American Society for Testing and Materials (ASTM) (Schmertmann, 1978). However details of these tests or penetrometers are not included in this paper, which focuses on agricultural applications of cone penetrometers.

WES CONE PENETROMETER

A cone penetrometer to evaluate off-road vehicle mobility was developed by the Waterways Experiment Station (WES, 1948). This penetrometer has a circular cone with an apex angle of 30° and base area of 1.61 cm^2 (0.5 in^2). It is mounted on a 91.4 cm (36 in.) long graduated shaft of 0.95 cm (0.38 in.) diameter. A proving ring with a dial gage to indicate the penetration

Article has been reviewed and approved for publication by the Power and Machinery Division of ASAE. Presented as ASAE Paper No. 83-1549.

Presented at a special session sponsored by ASAE Subcommittee PM-45/3 Soil Classification and Soil Strength Measurement, S. J. Clark, Chairman.

The author is: J. V. PERUMPRAL, Professor and Acting Department Head, Agricultural Engineering Dept., Virginia Polytechnic Institute and State University, Blacksburg.

TABLE 1. GENERAL CLASSIFICATION OF CONE PENETRATION TYPES*

Penetrometer type	Tip advance method	Rate	Comments
Static	With incremental constant load	0	Extremely slow
Quasi static	Hydraulic or mechanical	1-2 cm/s 10 cm^2	Cone base-10 cm^2 Apex angle 60°
Dynamic	Impact of drop weight	variable	Different size cone, weights etc.
Quasi static and dynamic	Combination of quasi static and dynamic		Uses special tips; uses dynamic when Q-S cannot penetrate
Screw	Rotation of weighted helical cone	variable	
Inertial	Dropped or propelled into soil	variable	good for inaccessible area

*Source: J. H. Schmertmann (1978)

resistance and a handle are mounted on the top of the shaft. The proving ring is calibrated so that the dial gage will indicate soil resistance in terms of force per unit base area, or cone index. Since the penetration resistance recorded depends on many factors—such as the size and shape of cone, rate of penetration and surface roughness—for both uniformity in testing and for convenience in interpreting the results, standards for soil cone penetrometer tests have been established by the American Society of Agricultural Engineers (ASAE, 1983).

When penetrometer tests are conducted, the dial indicator is first set to zero. Then, while the penetrometer is forced into the soil, dial gage readings are taken at every 2.5 cm (1 in.) penetration of the addition, it is difficult to maintain a constant penetration rate of 1829 mm/min (72 in./min) manually during the penetration test.

To reduce the manpower requirements and to avoid manual operation, recording type penetrometers with appropriate mechanism for maintaining a constant rate of penetration have been developed. The first of these modifications included the development of a hand operated recording penetrometer (Carter, 1967; Hendrick, 1969; Prather et al., 1970). The penetrometer developed by Prather et al. (1970) is a light weight penetrometer which could be operated by one person. It has the capability of providing an accurate, continuous recording of the penetration resistance data as a function of depth.

Carter (1969) developed an integrating penetrometer to provide the average soil strength. It consists of a force transducer, an operational amplifier, and a signal generator. Its continuous recording and integrating circuitry, by eliminating the laborious task of manual integration, make it possible to obtain the average penetrometer force.

Wilford et al. (1972) developed a tractor-mounted penetrometer for penetration tests. A hydraulic cylinder is used to force the penetrometer into the soil. An x-y recorder records the penetration data consisting of force-depth relationships at any point across three 1m (40 in.) rows. A similar but electrically operated soil penetrometer was designed by Smith and Dumas (1978) for evaluating soil strength condition across a 3.0 x 0.8 m cross section. The unit can measure cone index values in the range of 0-14000 kPa.

Microcomputer-based cone penetrometers have also been developed for recording penetration resistance. Phillips and perumpral (1983) modified a conventional cone penetrometer to provide an electrical signal corresponding to the penetration resistance by placing strain gages on the proving ring. A microcomputer-based data logger was developed to collect and store the penetration resistance data. Although it provides very good resolution (1 part in 256), the design requires two individuals for conducting tests and recording data. Woodruff and Lenker (1984) designed a manually-operated recording type penetrometer, which can record the penetration resistance data at depth increments of 12 mm to a depth of 100 mm on an electronic data logger. The data logger can store data from 60 to 70 penetration tests each with 48 readings.

Wilkerson et al. (1982) developed a more elaborate test unit for soil strength measurements. It consists of a tractor-mounted hydraulically- operated cone penetrometer designed to operate to a depth of 61 cm (24 in.) over a 4-row width. A microprocessor-based control unit is used to activate all moving mechanisms and to automatically record the data on a magnetic tape. The primary advantage of this system appears to be the labor savings.

CONE PENETROMETER FOR ROOT IMPEDANCE

Cone penetrometers have also been used to evaluate soil resistance to root elongation (Taylor et al. 1966; Camp and Lund, 1968; Greacen et al. 1968; Bowen, 1976). The penetrometers used for this purpose are considerably smaller than those used for the previously described applications. Since no standard exists for this type of application, penetrometers of various sizes, tips, and rates of penetration have been used for the last two decades or more. Among the various cones used, the most common has a base diameter of 3 mm and an apex angle of 60 deg. The rate of penetration is extremely slow, in the range of 0.1 to 1 cm/h.

In an effort to assess the soil mechanical impedance more accurately by simulating root behavior, Tollner and Verma (1984) developed a device called an impedometer. The impedometer is a cone penetrometer with a lubricated cone tip to reduce resistance due to soil-moisture friction. Its effectiveness in determining the mechanical impedance to root growth has not yet been demonstrated.

FACTORS AFFECTING CONE INDEX

Penetration resistance of a cone may depend on many factors. Freitag (1968) discussed the effect of selected factors such as the size of the penetrometer shaft relative to cone base dimeter, surface finish of the cone and penetration rate. He found that penetration resistance (measured force/unit area of cone base) of a cone increases with an increase in shaft diameter, roughness of cone, and penetration rate, decrease in apex angle and diameter of cone base.

Turnage (1970) conducted penetration tests in fine-grained soil at 90% saturation and at various densities. Based on these tests, he developed an empirical relationship between the penetration resistances recorded using standard and the non-standard tests. The relationship is:

$$Cx/Cs = [(Vx/Dx)/(Vs/Ds)]^{N} \quad \ldots\ldots\ldots\ldots\ldots [1]$$

where,

- Cx = average soil resistance using non-standard procedure, kPa
- Cs = average soil resistance using standard procedure, kPa
- Vx = penetration rate for non-standard procedure, cm/min
- Vs = penetration rate for standard procedure, 182.9 cm/min
- Dx = base diameter of the cone used in the non-standard procedure, cm
- Ds = base diameter of the standard cone, 2.03 cm
- N = an exponent depending on soil type (for fine-grained soil, N = 0.1)

In another study a similar relationship was developed for sand (Turnage, 1974)

$$Gx = (G - 1)[0.20 + \{0.80(Ls/Lx)\}] + 1.0 \quad \ldots\ldots [2]$$

where,

- Gx = penetration-resistance gradient in sand obtained using non-standard procedure
- G = sand-penetration resistance gradient obtained using standard procedure
- Ls = square root of the base area of the standard cone (1.8 cm)
- Lx = square root of the base area of the non-standard cone

No velocity terms are included in the relationship because both penetration resistance and sand-penetration resistance gradients are not affected by the penetration rate.

Effect of apex angle on penetration resistance in different soils has been frequently studied. In air-dry sand the penetration resistance increases with increase in cone apex angle (Nowatzki and Karafiath, 1972). In fine-grained soils, increasing the apex angle from 7.5 to 30° decreased the penetration resistance. However, further increases in the apex angle (from 30 to 60 deg), gave a slight increase in the penetration resistance (Gill, 1968).

In addition to the factors listed above, soil type, bulk density and moisture level influence penetration resistance. Experimental studies have shown that the cone index increases with increasing density and decreases with increasing soil moisture level. Penetration tests conducted in air-dry sand under different densities show that relatively large increases in cone index can be expected from small increase in bulk density (WES, 1964; Melzer, 1971; Turnage, 1974).

More extensive studies dealing with cone index-moisture-densities relationships for the fine grained soils have been reported at high moisture levels (20 - 50%) because such soils are more susceptible to trafficability problems (WES, 1958; Knight 1961; Smith, 1964; Turnage, 1970). In the range considered, the penetration resistance decreased logarithmically as a function of soil moisture level for different densities. Voorhees and Walker (1977), in a similar study on silt loam, investigated penetration resistance at different moisture levels ranging from 20-30%. From the results, the following relationship was developed:

$$CI = 4527.75 - 137.09\ MC \quad \ldots\ldots\ldots\ldots\ldots\ldots [3]$$

where,

- MC = percent moisture content (dry basis)
- CI = cone index, kPa

Even though good agreement between experimental and predicted cone index was observed, density effects were not considered during this study.

Collins (1971) developed a similar relationship between cone index and moisture level from a field study as

$$\ln CI = a + b(\ln MC) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [4]$$

where, a and b are constants based on soil types. He observed that cone index decreases with increasing soil moisture level, and the moisture level which produced a particular penetration resistance was dependent upon the percentage of fine and coarse particles in soils. An increase in percentage of fine particles in soil was found to increase that moisture level requirement. The reverse was true for coarse-grained soil.

Knight (1948) investigated the cone index-moisture-density relationship for different soil types. Soils ranging from coarse to fine were considered. Penetration tests were conducted in soil samples prepared in molds using three levels of compactive effort to vary the density. Although many important observations were made during this study, no effort was made to develop any relationships. Observations made during the study were:

1. Penetration resistance decreased as moisture content increased.
2. At high moisture content, density had minimal effect on penetration resistance. However, the reverse was true at low moisture content.
3. Penetration resistance was influenced by soil type.

Results of penetration tests conducted in sandy clay loam and clay loam soils showed that the dependency of maximum penetration resistance on bulk density was greater at lower moisture levels than at higher moisture levels (Mulqueen et al., 1977). During this study, a linear relationship between peak cone index and bulk density was observed at higher moisture content. However, at lower moisture contents, the relationship became exponential. Similar observations were also made by Hayes and Ligon (1977) from the results of penetration tests conducted in clay loam and loamy sand.

Wells and Tresuwan (1977) investigated the penetration resistance of silt loam at three bulk densities and at moisture levels ranging from 2 to 25%. They also observed a reduction in cone index with an increase in soil moisture level. This study also showed that for silt loam at a constant bulk density, the cone index peaks at a moisture content of 15%. For moisture levels of 15% and greater, Wells and Tresuwan employed equation [4] to predict the cone index at constant densities. Close agreement between predicted and experimental results was obtained.

Using results from additional penetration tests in three different soil types (silty loam, silty clay loam, and loamy sand) at two bulk densities and four moisture levels, Wells and Baird (1978) developed two empirical relationships for predicting the cone index and slope of penetration resistance. The equations are:

$$CI = K0 + K1(BD) + K2(PCL) + K3(POM)$$

$$K4(\log MC)^2 + K5(\log MC)^3 \quad \ldots\ldots\ldots\ldots\ldots [5]$$

$$PSL = D0 + D1(BD) + D2(POM) + D3(\log MC)$$

$$+ D4(\log MC)^2 + D5(\log MC)^3 \quad \ldots\ldots\ldots\ldots\ldots [6]$$

where,

CI = cone index, kg/cm^2
BD = bulk density, kg/m^3
PCL = percent clay
POM = percent organic matter
MC = moisture content (wet basis)
K0 - K5 = constants
PSL = slope of penetration resistance
D0 - D5 = constants

Ayers and Perumpral (1982) investigated the influence of density, moisture content, and soil type of cone index. Five soil types were considered by mixing known quantities of Zircon sand and Fire clay. Three levels of density and eight moisture levels in the 2 to 25% range were considered. Following empirical model was developed from the test results to represent the cone index as a function of density and moisture content:

$$CI = (C1 \times DD^{C4})/[C2 + (MC - C3)^2] \quad \ldots\ldots\ldots [7]$$

where,

CI = cone index, kPa
DD = dry density, gm/cc
MC = moisture content, (% dry basis)
C1 - C4 = constants based on soil type

Upadhyaya et al. (1982) developed equations for predicting cone index in certain agricultural soils of Delaware. Using dimensional analysis techniques, they proposed the following prediction equation for silt loam.

$$\alpha(CI/K) = a(\rho/\rho_s)^n e^{-b\varphi} \quad \ldots\ldots\ldots\ldots\ldots\ldots [8]$$

where,

a, b, n are soil constants
C1 = cone index
K = bulk modulus
ρ = dry bulk density
ρ_s = soil particle density
ϕ = soil moisture content
α = nondimensional factor

CONE PENETROMETER APPLICATIONS

Civil engineering has seen a number of applications for cone penetrometers. Previous studies have shown that penetration test results can be used:

1. to derive information on soil type and soil strength (Plantema, 1957; Kondner, 1960; Meyerhof, 1956; Begemann, 1969).
2. to determine the pile-supporting capacity (Van der Veen, 1957; Bogdanovic, 1961).
3. to estimate the compressibility and in-situ density of cohesionless soils (Meyerhof, 1956; Rodin, 1961; Leigh Nixon, 1961; Schultz and Melzer, 1965).
4. to estimate the settlement of footings on sands (DeBeer and Martens, 1957; Schmertmann, 1970).

Other applications include evaluating the uniformity of soil conditions, locating water tables, estimating sensitivity and over-consolidation of clay, and for determining the degree of soil compaction. Use of quasi-static penetration tests for the above mentioned applications is discussed by Schmertmann (1978).

In much of the research reported in the literature, attempts were made to relate penetration resistance to soil strength characteristics. However, very little effort has been directed toward the theoretical analysis of soil-penetrometer interaction. Durgunoglu and Mictchell (1975) developed a theory to predict the cone penetration resistance. The theory is based on the failure mechanism associated with penetration resistance of wedges into soil. Because both penetrometer apex angle and surface roughness influence penetration resistance significantly, new equations for bearing-capacity factors that incorporate these parameters were derived for the failure mechanism. Empirical shape factors were also suggested to adapt the factors developed for wedges to analyze the cone penetration resistance.

Karafiath and Nowatzki (1978) analyzed the cone penetrometer problem by applying plasticity theory. They concluded that:

1. Cone penetration resistance represents the strength properties of relatively incompressible soils. The smaller the apex angle the larger the relative volume of soil to be compressed. The volume of soil affected also increases with the depth of cone.
2. The penetration resistance of cone depends more on the shear strength mobilized at the interface than on the shear strength of the soil mass.

The WES cone penetrometer is used to predict the soil trafficability for off-the-road vehicles. Using a procedure developed at the Waterways Experiment Station, the Corps of Engineers has demonstrated the use of penetrometer readings for predicting the number of passes of certain vehicles a particular terrain can support (WES, 1948). The average penetration resistance in the top 0 to 15 cm soil layer (cone index) is also used to predict the tractive performance of off-the-road vehicles (Wismer and Luth, 1974). In this model, the cone index is the only parameter used to characterize the terrain condition. Frietag and Richardson (1968) demonstrated the use of cone index for predicting tractive capability of forestry vehicles.

Some attempts have been made to relate cone index to soil strength parameters such as cohesion and friction angle (smith, 1964; WES, 1964; Turnage, 1972; Mulqueen et al., 1977; Rohani, 1979).

Cone penetrometers have also been used to evaluate the soil compaction resulting from vehicle traffic (Raghavan and McKyes, 1977) and to evaluate the residual effects of different tillage practices (Threadgill, 1982).

Numerous studies have dealt with the use of cone penetrometers of different size and shape to determine the mechanical impedance to root growth and to plant emergence (Farrell and Greacen, 1966; Taylor et al., 1966; Greacen et al., 1968, Camp and Lund, 1968; Cockroft et al., 1969; Russel and Goss, 1974; Voorhees et al., 1975; Bowen, 1976; Blancher et al., 1978; Bradford, 1980). Many of these studies have shown that penetration resistance of small cones can be correlated with root development.

In recent years the WES cone penetrometer has seen some non-traditional applications. Morrison (1980) demonstrated the use of a recording penetrometer for determining the relative magnitudes of compaction gradients within tobacco bales. Most recently, White et al. (1983) used the cone penetrometer to control the density of wood chips stored in bins.

CONCLUSIONS

Penetrometers are simple instruments and they are easy to use. Depending upon the application, different types of penetrometers are used. They are widely used in site explorations, soil strength assessment, trafficability predictions, assessments of impedance to root penetration and soil compaction. Penetration resistance information obtained using penetrometers must be interpreted carefully because many factors such as soil type, soil strength, moisture level, penetration rate, cone size and shape, and surface roughness of cone affect it in a significant fashion. More recent applications show wider use of mechanically operated recording type penetrometers.

References

1. ASAE. 1983. Soil cone penetrometer. ASAE Standard S313.1. Agricultural Engineers Yearbook, p. 283.
2. Ayers, P. D. and J. V. Perumpral. 1982. Moisture and density effect on cone index. TRANSACTIONS of the ASAE 25(5): 1169-1172.
3. Begemann, H. K. S. 1969. The Dutch static penetration test with the adhesion jacket cone. L.G.M. Medelingen, Publications Delft Laboratory for Soil Mechanics, 12(4), April.
4. Blancher, R. W., C. R. Edmonds and J. M. Bradford. 1978. Root growth in cores formed from fragipan and B2 horizons of Hobson soil. Soil Sci. Soc. Am. J., 42: 437-440.
5. Bogdanovic, L., J. 1961. The use of penetration tests for determining the bearing capacity of piles. Proceedings, Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, France, 2:17-22.
6. Bowen, H. D. 1976. Correlation of penetrometer cone index with root impedance. ASAE Paper No. 76-1516, ASAE, St. Joseph, MI 49085.
7. Bradford, J. M. 1980. The penetration resistance in a soil with well defined structural units. Soil Sci. Soc. Am. J., 44:601-606.
8. Camp, C. R. and Z. F. Lund. 1968. Effect of mechanical impedance on cotton root growth. TRANSACTIONS of the ASAE 11(2):188-190.
9. Carter, L. M. 1967. Portable recording penetrometer measures soil strength profiles. AGRICULTURAL ENGINEERING. 46(6): 348-349.
10. Carter, L. M. 1969. Integrating penetrometer provides average soil strength. AGRICULTURAL ENGINEERING 50(10): 618-619.
11. Cockroft, B., K. P. Barley and E. L. Greacen. 1969. The penetration of clays by fine probes and root tips. Aust. J. Soil Res., 7: 333-348.
12. Collins, J. G. 1971. Forecasting Trafficability of Soils. Tech. Memo. 3-331. U. S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
13. De Beer, E. E. and A. Martens. 1957. Method of computation of an upper limit of the heterogeneity of sand layers on the settlement of bridges. Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, London, England, I:275-282.
14. Durgunoglu, H. T. and j. K. Mitchell. 1975. Static penetration of soils: I — Analysis. Proceedings Conference on In-Situ Measurement of Soil Properties, North Carolina State University, Raleigh, N.C., 1:151-172.
15. ESOPT. 1974. European symposium on penetration testing, Stockholm, June, Vol. 1. State of the art reports.
16. Farrell, D. A. and E. L. Greacen. 1966. Resistance to penetration of fine probes in compressible soil. Aust. J. Soil Res. 4, 1-17.
17. Frietag, D. R. 1968. Penetration tests for soil measurements. Misc. Rep. 4-284. U. S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
18. Freitag, D. R., A. J. Green, and K. J. Melzer. 1970. Performance evaluation of wheels for lunar vehicles. Tech. Rep. Mm-70p2. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
19. Frietag, D. R. and B. Y. Richardson. 1968. Application of trafficability analysis to forestry. Misc. Rep. 4-959, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
20. Gill, W. R. 1968. Influence of compaction hardening of soil on penetration resistance. TRANSACTIONS of the ASAE 11(6): 741-745.
21. Greacen, E. L., D. A. Farrell and B. Cockroft. 1968. Soil resistance to metal probes and plant roots. Trans. 9th Int. Congr. Soil Sci., Adelaide, Australia, 1:769-779.
22. Hayes, J. C. and J. T. Ligon. 1977. Prediction of traction using soil physical properties. ASAE Paper No. 77-1054, ASAE, St. Joseph, MI 49085.
23. Hendrick, J. G. 1969. Recording soil penetrometer. J. Agric. Engr. Res. 14(2): 183-186.
24. Karafiath, L. L. and E. A. Nowatzki. 1978. Soil mechanics for off-road vehicle engineering. Trans. Tech Publications, Clausthal, Germany, p. 515.
25. Knight, S. J. 1948. Trafficability of soils — laboratory tests to determine effects of moisture content and density variations. Tech. Memo 3-240, 1st supplement. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
26. Knight, S. J. 1961. Some factors affecting moisture content-density- cone index relations. Misc. Rep. 4-457. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
27. Kondner, R. L. 1960. A non-dimensional approach to the vibratory cutting, compaction and penetration of soils. Tech. Rep. 8. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
28. Leigh, A. C. and I. K. Nixon. 1961. Comparison of in-situ tests for granular soils. Proceedings, Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, France, 1:499-507.
29. Lukenbach, B. 1961. The determination of the permissible point load of piles by means of static penetration tests. Proceedings, Fifth International Conference on Soil Mechanics and Foundation Engineering, Vol. II, p. 99.
30. Melzer, K. J. 1971. Relative density and cone penetration resistance. Tech. Rep. 3-652. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
31. Meyerhof, G. G. 1956. Penetration tests and bearing capacity of cohesionless soils. J. Soil Mech. Found. Div., ASCE, 82(SM1):1-19.
32. Meyerhof, G. G. 1963. Some recent research on the bearing capacity of foundations. Can. Geotech. J., 1(1): 16-26.
33. Morrison, Jr., J. E. 1980. Use of recording penetrometer for evaluation of density profiles in bales of tobacco. TRANSACTIONS of the ASAE 23(1):261-264.
34. Mulqueen, J. J. V. Stafford and D. W. Tanner. 1977. Evaluation of penetrometers for measuring soil strength. J. Terramech. 14(3): 137-151.
35. Murphy, N. R. 1965. Measuring soil properties in vehicle mobility research—an evaluation of the rectangular hyperbola for describing the load-deformation response of soils. Tech. Rep. 3-652. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
36. Nowatzki, E. A. and L. L. Karafiath. 1972. Effect of cone angle on penetration resistance. Highway Res. Rec. 405: 51-59.
37. Phillips, J., and J. V. Perumpral. 1983. Designing a microcomputer data logger for a soil cone penetrometer. AGRICULTURAL ENGINEERING 64(6): 13-14.
38. Plantema, G. 1957. Influence of density on sounding results in dry, moist and saturated sands. Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, London, England, 1:237-240.
39. Prather, O. C., J. G. Henrick and R. L. Schafer. 1970. An electronic hand-operated recording penetrometer. TRANSACTIONS of the ASAE 13(1): 385-386, 390.
40. Raghavan, G. S. V. and E. McKyes. 1977. Study of traction and compaction problems of eastern Canadian agricultural soils. Dept. of Agric. Engr., McGill University, Quebec, Canada.
41. Rodin, S. 1961. Experiences with penetrometers, with particular reference to the standard penetration test. Proceedings,

Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, France, 1:517-521.

42. Rohani, B. 1979. Personal communications. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

43. Russel, R. S. and M. J. Goss. 1974. Physical aspects of soil fertility—the response of roots to mechanical impedance. Neth. J. Agric. Sci. 22: 305-318.

44. Sanglerat, G. 1972. The penetrometer and soil exploration. Elsevier Publication Company, Amsterdam.

45. Schmertmann, J. H. 1970. Static cone to compute static settlement over sand. J. Soil Mech. and Found. Div. ASCE, 96(SM3): 1011-1043.

46. Schmertmann, J. H. 1975. Measurement of in situ shear strength. Proceedings Conference on In Situ Measurement of Soil Properties, North Carolina State University, Raleigh, N.C., 2:57-138.

47. Schmertmann J. H. 1978. Guidelines for cone penetration test performance and design. FHWA-78-209, U.S. Department of Transportation, Federalf Highway Administration, Offices of Research and Development, Implementation Division, Washington, DC 20590.

48. Schultz, and K. J. Melzer. 1965. The determination of the density and the modulus of compressibility of noncohesive soils by soundings. Proceedings, Sixth International Conference on Soil Mechanics and Foundations Engineering, Montreal, Canada, 1:354-358.

49. Smith, J. L. 1964. Strength-moisture-density relations of fine grained soils in vehicle mobility research. Tech Rep. 3-369. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

50. Smith, L. A. and W. T. Dumas. 1978. A recording soil penetrometer. TRANSACTIONS of the ASAE 21(1): 12-14, 19.

51. Taylor, H. M., G. M. Roberson and J. S. Parker, Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soil materials. Soil Sci. 102(1): 18-22.

52. Threadgill, E. D. 1982. Residual tillage effects as determined by cone index. TRANSACTIONS of the ASAE 25(4): 859-863, 867.

53. Tollner, E. W. and B. P. Verma. 1984. Modified cone penetrometer for measuring soil mechanical impedance. TRANSACTIONS of the ASAE 27(2): 331-336.

54. Turnage, G. W. 1970. Effects of velocity, size and shape of probes on penetration resistance of fine-grained soils. Tech. Report No. 3-652. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

55. Turnage, G. W. 1972. Performance of soils under tire loads. Report No. 3-652, Waterways Experiment Station, Vicksburg, MS.

56. Turnage, G. W. 1974. Resistance of coarse-grained soils to high-speed penetration. Tech. Report No. 3-652. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

57. Upadhyaya, S. K., L. L. Kemble, N. E. Collins and T. H. Williams. 1982. Cone index prediction equations for Delaware soils. ASAE Paper No. 17 82-1542, ASAE, St. Joseph, MI 49085.

58. Van der Veen C. 1957. The bearing capacity of a pile predetermined by a cone. Proceedings, Fourth International Conference on Soil Mechanics and Foundation London, England, 12:72-75.

59. Voorhees, W. B., D. A. Farrell and W. E. Larson. 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. Proc. 39:948-953.

60. Voorhees, M. L. and P. N. Walker. 1977. Tractionability as a function of soil moisture. TRANSACTIONS of the ASAE 20(5): 806-809.

61. Waterways Experiment Station. 1948. Trafficability of soils—Development of testing instruments. Tech. Memo. 3-240 3rd Supplement, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

62. Waterways Experiment Station. 1958. A limited study of the factors that affect soil strength. Misc. Report No. 4-284. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

63. Waterways Experiment Station. 1964. Strength-density relation of an air-dry sand. Tech. Rep. 3-652. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

64. Wells, L. G. and O. Treesuwan. 1977. The response of various soil strength indices to changing water content. ASAE Paper No. 77-1055, ASAE, St. Joseph, MI 49085.

65. Wells, L. G. and R. D. Baird. 1978. A technique for predicting vehicular tractive performance. ASAE Paper No. 78-1000, ASAE, St. Joseph, MI 49085.

66. White, M.S., M. C. Vodak and D. C. Cupp. 1983. The effect of surface compaction on the moisture content of piled green hardwood chips. Forestry and Foresty Products Dep., School of Forestry, VPI&SU, Blacksburg, VA 24061.

67. Wiendieck, K. W. 1970. A preliminary study of seafloor trafficability and its prediction. Tech. Rep. S-70-8. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

68. Wilford, J. R., O. B. Wooten and F. E. Fulgham. 1972. Tractor mounted field penetrometer. TRANSACTIONS of the ASAE 15(2): 226-227.

69. Wilkerson, J. B. F. D. Tompkins and L. R. Wilhelm. 1982. Microprocessor based, tractor mounted soil cone penetrometer. ASAE Paper No. 82-5511, ASAE, St. Joseph, MI 49085.

70. Wismer, R. D. and H. J. Luth. 1974. Off-road traction prediction for wheeled vehicles. TRANSACTIONS of the ASAE 17(1): 8-10, 14.

71. Woodruff, D. W. and D. H. Lenker. 1984. A handheld digital penetrometer. ASAE Paper No. 84-1038, ASAE, St. Joseph, MI 49085.

Single and Dual Probes for Soil Density Measurement

(continued from page 934)

8. Rawitz, E., H. Etkin, and A. Hazan. 1982. Calibration and field testing of a two-probe gamma gauge. Soil Sci. Soc. Amer. J. 46:461-465.

9. Reginato, R. J. 1974. Gamma radiation measurements of bulk density changes in a soil pedon following irradiation. Soil Sci. Soc. Amer. Proc. 38:24-29.

10. Reginato, R. J., and C. H. M. Van Bavel. 1964. Soil water measurement with gamma attenuation. Soil Sci. Soc. Amer. Proc. 28:721-724.

11. Stoosnijder, L., and J. G. De Swart. 1974. Column scanning with simultaneous use of 241Am and 137Cs gamma radiation. Soil Sci.118:61-69.

12. Van Bavel, C. H. M., N. Underwood, and S. R. Ragar. 1957. Transmission of gamma radiation by soils and soil densitometry. Soil Sci. Soc. Amer. Proc. 21:588-591.

13. Vigier, B., and J. A. Campbell. 1980. Calibration of a single gamma probe for measuring wet bulk density in organic soil. Can. J. Soil Sci. 60:133-135.