CHAPTER

11

Penetrometers

As we pointed out in Chapter 1, the four soil physical factors that affect plant growth are mechanical impedance, water, aeration, and temperature (Kirkham, 1973). In Chapter 5, we learned how to measure matric potential of water in the soil using tensiometers. In later chapters, we shall study other techniques to measure water in soils and plants, and in the next chapter, we shall see how to measure soil aeration. In this chapter, we learn how to measure mechanical impedance using penetrometer measurements.

We first will define a penetrometer and then look at different kinds of instruments and their uses. We will consider the type of tests that are done with penetrometers and what factors affect the measurements, and then look specifically at the cone penetrometer.

11.1 DEFINITION, TYPES OF PENETROMETERS, AND USES

A penetrometer is any device forced into the soil to measure resistance to vertical penetration (Davidson, 1965). The earliest soil penetrometers were fists, thumbs, fingernails, pointed sticks, and metal rods. They are still used for qualitative measurements.

Results of such tests are expressed in terms such as "loose," "soft," "stiff," and "hard". However, penetrometers are designed to give quantitative measurements of soil penetration resistance for a more precise correlation with properties such as bearing value, safe soil pressure, rolling resistance, trafficability of wheels or crawler tracks on soil, relative density, crop yield, and tilth (Davidson, 1965). *Tilth* is from the Anglo-Saxon word *tilthe* and means a tilling or cultivation of land. Dr Jerry L. Hatfield, a Kansas native and the director of the United States National Soil Tilth Laboratory, located on the campus of Iowa State University in Ames, Iowa, has a nonscientific definition of tilth: "The wellness of the seedbed" (Muhm, 1990). The $11.9 million Tilth Laboratory opened in

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April, 1989, and has the goal of quantifying the effects of tillage on the soil. Using penetrometers is one method to do this quantification. In 2009, the name of the laboratory was changed to the National Laboratory for Agriculture and the Environment.

11.2 TYPES OF TESTS

Two types of tests are done, when making penetration-resistance measurements: a static test or a dynamic test. In a static penetration test, the penetrometer is pushed steadily into the soil. A static penetration test is exemplified by the use of the cone penetrometer, which we discuss in detail in Section 11.4. In a dynamic penetration test, the penetrometer is driven into the soil by a hammer or falling weight. A dynamic penetration test can be done with a spray-tainer or spra-tainer. The apparatus was designed in the 1950s by Professor Champ B. Tanner of the University of Wisconsin in Madison, Wisconsin. For a biography of Tanner, see the Appendix, Section 11.5.

The spra-tainer is shown in Figure 11.1 (Kirkham et al., 1959b). It is a thin-walled can of 12-ounce size (341 g) manufactured to dispense products such as shaving cream and bug spray under pressure. The bottom of the can is removed and the top is left open. The can, which is 8 cm long and 6.9 cm in diameter, is driven into the soil with a special hammer weighing 2.35 kg and dropped from a height of 42.5 cm (Kirkham et al., 1959a). This driving of the cans into the soil is done when

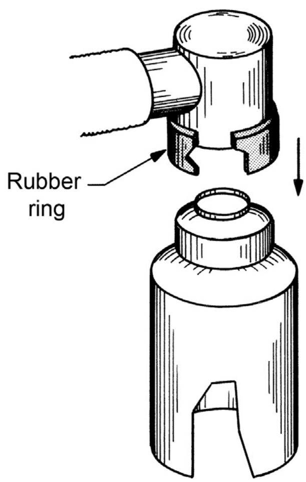

FIGURE 11.1 The spra-tainer can. *From Kirkham et al. (1959b); Reprinted by permission of Marcel de Boodt for the Landbouwhogeschool en de Opzoekingsstations van de Staat te Gent, Ghent, Belgium.*

the soil is at or near field capacity. The cans are driven entirely into the soil (to a depth of 8 cm). The cans are steel, and, unless they encounter rocks in the soil, they may be used repeatedly. A thin coating of petroleum jelly is wiped on the cans before each use. The special hammer is used, together with a special driving head and driving tube, in order that the driving is done the same way by all operators. The spra-tainer can and the driving head fit in a driving tube, the latter having triangular-shaped legs with spikes in their ends to hold the driving tube vertically on the soil surface. The top of the driving head has, extending upward on its axis, a guide rod. A photograph of the setup is shown by Kirkham et al. (1959b). The number of blows to drive in the cans (acting as penetrometers) is counted, and this number is the quantified measurement. The seamless tube cans are an important feature of the equipment. Because of the thin and sharp walls of the spra-tainer cans, the soil is relatively undisturbed, and, if soil samples are taken after getting the penetration resistance, the samples (8 cm long and 6.9 cm in diameter) may be called undisturbed. After penetrometer measurements are made using the spra-tainers, air permeability measurements may be made on the samples in place in the field (Kirkham et al., 1959a). The method is described by Kirkham et al. (1959b). For the air permeability measurements, air is delivered at a constant small pressure through a vacuum-cleaner-type flexible hose that is attached to the spra-tainer. At the top of Figure 11.1, the end of the air hose which connects to the spra-tainer is shown for the air permeability measurements. Grover (1955) used an equipment similar to Kirkham et al. (1959a) to measure air permeability, and Sweeney et al. (2006) used the method of Grover (1955) plus the cone penetrometer designed by Christensen et al. (1998) to measure air permeability and penetration resistance of soil after wheel-track compaction resulting from commonly used heavy-weight tractors and equipment.

Even though used in past decades, dynamic penetration tests are not often employed in agricultural situations today. Dynamic penetrometers are mostly used for highway pavement evaluations and few include modern, high-resolution automated data acquisitions systems (Lowery and Morrison, 2002).

11.3 WHAT PENETROMETER MEASUREMENTS DEPEND UPON

All penetrometer measurements depend upon two factors: the water content of the soil and time. Above freezing, differences in measurements due to temperature are not detectable (Loyd Stone, personal communication, February 4, 1983). Therefore, measurements depend on temperature only if the soil is frozen.

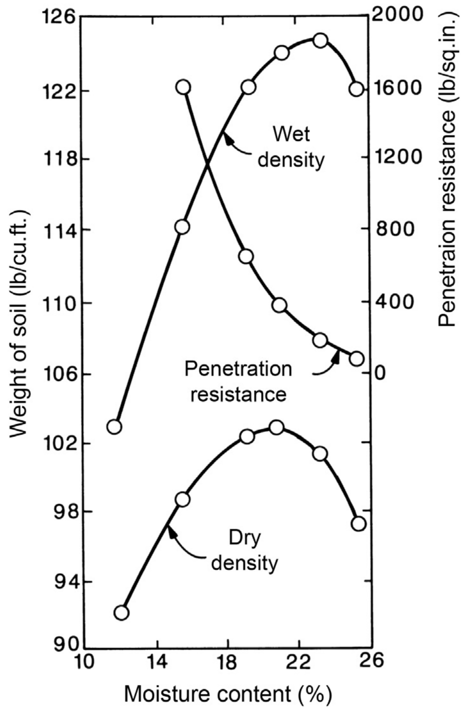

FIGURE 11.2 Typical curves illustrating the relation of water content of soil to density and penetration resistance. *From Davidson (1965); Reprinted by permission of the American Society of Agronomy.*

Figure 11.2 (Davidson, 1965) shows that as the water content increases, the penetration resistance decreases. As noted above, measurements with the spra-tainers are made when the soil is near field capacity. A measurement made with the cone penetrometer in a cohesive, fine-grained soil is an inverse function of water content (Davidson, 1965). In humid climates, trafficability measurements are made during the wet season. In dry or hard soils, or in soils containing pebbles and stones, any operator will find it difficult to obtain consistent and reliable penetrometer measurements, especially as penetration depth increases. Simultaneous and conjoint measurements of penetration resistance and water content need to be made (Topp et al., 2003).

Measurements depend upon time because of impulse. In physics, impulse is defined as follows (Schaum, 1961, p. 62):

$$\text{Impulse} = \text{force} \times \text{length of time the force acts} = Ft. \tag{11.1}$$

Units of impulse are the N-s in the MKS system, the dyne-s in the CGS system, and the lb-s in the English system.

Impulse and momentum are related. The change of momentum produced by an impulse is equal to the impulse. Thus if an unbalanced force F acting for a time t on a body of mass m changes its velocity from an initial value v_o to a final value v_t, then

$$\text{Impulse} = \text{change in momentum},$$

$$Ft = m(v_t - v_o). \tag{11.2}$$

This equation indicates that the unit of impulse in any system is equal to the corresponding unit of momentum. Therefore, 1 N-s = 1 (kg-m)/s and 1 lb-s = 1 (slug-ft)/s (Schaum, 1961, p. 62).

Because of impulse (dependent upon time), a penetrometer, like a cone penetrometer, must be pushed at a steady rate into the soil. It should take about 15 s to go 24 in (4 cm/s) (Davidson, 1965, p. 480). According to Don Kirkham (personal communication, February 20, 1982), penetrometer measurements are a "pain in the neck" for two reasons: their dependence upon time and water content.

11.4 CONE PENETROMETER

Now let us look at the cone penetrometer (SoilTest, 1978a), which is a penetrometer that has gained wide acceptance. It was developed by the U.S. Army Corps of Engineers for predicting the carrying capacity of cohesive, fine-grained soils for army vehicles in off-road military operations (Davidson, 1965). The strength of the soil has long been of concern to the military. Frederick I Barbarossa (ca 1123–1190), emperor of the Holy Roman Empire, drowned in Cilicia (now Turkey) on June 10, 1190, while marching his army into Asia Minor (Davis, 1971). He died in quicksand (Don Kirkham, personal communication, undated, who lived in Turkey in 1959 and saw the sight where Barbarossa died). Before D-Day (June 6, 1944; D stands for "Day"), the day of the invasion of western Europe by Allied forces in World War II, General Dwight D. Eisenhower (1890–1969) did not know if the beaches at Normandy in France were rocky and firm enough to hold tanks, or if they would turn out to be soft sand (Smith, 2004).

The applied force required to press the cone penetrometer into a soil is an index of the resistance or impedance of the soil and is called the *cone index* (CI). Cone index readings are taken to depths of 24 in (61 cm) to permit plotting of a cone index curve, which, in addition to its significance in trafficability studies, gives quantitative information on soil compactness or density that can be correlated with other soil physical properties or with crop yields (Davidson, 1965).

The parts of the cone penetrometer made in the United States consist of the handle, proving ring, dial gauge, rod graduated in 6 in (15 cm) or 12 in

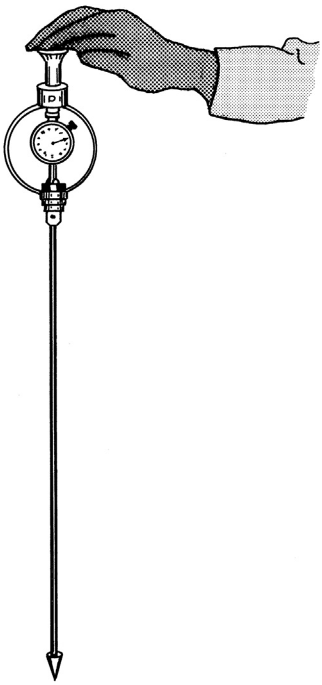

FIGURE 11.3 The cone penetrometer. *From SoilTest (1978b); Reprinted by permission of ELE International, Loveland, Colorado.*

(30 cm) intervals, and a stainless-steel cone (Figure 11.3) (SoilTest, 1978b). The operator's handle is mounted at the top of the proving ring. The staff is 19 in long (48.3 cm), making it possible to take readings to that depth. The cone is 1.5 in (3.8 cm) in height and has a 30° apex angle and a base area of 0.5 in squared (3.14 cm^2). The diameter of the base of the cone is 0.79 in (2.0 cm). The cone index or force per unit area required to move the cone to a given plane of soil to show the shearing resistance of that soil is indicated on the proving ring dial. The proving ring has 150 pound capacity and the dial indicator reads the cone index in the range of 0–300 pounds per square inch (psi). (See next paragraph for SI units.) In Europe, Eijkelkamp Agrisearch Equipment (Nijverheidsstraat 30, 6987 EM Giesbeek, The Netherlands) sells penetrometers. Hartge et al. (1985) in Germany report results using the Eijkelkamp penetrometer. Gauges in Europe read in kilogram per square centimeter (Don Kirkham, personal communication, February 18, 1982). In Australia, Rimik (1079 Ruthven Street, Toowoomba, Queensland 4350) makes a cone penetrometer that has a cone index read-out in kilopascal (Figure 11.4).

Because the Corps of Engineers' cone penetrometer is made in the United States, its dial gauge reads out in the English units of pounds per square

FIGURE 11.4 Picture of a cone penetrometer in use. The cone penetrometer shown is made by Rimik Pty. Ltd., Toowoomba, Queensland, Australia. *Photograph courtesy of Dr Peggy S. Althoff, Kansas State University, Manhattan, Kansas.*

inch (psi). Therefore, we need to know how to convert the dial readings, in lb/in^2, into SI units. Remember $F = ma$ (force = mass times acceleration) and in a gravitational field, $w = mg$ (weight = mass times acceleration due to gravity). So each gram has an earth-pull on it of 980 dynes and each kilogram has an earth-pull on it of 9.8 N. In the CGS system of units, we make the following calculations (remember 1×10^6 dynes/cm^2 = 1 bar).

To convert from the English system to the CGS system,

$$\begin{aligned} 1 \text{ psi} &= 1 \text{ lb/in}^2 = [(454 \times 980) \text{ dynes}]/(2.54 \text{ cm})^2 \\ &= 68962.7 \text{ dynes/cm}^2 = 68962.7/10^6 \text{ bar} \\ &= 0.0689627 \text{ bar or, to 4 significant figures, } 0.06896 \text{ bar.} \end{aligned}$$

This agrees with the value that Taylor and Ashcroft (1972, p. 511) give in their extensive list of conversion factors: 1 psi = 0.06895 bar, the slight difference (0.06895 bar vs 0.06896 being due to rounding of values).

We know that 10 bar = 1 MPa. Thus,

$$0.0689627 \text{ bar} = 0.00689627 \text{ MPa} = 6896.27 \text{ Pa}.$$

To convert from the English system to the MKS system,

$$1 \text{ psi} = [(0.454 \times 9.8) \text{ N}]/[(2.54/100) \text{ m}]^2 = 0.68962 \times 10^4 \text{ N/m}^2$$
$$= 6.896 \times 10^3 \text{ N/m}^2 = 6896 \text{ N/m}^2.$$

Note the conversion units:

$$14.7 \text{ psi} = 1 \text{ atm}; \;\; 0.987 \text{ atm} = 1 \text{ bar}.$$

One Pascal = 1 N/m^2 and 14.5 lb/in^2 = 1 bar; 0.06896 bar per psi × 14.5 psi per bar = 1.0. The value 0.06896 bar per psi checks out.

The cone penetrometer that Loyd R. Stone in the Department of Agronomy at Kansas State University uses was made by the Physics Shop at Kansas State University (personal communication, March 6, 1990). He has penetrometers with different cone tips and base areas. Dr Stone's penetrometers are calibrated by pressing the cone on a balance with known masses in kilograms. The probe scale has no units, just numbers. The readout (number) on the probe is calibrated against kilograms. The value in kilograms is divided by area for that cone tip, and he gets probe readings in units of kg/cm^2 (mass per unit area) (Intrawech et al., 1982). Others also use a cone index in units of kg/cm^2 (Cruse et al., 1981; Bradford, 1986).

Note that acceleration due to gravity is not included when one gets a reading of mass per unit area (kg/cm^2). As noted in Chapter 2, we must express values in SI units, and journals require them for publication. But either kg/cm^2 or the units converted to SI units from the English units on the U.S. Army Corps of Engineers' cone penetrometer (force per unit area or MPa) are all right. Engineers around the world (like those in the U.S. Army Corps of Engineers) think in terms of living on earth and talk of weight on earth. For example, they say, "This man weighs 185 lb." They do not say, "This man has a mass of 5.8 slugs." The 185 pounds is the man's force on the surface of a floor. It is a valid reading because the springs on a calibrated bathroom scale will give the man's weight in pounds. If the man were standing on scales on the moon, where surface gravity is 0.17 of the Earth's, he would weigh 31 pounds. So when the astronauts were on the moon, they needed lead weights in their boots to hold them down.

In sum concerning units, we need to recognize that the U.S. Army Corps of Engineers' gauge is reporting a force per unit area or a weight per unit area (remember $w = mg$), and units of kg/cm^2 report a mass per unit area. A gravity constant is associated with the Corps of Engineers' gauge, and it is not with a reading given in kg/cm^2.

Loyd Stone often uses a penetrometer with a cone angle of 45°. He prefers a wider angle than that on the penetrometer of the Corps of Engineers (45° vs 30°). With the wider angle, the soil does not get so compressed as the cone moves in, especially at lower depths (personal communication, March 6, 1990). To get more accurate readings, he uses a smaller area on the cone and a more sensitive proving ring. If a proving ring needs a 500 pound (227 kg) force to move it, it is no good because a man cannot push 500 pounds. So Dr Stone uses a 0–50 lb proving ring and has a small cone area. The proving ring and the cone area must be matched. Some people like to go to larger cone areas, which are harder to push into the ground, to get better representation of the soil, because a larger area is sampled (Loyd Stone, personal communication, March 6, 1990). Dr Stone's meter has a brake and holds the reading until it is released. The Corp of Engineers' penetrometer does not hold the reading. It is not necessary to core soil first when using a cone penetrometer (Loyd Stone, personal communication, February 17, 1982), but to use a blunt-end penetrometer, it is necessary to core the soil to the depth of interest because the soil becomes compacted.

When reviewing a paper describing a study in which a cone penetrometer has been used, make sure that the authors give (1) the cone angle; (2) the rate of penetration; (3) water content of the soil; and (4) the physical meaning of their units (i.e., whether or not gravity is taken into account in the units).

The correlation between readings made with cone penetrometers is good, if the same model of penetrometer is used at the same location, and even if two different people make the measurements (Loyd Stone, personal communication, February 7, 1983). Differences in readings occur due to fractures in the soil (e.g., holes), which result in much variability between readings. However, there is still some variability due to operators.

In this chapter, only commonly used penetrometers have been noted. Specifically designed ones for laboratory experimentation have been developed. For example, see Whiteley et al. (1981). Perumpral (1987) reviews applications of cone penetrometers in engineering, and Lowery and Morrison (2002) review different types of penetrometers used in soil science.

The need to take penetrometer measurements becomes ever more important as the weight of farm equipment increases (Horn et al., 2007; Zink et al., 2010). Physical soil degradation is occurring due to heavy machinery that farmers are using. In Germany, soil scientists are urging their federal government to limit the weight of the farm machinery. The largest sugar beet (*Beta vulgaris* L.) harvester in Germany weighs, when loaded, about 60 metric tons (60 Mg), just as much as the biggest US battle tank (Rienk van der Ploeg, Professor, University of Hannover, personal communication, February 16, 2004). In Germany, a truck of that weight is not allowed to use the highways, but for arable fields no weight limit exists (van der Ploeg et al., 2006).

Military training commonly results in land degradation but protocols for assessing long-term environmental impacts are lacking. Althoff and Thien (2005) and Althoff et al. (2010) determined the damage done by battle tanks weighing 57.2 Mg (57.2 metric tons) on prairie soil at Fort Riley Military Installation in northeastern Kansas. Soil compaction, as measured by a cone penetrometer, was severe for tank traffic under wet conditions and remained significant to depths of 5 and 10 cm throughout the length of the study (2003–2007). As with heavy pieces of farm equipment (Zink et al., 2010), apparently irreversible soil compaction occurs with battle tanks.

11.5 APPENDIX: BIOGRAPHY OF CHAMP TANNER

Champ Bean Tanner, the inventor of the spra-tainer, was born in Idaho Falls, Idaho, on November 16, 1920, the son of Bertrand Myron Tanner and Orea Bean Tanner. After the death of his father in 1924, he was raised by his widowed mother. The family moved to Teton City and then to Rexburg, Idaho, where his mother taught high school until 1930. In 1930, the family (Champ, two brothers, and his mother) moved to Provo, Utah, to continue Orea's education at Brigham Young University. After earning her B.S., Mrs Tanner taught at Provo High until 1938, when she joined the English Department at Brigham Young University.

Tanner graduated from Provo High School in 1938. He received his undergraduate degree from Brigham Young University in 1942 with high honors in chemistry and soil science. After 4 years of service in the U.S. Army (1942–1946), he entered graduate school at the University of Wisconsin in Madison. He earned his Ph.D. in soils in 1950 under the joint direction of Professors E.E. Miller and M.L. Jackson (American Society of Agronomy, 1988). He joined the Department of Soil Science as the first agricultural physicist employed since F.H. King's retirement in 1901. (For a biography of King, see Tanner and Simonson, 1993.) He remained at the University of Wisconsin for 40 years, and served as chair of the department of soil science from 1984 until his retirement in 1988.

In soil physics, he studied water flux in unsaturated soils, the thermal regime in soils, and soil aeration and redox potentials. His ability to develop instrumentation such as the spra-tainer for the dynamic penetration test was recognized by his colleagues (Don Kirkham, personal communication, undated). Tanner was the first to make in situ measurements of oxygen tension in the field. As a pioneer in micrometeorology, he dedicated much of his research to near-ground measurements of heat and water vapor transport from soil, water, and plant surfaces. He was the first to apply approaches of energy balance and the Bowen ratio to agronomic crops, and he devised the instruments for the necessary measurements. He developed the measurement of net radiation absorbance in crop foliar canopies and estimated soil evaporation and plant evaporation as functions of plant density and row spacing (Walsh et al., 1991).

In the area of plant–water relations, Tanner provided fundamental information on the relationship between water availability and plant growth. He created original instruments and techniques for estimating plant physiological responses, including the use of pressure chambers to measure water potential in plant storage organs and in situ water potential measurements of potato tubers and other root crops (Walsh et al., 1991). The paper describing the stomatal meter that he made with graduate students Edward T. Kanemasu and George W. Thurtell (Kanemasu et al., 1969) became a citation classic (Institute for Scientific Information, 1979). His *Soils Bulletin No. 6* (Tanner, 1963) is still regularly referred to.

Tanner directed the research for 25 Ph.D. and 15 M.S. students (American Society of Agronomy, 1990) and worked with several postdoctoral scientists. His students became leaders in agricultural meteorology and soil physics. He took pleasure in their achievements, but little credit, because he believed that the qualities ensuring success, such as integrity, imagination, deep curiosity, and hard work, are native and not taught (American Society of Agronomy, 1988). I worked in Tanner's laboratory when I was a graduate student studying under Wilford R. Gardner at the University of Wisconsin. There Tanner taught me how to weld thermocouples and make thermocouple psychrometers. His attention to detail was well known, and both field and laboratory measurements had to be done exactly right. He started work early in the morning. The going bet was that some day Tanner would arrive so early that he would meet Marvin L. Wesely (Gaffney, 2003), one of his students who worked late into the nights.

Tanner was the first soil scientist to be elected to the National Academy of Sciences (1981). He received the Award for Outstanding Achievement in Biometeorology from the American Meteorological Society in 1980 and the Soil Science Society of America's Soil Science Research award in 1978. He was a Fellow of the American Meteorological Society, the American Society of Agronomy, the Soil Science Society of America, the Crop Science Society of America, and the American Association for the Advancement of Science (American Society of Agronomy, 1988). He was awarded the Emil-Truog named professorship at the University of Wisconsin in 1979. He was a Fulbright lecturer in Australia and Papua New Guinea. He served as editor for the American Meteorological Society, the Soil Science Society of America, the American Society of Agronomy, and the American Society of Plant Physiologists.

A symposium on the subject of biophysical measurements was held at the annual meetings of the American Society of Agronomy in November, 1988, to honor Tanner. Papers from the symposium were published in an issue of *Theoretical and Applied Climatology* (Campbell, 1990).

Tanner married Kay (Catherine May Cox) on September 24, 1941. They had five children: three sons—Bertrand D., Myron S., and Clark B.—and two daughters—Catherine and Terry Lee. Clark—born in 1960, died in 1977 of acute leukemia. Bertrand, like his father, was skilled in instrumentation, and was an executive at Campbell Scientific, Inc., the company best known for its data loggers. Bertrand died of cancer on September 16, 2008 (Meek, 2009). Champ Tanner's accomplishments were all the more remarkable because he got polio in the early 1950s, and, although he recovered, he walked with difficulty. He died of cancer on September 22, 1990, at the age of 69.

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