A DYNAMIC CONE PENETROMETER FOR MEASURING SOIL PENETRATION RESISTANCE

Jeffrey E. Herrick* and Tim L. Jones

Abstract

Recognition of the importance of soil compaction is increasing, but instrument cost, measurement repeatability, and data interpretation limit its measurement on agricultural and rangelands. The dynamic penetrometer described here follows American Society of Agricultural Engineers standards, but replaces the proving ring with a strike plate, a shaft extension, and a sliding hammer. The penetrometer cone is pushed into the soil by successive hammer blows. Penetration resistance is calculated as the work by the soil needed to stop cone movement divided by the penetration distance. The work by the soil is defined as the kinetic energy of the hammer when it impacts the strike plate. Construction cost is approximately $100 to $150. The standard drop height and hammer mass ensure measurements are consistent between operators.

Increased interest in the effects of soil compaction on soil quality has created a demand for tools which measure soil penetrability or penetration resistance on a routine basis (Romig et al., 1995). It has long been recognized that compaction affects both root growth and soil water and air availability to roots, and that increased penetrometer resistance is correlated with compaction when all other factors are held constant (Baver et al., 1972). The most common method for measuring compaction is to determine cone index values using static penetrometers. Static penetrometers are designed to measure the force required to push a probe (usually a cone or blunt tip) through the soil at a constant (static) velocity. Dynamic penetrometers form a second general class (Perumpral, 1987). These probes rely on one or more discrete applications of kinetic energy to advance the probe (Table 1).

Cone indices, computed from static penetrometer data, have been used to characterize soil compaction and resistance to root growth (Barber, 1994; Mullins et al., 1994), tillage effects (Vyn and Raimbault, 1993; Busscher et al., 2000), wheel traffic effects (Sharratt et al., 1998), and hard pan resistance (Radcliffe et al., 1989). The values (Fritton, 1990) depend on cone properties (i.e., diameter, height, and included angle), as well as soil properties (e.g., bulk density, shear strength, water content, and texture). Use of existing penetrometers to characterize both agricultural and rangeland soils, however, has been limited by concerns about (i) instrument cost, (ii) measurement repeatability, (iii) limited ranges of soil resistance that can be measured by a single penetrometer, and (iv) difficulties in comparing data collected using penetrometers designed for different soil resistance ranges (Fritton, 1990; Vyn and Raimbault, 1993). The dynamic penetrometer design described addresses these concerns.

Static Penetrometers

A number of static designs are commercially available. Most consist of a rigid, cone-tipped rod attached to a pressure measuring device. The measuring device is usually a load cell or strain gauge coupled with an analog dial or pressure transducer for readout. The force exerted by the operator (either average or maximum) is normalized to the basal area of the cone to form a parameter called the cone index (i.e., pressure applied to the cone), usually reported in kilopascals (American Society of Agricutlural Engineers, 1992). A manually operated, static penetrometer developed by the U.S. Army Corps of Engineers WES (Waterways Experiment Station, 1948) is endorsed by the ASAE (American Society of Agricutlural Engineers, 1992) and is commonly referred to as the "Corps of Engineers" or "COE" penetrometer (Bradford, 1986). This design is widely used in agricultural soils (Radcliffe et al., 1989; Clark et al., 1993; Vyn and Raimbault, 1993; Mullins et al., 1994). A variation on this design, found in pocket penetrometers, uses a blunt tip and nonrecessed shaft to measure unconfined compressive strength (Bradford, 1986).

Manually operated static penetrometers suffer from several limitations. They (i) are relatively expensive, (ii) must be moved through the soil at a constant velocity, (iii) must be recalibrated on a regular basis in order to generate consistent, repeatable measurements, and (iv) are designed for a relatively limited range of soil resistance. The cost for a standard Corps of Engineers instrument equipped with a strain gauge is ≈$600. While not unreasonable when compared with other research tools, this puts the instruments out of range of most extension workers and crop consultants who are seeking a rapid, reliable indicator of soil compaction. More recently, lower-priced strain gauge-based instruments have become available, but these appear to be less durable and lack a recalibration option. Manually operated penetrometers often yield variable results when used by the same operator and especially when used by different operators because of differences in the rate of insertion. Correct interpretation of static penetrometer data also requires insertion into the soil at a constant velocity (i.e., probe acceleration equal to zero), so that the soil resistive force can be assumed equal to the total force applied to the penetrometer. If penetrometer velocity changes, then the soil resistive force will be either more (negative probe acceleration) or less (positive probe acceleration) than measured by the operator. Constant probe velocity is difficult to maintain in manually operated penetrometers.

In addition to variable penetration velocity within a single measurement, different operators generally develop different average penetrometer velocities because of different physical strength and leverage. Laboratory studies have demonstrated that differences in average penetrometer velocities alone

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J.E. Herrick, USDA-ARS Jornada Exp. Range, MSC 3JER, and T.L. Jones, Dep. of Agronomy and Horticulture, New Mexico State Univ., Box 30001, Dep. 3Q, Las Cruces, NM 88003-0003. Joint contribution from the USDA-ARS Jornada Experimental Range, and the New Mexico Agric. Exp. Stn. Received 8 Jan. 2001. *Corresponding author (jherrick@nmsu.edu).

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Table 1. Comparison of proposed penetrometer design with three alternatives.

	Dynamic cone	Dynamic core	Static cone	Static cone – hydraulic
Energy source	**Sliding hammer**	**Sliding hammer**	**Hand pressure**	**Hydraulic**
Factors affecting repeatability	**Drop height consistency**	**Drop height consistency**	**Operator consistency**	**Hydraulic consistency**
Limitations to use in dry soils	**None found**	**Increased (corer) resistance at greater depth(s)**	**Operator strength**	**Hydraulic strength**
Measurements units	**Energy per unit depth**	**Energy per unit depth**	**Force per base area (cone index)**	**Force per base area (cone index)**
Costs	**$100**	**soil corer**	**$600**	**≫$1000 (est.)**
Change in shaft resistance with depth	**Minimal**	**High**	**Minimal**	**Minimal**
Description†	**This article**	**Parker and Jenny, 1945**	**Waterways Exp. Stn., 1948**	**Rooney and Lowery, 2000**

† Only one sample reference is listed for each type to save space.

(even if constant within a single measurement) can result in an 11% variation in cone index for a soil material (Fritton, 1990).

The problem of variable penetrometer velocity can be eliminated by using mechanical devices which adjust penetrometer force to maintain constant penetrometer velocity (Clark et al., 1993; Barone and Faugno, 1996). Their use in routine measurements, however, is limited by cost and the need to transport a large platform with a power supply (such as a truck or tractor) to each measurement point. The variable velocity problem can also be minimized through the use of audible devices which are triggered by velocities outside of a specific range.

The adaptability or range of soil conditions to which strain gauge penetrometers can be applied is limited by the strength and weight of the operator. The range can be increased by using cones of different dimensions. However, it is extraordinarily difficult to compare data from penetrometers using different cones, and the error associated with conversion procedures is quite high (Fritton, 1990).

Dynamic Penetrometers

Dynamic penetrometers do not attempt to push the penetrometer through the soil at a constant velocity, nor do they apply continuous force to the penetrometer. Dynamic penetrometers supply a known amount of kinetic energy to the penetrometer, which causes the penetrometer to move a distance through the soil. The penetration distance depends on the kinetic energy applied to the penetrometer, the geometry of the penetrometer tip, and the soil penetration resistance. Dynamic penetrometers are not subject to operator variability since they do not rely on constant penetration velocity, and the kinetic energy applied by these devices is mechanically controlled (i.e., fixed hammer mass and drop heights).

Currently available dynamic penetrometer designs include some that are dropped onto the soil from a specified height (e.g., drop cones), and others that are driven into the soil with repeated hammer blows. The drop cone method measures the depth of penetration resulting from a cone of fixed mass being dropped from a standard height. These have been successfully used to measure shear strength in soils (Campbell and Hunter, 1986; Godwin et al., 1991). The hammer-type penetrometers use a slide hammer of fixed mass and drop height to apply consistent kinetic energy with each blow. Either the number of blows required to penetrate a specified depth, or the depth of penetration per blow are measured in this method.

The use of hammer-type penetrometers has been largely limited to drilling applications where standard drilling tools (e.g., split-spoon or core samplers) have been adapted to act as penetrometers (Swanson, 1950). A standard procedure for a split-spoon or split-barrel penetrometer which uses a 63.5-kg hammer dropped from a height of 75 cm is described by Davidson (1965) and more recently by the Annual Society of Testing Materials (1992). Due to their size and design, these penetrometers are generally not appropriate for agricultural, forest, and rangeland management applications. Parker and Jenny (1945) report one of the few agricultural applications of dynamic penetrometers. They compared management treatments in a citrus orchard using a soil corer with a 9.1-kg sliding hammer dropped from a height of 30.5 cm. This design is limited by the fact that resistance increases with increasing depth due to the increased contact area with the corer.

Dynamic Penetrometer Design

The design of the cone and the rigid supporting rod illustrated in Fig. 1 follows the ASAE (American Society of Agricutlural Engineers, 1992) standard for a soil cone penetrometer, which is based on the design developed by the United States Army Corps of Engineers WES (Waterways Experiment Station, 1948). It consists of a removable 30° hardened steel cone with a 20.3-mm-diameter base mounted on a 72.4-cm-long, 15.9 mm-diameter shaft (Fig. 1). The measuring device of the ASAE standard (American Society of Agricutlural Engineers, 1992) is replaced by a strike plate (anvil), which is welded to the shaft. The shaft continues through the plate and is used to guide a 2-kg slide hammer. An adjustable collar is used to fix the drop height of the hammer. The collar and extended shaft length help insure repeatability since the hammer is dropped from a specified height instead of relying on human energy to move the cone forward. This also makes the instrument adaptable to a wide range of field conditions because of its reliance on repeated hammer blows rather than the strength of a particular operator. The range can be increased further by simply changing the drop height (see "Adaptability for a Range of Soil Resistance" below). Finally, there are no gauges to be recalibrated, and of most importance, it was produced in a local farm implement machine shop for approximately $100 to $150 including labor.

Operation

The penetrometer is operated by placing the cone on the soil surface with the shaft oriented vertically. The cone is then pressed into the soil until it just becomes buried (i.e., soil surface is level with the base of the cone). This minimizes variability in starting depth. The slide hammer is raised until it touches (but does not strike) the collar and is then released. This operation defines one blow of the penetrometer and is repeated until the desired penetration depth is reached. Depth of penetration after each blow and total blows to reach a desired depth can be recorded. We have used the penetrometer to depths of 30 cm, which covers most, but not all, compaction problems in agricultural settings. Greater depths are possible, but extraction can be a problem. A circular bubble level glued onto a 20-mm diameter, 50-mm-long section of polyvinyl chloride tubing can be mounted on top of the shaft and used to help keep the instrument vertical during operation. The

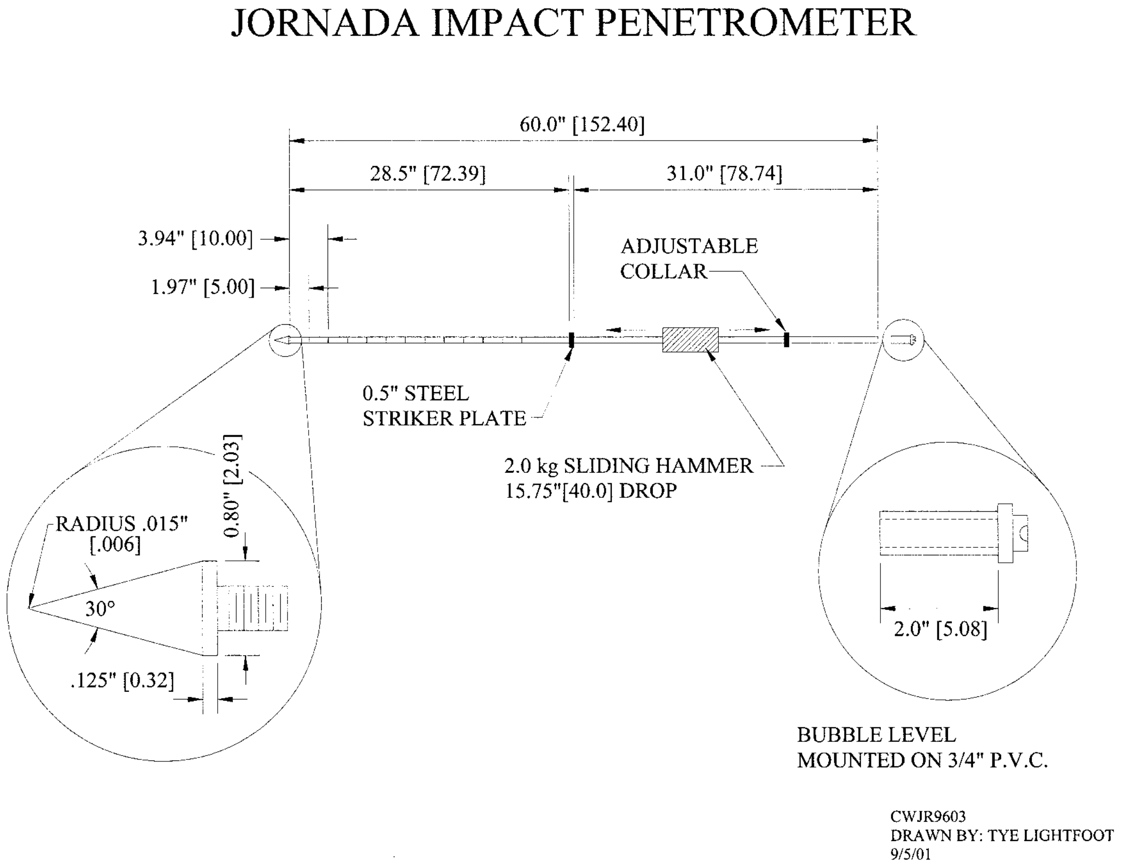

Fig. 1. Impact penetrometer design. All dimensions are in inches [cm]. Steel was used for all parts except for the bubble level mount, which is a polyvinyl chloride tube. The striker plate should be welded to the center of a single rod, or to the bottom half of a two-piece rod. The top half is then threaded. Cone is cut from steel on a lathe, then hardened. Penetrometer can be shortened for transport by threading bottom end of top section of shaft into striker plate.

operator periodically checks the bubble to ensure that it is in the center of the level before and after dropping the mass. Operators should exercise caution when using the penetrometer. Gloves and ear protection are recommended.

Units and Calculations

The hammer-type, dynamic cone penetrometer described here can be used to calculate a soil penetration resistance averaged across the distance the cone moves through the soil after each hammer blow. Soil penetration resistance is defined as the force applied to the penetrometer by the soil causing the penetrometer to decelerate from its initial velocity, resulting from the hammer blow, to zero velocity. Resistance can be calculated as the work done by the soil to stop the movement of the penetrometer divided by the distance the penetrometer travels:

$$R_s = \frac{W_s}{P_d} \qquad [1]$$

where R_s is the soil resistance (N), W_s is the work done by the soil (J), and P_d is the distance the penetrometer travels through the soil (m).

The work done by the soil is calculated according to the Energy-Work theorem (Halliday and Resnick, 1963) as the change in the kinetic energy of the penetrometer. When the penetrometer is driven into the soil by the hammer, the kinetic energy of the hammer is transferred to the penetrometer cone. When the penetrometer is stopped by the soil, its kinetic energy is zero. Therefore, the work done by the soil equals the kinetic energy transferred to the cone from the penetrometer when the hammer contacts the strike plate. The calculations here assume that all of the hammer's kinetic energy is transferred to the cone. A mass falling a distance of 0.4 m will be traveling at a velocity (v) of 2.8 m s^{-1} when it reaches the strike plate (Eq. [2]).

$$v = \sqrt{v_0^2 + 2a(x)} = 2.8 \text{ m s}^{-1}, \qquad [2]$$

where v_0 is the velocity at time 0 (0 m s^{-1}), a is the acceleration due to gravity (9.8 ms^{-2}) and x is the negative change in height (0.4 m). The kinetic energy (KE) for a hammer of mass of 2 kg falling 40 cm is 7.84 J (Eq. [3]).

$$KE = W_s = \frac{1}{2}\text{m}v^2 = 7.84 \text{ J} \qquad [3]$$

Substituting the KE of the hammer into Eq. [1] for W_s allows a soil resistance to be calculated for each blow of the hammer. The resistance calculated by Eq. [1] represents the average value of soil resistance across the penetration distance of the penetrometer. The penetrometer measurements can either be expressed as the number of blows per meter of penetration, or as the average soil resistance for each depth of soil traveled by each blow of the hammer. This approach does not assume soil uniformity because it generates an average resistance across the depth the cone travels. These average numbers are clearly more informative for soils which are relatively uniform within the depth increment covered by each strike.

Repeatability of Measurements

The repeatability of the measurements depends on the consistency of the height from which the mass is dropped. The error can be reduced to ≈1 mm by always raising the hammer to the collar (Fig. 1). This is equivalent to just 0.02 J strike^{-1} using a 2-kg hammer.

Adaptability for a Range of Soil Resistance

Equation [3] explicitly accounts for hammer drop height, allowing the kinetic energy delivered with each hammer blow to be easily adjusted. This flexibility also allows a single penetrometer to be used on a broad range of soils without a loss in sensitivity or an increase in measurement time by simply moving the adjustable hammer stop. Furthermore, it allows the operator to increase the sensitivity in specific zones in which compaction is expected to occur. For example, if a compaction zone is anticipated at a depth of 12 cm, drop height could be reduced by 75% for the 10- to 15-cm depth. Sensitivity could be further enhanced by recording impacts within more narrowly defined zones (e.g., 11–13 cm) or by recording the depth of insertion generated by every strike. A recording device could be designed to automate this, but would result in a more expensive and less durable instrument.

The kinetic energy required to drive the penetrometer to a depth of 15 cm was compared using a 2-kg mass and three drop heights: 20, 40, and 60 cm. These configurations were designed to generate 3.92, 7.84, and 11.76 J strike^{-1}, respectively. These figures are based on Eq. [3]. The test was repeated at 20 randomly selected points in a flood-irrigated pasture on the New Mexico State University Experimental Farm using the methods described above under "Operation". Any sampling points which fell within 1 m of another point were discarded and another point was randomly selected. The field is mapped as a Glendale clay loam (fine-silty, mixed, superactive, calcareous, thermic Typic Torrifluvents). Gravimetric soil moisture content for the surface 15 cm averaged 24.3 ± 3.7% (mean ± SD; $n = 3$).

The average kinetic energy required was not significantly different for all three drop heights (Table 2; ANOVA; $n = 20$; $P = 0.25$). This supports the theoretically based conclusion that data collected using different drop heights can be reliably compared, allowing a single instrument to be applied to a wide range of soil conditions.

The coefficient of variation (standard deviation divided by the mean) was similar for all three drop heights. This suggests that for the soil and range included in this test (5 to 14 strikes per 15 cm; Table 2), the selection of a drop height may be based on other factors such as operator comfort or time limitations. The time required per measurement declined from ≈14 s at the 20-cm drop height to 5 s at the 60 cm drop, based on ≈1 s strike^{-1} (Table 2).

Comparison with Existing Designs

Because "the pattern of resistance is not affected by the type of instrument" (Baver et al., 1972), both static and dynamic penetrometers can be used to monitor changes within a particular soil at a selected moisture content. Direct comparisons between the two types of instruments cannot be made because they are measuring different parameters: Static penetrometers generate a cone index, which as force per unit area, while dynamic penetrometers measure actual resistance in terms of energy per unit depth.

One advantage of static cone penetrometers over the dynamic penetrometer described here is that the methods have been standardized (American Society of Agricutlural Engineers, 1992) and there is a large and growing body of literature relating the values to soil properties including bulk density and moisture content (Ayers and Perumpral, 1982). For example, Ley et al. (1995) found that root growth restriction in the Nigerian soils they studied may occur at matric potentials as high as −100 kPa. However, it has been difficult to develop equations which can be applied consistently across a range of treatments, even within a single soil series (Busscher et al., 1997). Consequently, most investigators attempt to make penetrometer measurements at near-constant moisture content in order to allow moisture-independent comparisons to be made. Changes in structure without changes in bulk density can also affect results. Future research should consider the relative effects of different soil properties on results obtained with dynamic penetrometers.

The proposed dynamic penetrometer combines the advantage of operator-independence found in dynamic penetrometers and the high-end mechanically operated static designs with the simplicity and portability of the manually operated static designs, and thus overcomes many of the limitations described above. It improves on the dynamic penetrometer design of Parker and Jenny (1945) by minimizing the problem of variable resistance with depth. Comparisons with other penetrometer designs which have been used for agricultural soils are summarized in Table 1.

Conclusions

The dynamic penetrometer described here represents a low-cost, durable, and reliable alternative to strain-gauge-based instruments. It is particularly appropriate for nearly all applications for which a manually operated static penetrometer would be used. It is particularly useful for applications in which soil conditions are highly variable, or operator consistency is questionable. Due to its durable, all-steel design and ease of use, it is easily adopted by farmers and ranchers. It, like other penetrometer designs, is sensitive to differences in soil moisture and texture, and cannot be used as a substitute for direct measurements of soil bulk density. The penetrometer can, however, be used to monitor changes in soil condition in response to management and to identify areas in which more detailed measurements are required. It can also be used to rapidly locate potential zones of compaction within a profile and areas of compaction within a field.

Table 2. Field comparison of penetrometers using different drop heights with a 2-kg mass. Data are based on number of hammer strikes necessary to reach a depth of 15 cm ($n = 20$). Values in the same column followed by the same letter are not significantly different ($P > 0.2$).

Drop height	Kinetic energy/strike	Strikes	Resistance	Total kinetic energy	CV
cm	J	mean ± S.E.	J cm^{-1}	J	%
20	3.92	13.8 ± 0.4	3.62a	54.3a	12.9
40	7.84	7.1 ± 0.3	3.72a	55.9a	17.7
60	11.76	4.9 ± 0.2	3.84a	57.6a	14.3

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