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COMMENTS & LETTERS TO THE EDITOR

Comments on "Simultaneous Measurement of Soil Penetration Resistance and Water Content with a Combined Penetrometer–TDR Moisture Probe" and "A Dynamic Cone Penetrometer for Measuring Soil Penetration Resistance"

Herrick and Jones (2002) described a dynamic penetrometer for use in soil science, and calculated the soil resistance from the work done to raise the hammer against the force of gravity. Vaz and Hopmans (2001) developed a dynamic penetrometer combined with a time-domain reflectometer (TDR) and presented an analysis for the calculation of the penetration resistance which takes into account the energy from the impact of the hammer and an additional energy due to penetration.

In this letter, we should like to point out the incomplete calculation of the penetration resistance by Herrick and Jones (2002), and the incorrect formulation by Vaz and Hopmans (2001). First we review the physics of the dynamic penetrometer. Consider the dynamic penetrometer (Fig. 1), initially with the hammer (mass M) lifted to a height h above the anvil. Assume that, before the mass is dropped on the anvil, the penetrometer is at equilibrium with the indented soil surface. When the hammer hits the anvil, the hammer and the shaft (mass m) move together into the soil. The energy applied by the action of dropping the hammer is

$$W = Mgh, \qquad [1]$$

where W is the energy (in J) and g is the gravity-acceleration constant. Herrick and Jones (2002) suggested Eq. [1] as the energy of penetration resistance of the soil. However, not all of this energy is transmitted to the soil. Upon impact (when the hammer hits the anvil), both the hammer and the shaft move together in the soil and there is a loss of energy. The energy balance for this system can be written as

$$W = W' + \Delta W, \qquad [2]$$

where W is the kinetic energy before the impact, W' is the energy after the impact, and ΔW is the energy loss. The equation for the conservation of linear momentum for this system is

$$Mv_M + mv_m = Mv'_M + mv'_m, \qquad [3]$$

where v_M is the velocity of the hammer just before the impact, v_m is the velocity of the shaft just before the impact (= 0), v'_M is the velocity of the hammer after the impact, and v'_m is the velocity of the shaft after the impact. Assuming an inelastic collision, the hammer and shaft move together immediately after the impact with velocity $v'_M = v'_m = v'$:

$$v' = Mv_M/(M + m). \qquad [4]$$

The kinetic energy before the impact is

$$W = 1/2 \times Mv_M^2, \qquad [5]$$

and the kinetic energy after the impact is

$$W' = 1/2 \times v'^2(M + m). \qquad [6]$$

Combining Eq. [6] with Eq. [4],

$$W' = 1/2 \times Mv_M^2[M/(M + m)]. \qquad [7]$$

From Newton's law, $v_M = \sqrt{2gh}$, thus

$$W' = Mgh[M/(M + m)]. \qquad [8]$$

This is assuming that all the energy loss is absorbed by the shaft and there is negligible friction between the penetrometer and soil. Dividing the right-hand term in Eq. [8] by the basal area of the cone and the distance of penetration, we obtain penetration resistance:

$$R = Mgh/(Ax) \times [M/(M + m)], \qquad [9]$$

where R is the resistance to penetration (Pa), x is the penetration distance (m), and A is the basal area of the cone (m^2). This is the well-known Dutch formula which can be found widely in the geotechnical literature (mostly in French) (Sanglerat, 1972; Waschkowski, 1983; Cassan, 1988; Maquaire et al., 2002).

Vaz and Hopmans (2001) suggested the inclusion of another term in Eq. [8] which accounts for the "energy available for penetration." The analysis is derived from Stolf (1991), who claimed that Eq. [8] is incomplete and the additional term has been ignored in the civil-engineering literature. We note that this analysis was presented much earlier by Scala (1956), and shall see later why this term has been absent from the literature. After the impact, the hammer and shaft ($M + m$) move together to distance x (Fig. 1), the work expended of this event according to Vaz and Hopmans (2001) is

$$W_x = (M + m)gx. \qquad [10]$$

Stolf (1991) and Vaz and Hopmans (2001) suggested inclusion of this term in the calculation of the energy for penetration resistance:

$$W'' = W' + W_x. \qquad [11]$$

The energy balance for this particular system is (Scala, 1956)

$$W + W_x = W' + \Delta W. \qquad [12]$$

As we will see by reductio ad absurdum, the addition of the term W_x in Eq. [11] and [12] is superfluous and violates the law of energy conservation.

Take the example from Vaz and Hopmans (2001), where M = 4 kg, m = 1.335 kg, and h = 0.4 m. The energy applied by dropping the hammer with falling height h = 0.4 m according to Eq. [1] is 15.7 J. If one blow produces penetration x of 5 cm, then the energy after the impact according to Eq. [11] is W'' = 14.4 J. Say, for a soil with weaker structure and higher moisture content, the penetration depth is 10 cm, the energy after the impact is W'' = 17.0 J. This is larger than the energy applied by the hammer! The resistance energy of the soil would be greater than the energy applied, yet the penetrometer moves 10 cm. We can see that the addition of the term W_x in Eq. [12] makes the penetrometer create 0.5 J of energy for every centimeter of penetration, whereas of course simply moving the penetrometer cannot create energy. The fact that the system ($M + m$) moves to distance x is due to the impact energy of the hammer and is not an additional energy input to the system, but a loss of available energy.

We have to note that this is an approximation based on Newton's principle for inelastic collision. In reality, the situation is more complicated; the fall of the hammer creates a wave impact in the rod which is transferred to the cone, which in turn transmits part of the energy to the soil (Cassan, 1988).

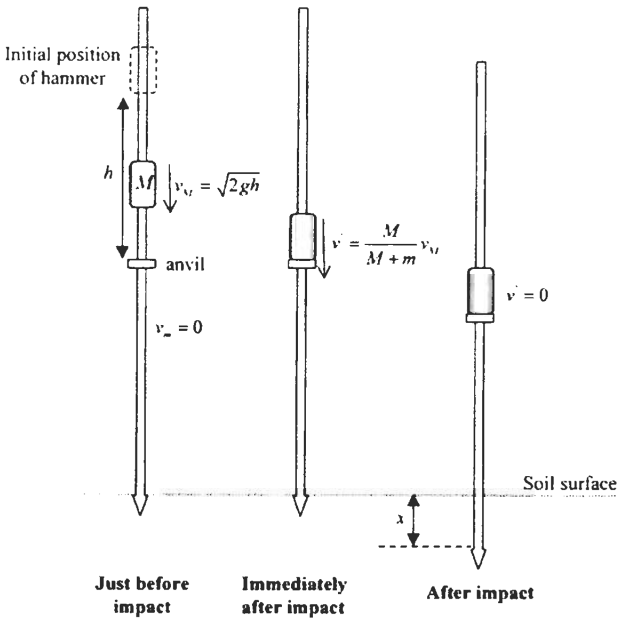

Fig. 1. The dynamic penetrometer with hammer mass M and shaft mass m before and after the hammer impact. v_M is the velocity of the hammer just before the impact, v_m is the velocity of the shaft just before the impact (= 0), and v' is the velocity of the hammer and shaft immediately after the impact with the anvil. The diagram is only for illustration, and is not drawn to scale.

It also does not take into account the work expended in compression of the soil (Gonin, 1999). The true energy can only be quantified with a time component; that is, observing the displacement of the cone tip with time. A proper analysis will require the wave equation, which has been used in civil engineering to determine pile driving (Isaacs, 1931; Smith, 1960). In the current condition of the dynamic penetrometer, Eq. [8] is a much better representation of reality than calculations based on either Eq. [1] or [11]. Finally, we note that Eq. [9] is an experimental measurement which does not give a unique soil property; rather it is a complex measure which depends on both the penetrometer and the soil condition.

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Response to "Comments on 'Simultaneous Measurement of Soil Penetration Resistance and Water Content with a Combined Penetrometer–TDR Moisture Probe' and 'A Dynamic Cone Penetrometer for Measuring Soil Penetration Resistance'"

My coauthor and I would like to thank Dr. Minasny and Dr. McBratney for their perceptive comments. We concur that by accounting for momentum, their Eq. [8] may more accurately reflect the energy transmitted from the sliding hammer to the penetrometer described in Herrick and Jones (2002). We also agree that their new estimate of resistance (Eq. [9]) remains "an experimental measurement which does not give a unique soil property; rather it is a complex measure which depends on both the penetrometer and the soil condition" (Minasny and McBratney, 2005).

Both statements are supported by an empirical test in which we compared the amount of energy required to push a 2.61-kg shaft 15 cm into the soil using 1-, 2-, and 4-kg hammers. The comparison was replicated at 10 randomly selected locations in a flood-irrigated pasture on the New Mexico State University Experimental Farm, resulting in a randomized complete block design. In theory, the energy required for all three hammers should have been identical. The relative difference in the average values for the three hammers generated by Eq. [8] of Minasny and McBratney (2005) (18.4 ± 4.0, 20.0 ± 3.6, and 25.4 ± 3.3 J) was somewhat smaller than differences in the average values generated by the equation reported in Herrick and Jones (2002) (66.6 ± 14.5, 46.6 ± 8.4, and 42.3 ± 5.5 J) (mean ± SD for 1-, 2-, and 4-kg hammers, respectively). This provides empirical support for the new equation. However, the new equation failed to eliminate the effect of hammer mass, which remained highly significant ($F_{2,18} = 10.3$; $P = 0.001$). The latter finding is likely due to a combination of instrument characteristics (e.g., mass-dependent variability in the elasticity of the collision) and mass-dependent soil–penetrometer interactions. It provides support for their statement that penetrometer measurements are the result of complex interactions between the soil and the instrument.

The complexity of these relationships does not, however, prevent penetrometers from being used to monitor changes in soil structure across time. As can be demonstrated mathematically, statistical comparisons among treatments are independent of the equation used. This is reflected empirically because the same coefficient of variation (CV) applies to both equations for replicate measurements made using the same hammer (21.8, 17.9, and 12.9% for a 1-, 2-, and 4-kg hammer, respectively). Identical CVs also result from an analysis of the raw data (number of strikes required to push the shaft 15 cm into the soil).

In conclusion, penetrometer data should continue to be treated as relative values, and comparisons should be limited to penetrometers of similar mass and dimensions regardless of the equation used. This restriction is similar to that applied to comparisons generated using the more common strain gauge penetrometers: treatment comparisons must be limited to instruments with similar dimensions that are inserted at a consistent rate (Bradford, 1986). Where the primary objective is to monitor change or make comparisons to a reference area, we recommend reporting the number of strikes per depth increment (e.g., Herrick et al., 2002) rather than using an energy or resistance indicator. A strike-based indicator is more easily communicated to land managers (Herrick et al., 2005). By maintaining the original data, reporting the number of strikes also allows subsequent application of different computational approaches.

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