The dynamic penetrometer for assessment of soil mechanical resistance

Christopher Vanags, Budiman Minasny and Alex B. McBratney

Faculty of Agriculture, Food and Natural Resources, The University of Sydney NSW, 2006, Australia. Email: cvan9487@mail.usyd.edu.au

Abstract

Soil penetration resistance is an important mechanical property that can be used as an indicator of soil compaction and is important in determining the least limiting water range. We present the use of a simple and relatively inexpensive instrument, the dynamic penetrometer, to measure soil mechanical resistance in the field. The dynamic penetrometer uses a calculated amount of kinetic energy to move a specialized cone a certain distance through the soil, which is then converted to penetration resistance using a simple formula. This paper shows the theory, calculation and practical application for quantifying soil penetration resistance with depth. Application in two adjacent fields in Narrabri, NSW, showed its effectiveness in comparing the soil strength in soils under differing management regimes.

Key Words

Soil strength, tillage, penetrometer, Dutch formula, soil structure.

Introduction

Soil strength is an important characteristic affecting many aspects of agricultural soils, such as the performance of cultivation implements, root growth, least-limiting water range and the trafficability. The strength of soil results from cohesive forces between soil particles and their frictional resistance to sliding past or over one another. Characterisation of soil strength is usually made by measuring the response of a soil to a range of applied forces. Penetrometers are widely used to measure the soil resistance to penetration, expressed as force per unit cross-sectional area of the cone-base (Bengough *et al.* 2001). Penetrometers are one of the most widely used methods of estimating resistance to root growth in soil, and may also be used for detecting layers of different soil strength. Penetrometer measurements can be done relatively quickly and easily, and can provide valuable data.

Different types of penetrometers have been developed to measure soil penetrability (Bengough *et al.* 2001; Lowery and Morrison 2002) that operate on static or dynamic principles. The static penetrometer is pushed into the soil at a constant rate, while the dynamic penetrometer is driven into the soil by repeated hammer-blows (used mainly in civil engineering). Herrick and Jones (2002) described a dynamic penetrometer for use in soil science, enabling cheap, repeatable soil strength assessments in the field. It consists of a metal rod with a conical tip at one end, an anvil or strike plate around the rod and a sliding hammer with a fixed mass at the other end (Figure 1). The cone is pushed into the soil by successive blows of the sliding hammer against the anvil. The strike of the hammer applies an amount of kinetic energy determined by the work required to raise the mass of the (frictionless) hammer through a distance influenced solely by gravity (Herrick and Jones 2002). Unlike the static penetrometer, the dynamic penetrometer does not push the cone through the soil at a constant velocity nor does it apply a continuous force to the penetrometer.

The first use of the dynamic penetrometer in soil science is Parker and Jenny (1945) that quantified the soil resistance by measuring the energy required to drive a soil-sampling tube into the soil. This is achieved by using a hammer of 9.1 kg lifted 30 cm above the tube and then measuring the distance the tube moved into the soil. The resistance is expressed as Joule per cm of soil. The dynamic penetrometer used in the present study (also known as the Scala penetrometer) comes from the design of A.J. Scala, an Australian engineer, who developed this method to measure soil strength for the purpose of road design (Scala 1956). Other application of the dynamic penetrometer in soil science is by Meshalkina *et al.* (1995). They used a 50 g weight falling from the height of 30 cm on a metal rod with a flat tip. Vaz and Hopmans (2001) developed a dynamic penetrometer combined with a TDR that allows for simultaneous measurement of penetration resistance and moisture content.

The purpose of this paper is to illustrate the application of the dynamic penetrometer to characterise soil strength as a function of depth under different land uses.

© 2004. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, 5 – 9 December 2004, University of Sydney, Australia.
Published on CDROM. Website www.regional.org.au/au/asssi/

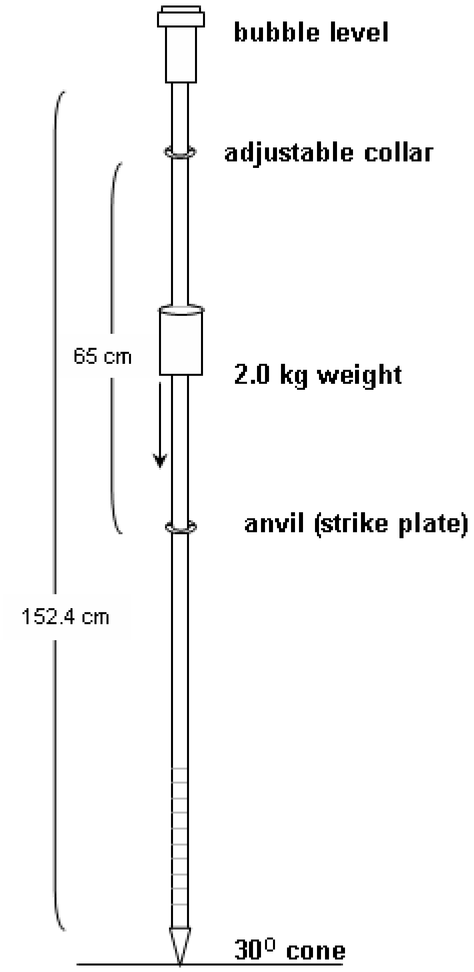


Figure 1. Simplified schematic of the dynamic penetrometer used. The parts consist of a 2 kg weight which slides between two collars (the anvil being welded in place) on a steel rod with a cone attached to the bottom and a bubble level on top. The total mass of the apparatus is 4.2 kg. Redrawn from Herrick and Jones, (2002).

Theory

The penetrometer was comprised of a hammer of mass, *m*, and a shaft mass *m'* (which included the rod, the anvil, cone and other parts attached to the penetrometer). The hammer (mass *m*) was lifted to height *H* and dropped to produce an amount of kinetic energy, *W* (in J kg^{-1}), described as:

$$W = mgH \ . \qquad (1)$$

Not all of the energy from the hammer was transmitted to the soil at the impact (when the hammer hit the anvil) because both the hammer and the shaft moved downward together into the soil. A modification to this energy therefore needs to be made using the so-called “Dutch formula” (Sanglerat 1972; Cassan 1988), which calculates the soil resistance as follows:

$$R = \frac{mgH}{A\Delta z}\frac{m}{m+m^{'}} \qquad (2)$$

where:
R is the resistance to penetration (Pa),
A is the basal area of the cone (m^2),
g is the gravity acceleration constant (= 9.81 m s^{-2}),
m is the mass of the hammer (kg),
m’ is the mass of the shaft (kg).
Δz is the depth of penetration (m).

We note that this is a better approximation over the formulation presented in Herrick and Jones (2002) and is a correction to the formulation presented in Vaz and Hopmans (2001).

Materials and Methods

A survey was conducted at the Australian Cotton Research Institute, Narrabri, NSW, Australia 149^o 35' 24" E and 30^o 12' 21" S. The survey area was approximately 7000 m^2 and comprised two different land use management practices adjacent to each other and separated by a line of well established trees. Approximately one third the survey area consisted of non-cultivated pasture, which had no known chemical or mechanical disturbances during the last ten years. The other two thirds of the survey area had been tilled regularly for the past ten years, and kept to a bare fallow (serving as a source for potting soil). The soil in both areas is a Epicalcareous epipedal Black Vertosol, which can be translated as a black self-mulching, cracking clay with evidence of calcium at depth and crusting on the surface. The organic carbon content of the cultivated soil (1.2 %) was considerably less than that within the pasture area (3.0%). This soil was agriculturally important and representative of many soils within the district. Under irrigation and natural precipitation, the high organic carbon content allowed for soil moisture to be held strongly for prolonged periods of time, which reduced potential deep drainage. Overall, it was a well structured soil with no evidence of salinity, only periodic wetting and hence, a good soil medium for optimal plant growth.

A total of 55 sample sites were visited randomly in the area covering both land uses, at each site the following measurements were taken: soil penetration resistance, shear strength, moisture content and apparent electrical conductivity. The penetrometer used in this study was based on the design of Herrick and Jones (2002). The hammer had a weight of 2 kg and the shaft (rod, cone and bubble level) weighed 2.2 kg. For the measurement, the penetrometer was placed with the cone tip pressed into the soil. A small circular bubble level placed on the end of the penetrometer enabled the operator to keep the shaft vertical. The slide hammer (weight 2 kg) was raised to a height of 65 cm and then released. This operation defined one 'blow' of the dynamic penetrometer and this was repeated until a penetration depth of 15 cm was reached.

Average soil water content of the top 15 cm of soil was measured using a TRASE time-domain reflectometer (TDR) with a 15 cm waveguide inserted vertically in the soil. In addition to the field survey, penetrometer resistance was measured on 10 sites (five sites under two different land uses), arranged along transects with 10 m separation. At each of the sites, the depth of penetration, Δz, for each hammer blow from the height of 55 cm was recorded. This method was used to evaluate changes in penetration strength down the soil profile. Because soil strength generally decreases with increasing soil water content in cracking clays, this method also indicated (indirect) changes in soil water content with depth (assuming relatively uniform particle packing – ie. bulk density - with depth). After measuring the penetration resistance at field moisture conditions, the sites were wetted to saturation and allowed to drain for 24 hours, after which measurements were taken a second time to evaluate soil resistance at a nominal 'field capacity'.

Results and Discussion

Penetration resistance due to cultivation

Contour maps were generated by interpolating the data points with ordinary kriging to a regular 1 m grid. The contour map of penetration resistance (Figure 2a) shows the relatively clear divide between land uses, where the majority of the field under cultivation had low penetrometer resistance.

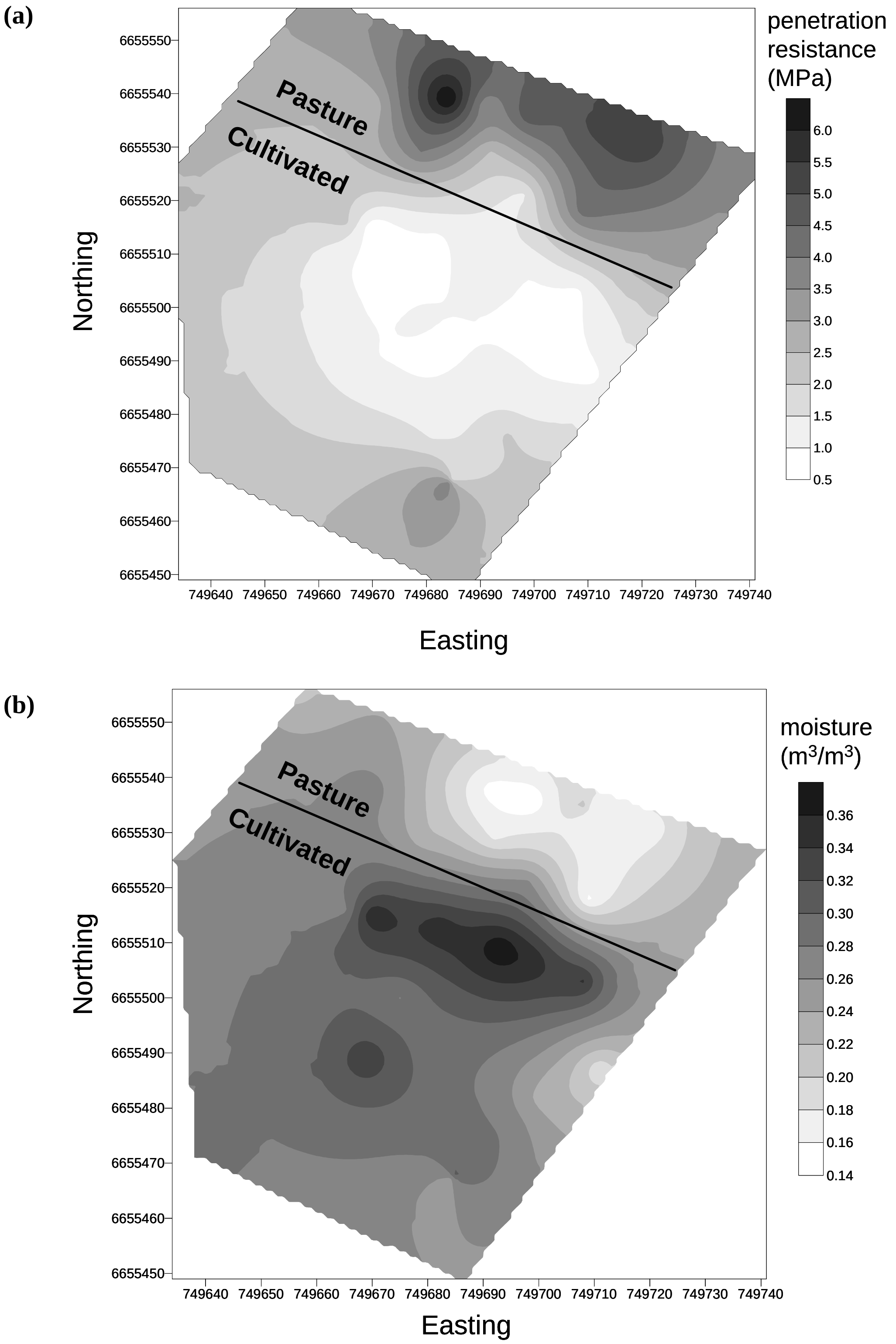


Figure 2. Contour plot of (a) penetration resistance (MPa) and (b) moisture content (m^3m^{-3}), shown across differing management zones (annotated on figure).

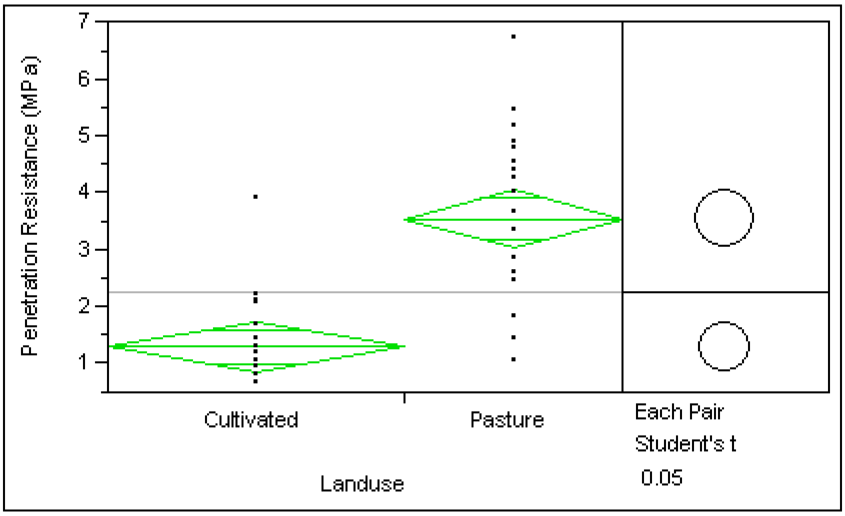


Figure 3. One way ANOVA t-test for landuse and penetration resistance. The means diamond illustrates the mean with 95% confidence interval. The circles represent the least significant differences for each land-use.

The non-cultivated area to the north had greater penetration strength. As expected, the soil strength (Figure 2a) was spatially correlated (inversely) with the soil water content (Figure 2b), wherein the pasture site had significantly smaller water content and greater penetration resistance compared to the cultivated soil (Figures 2b, 3).

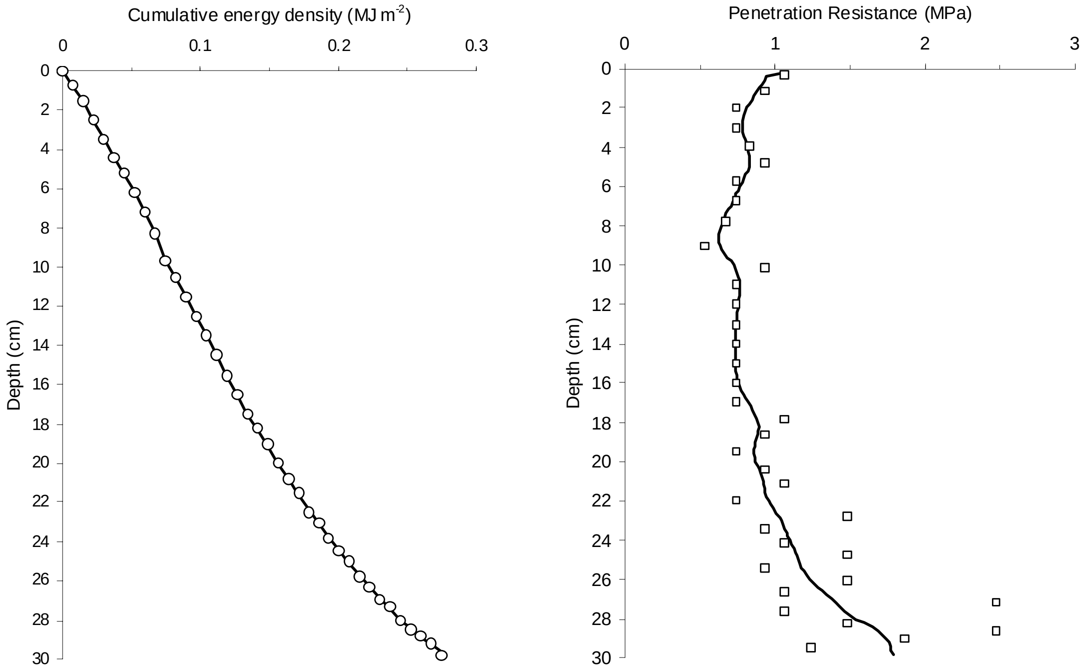
Penetration resistance depends on many factors, the more important ones being water content and bulk density. The cultivated area had larger water contents and smaller soil resistance, although it is likely that tillage broke the natural aggregates into weaker units, unlike the uncultivated pasture, which had stronger aggregates due to lack of soil disturbance and greater organic matter contents.

Profiling the penetration resistance

The penetration resistance profiles (e.g. Lowery and Morrison 2002, Figure 2.8-4) were obtained using the dynamic penetrometer by recording the depth of penetration, z, for each hammer blow. The direct way to analyse the data would have been to calculate the resistance (derived from depth of penetration) (equation (3)) at each blow. However each blow produced discontinuous values as a function of depth, so the values obtained by direct calculation were seen to be quite variable (e.g. Figure 4b). An alternative way of analysing the data was therefore to calculate the cumulative energy density (E_d in J m^{-2} or N m^{-1}) with the depth of penetration:

$$E_d\left(z\right) = N\frac{mgH}{A}\frac{m}{m+m'} \qquad (4)$$

where N is the number of blows required to reach depth, z, and fit a spline to the cumulative energy versus depth graph. This served to interpolate between the points and to smooth the curve (Figure 4a). The penetration resistance at each depth was then obtained by differentiating the cumulative energy with respect to the depth dE_d/dz (Figure 4b).



(a) **(b)**

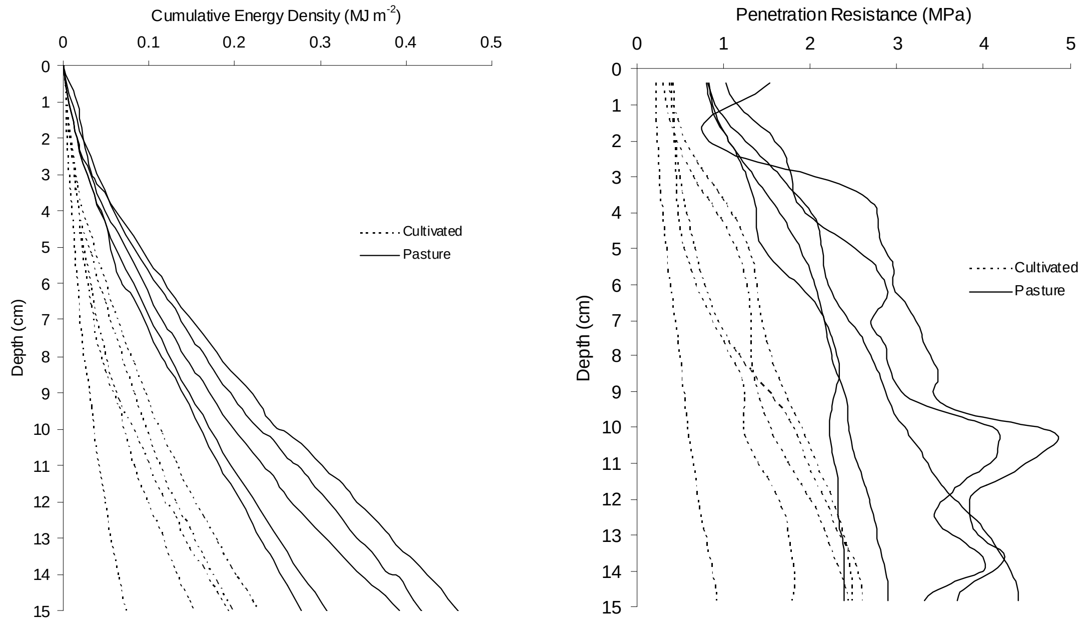
Figure 4. (a) Cumulative energy density (MJ m^{-2}) versus depth (cm) of a single wetted profile, the white dots represent measured values and the bold curve is a fitted spline. (b) Predicted penetration resistance (bold curve) from differentiating the cumulative energy density over depth, the white dots are values directly calculated from field data.

Figure 5a shows the relationship between cumulative penetration depth and cumulative energy density for sites under cultivation and pasture. This figure was used to discern the mechanical properties of the soil down the profile and identify the structural difference between the sites under pasture and cultivation. On both sites, the strength of the soil increased with depth, with the pasture having greater strength compared to the cultivated soil. Of particular interest was a dramatic increase in soil strength under pasture at a depth of 10-12 cm in two adjacent profiles. This may have been the result of localised compaction caused by animal or machinery traffic, or that of a localised pedological anomaly such as calcium carbonate precipitation.

Relationship with other soil properties

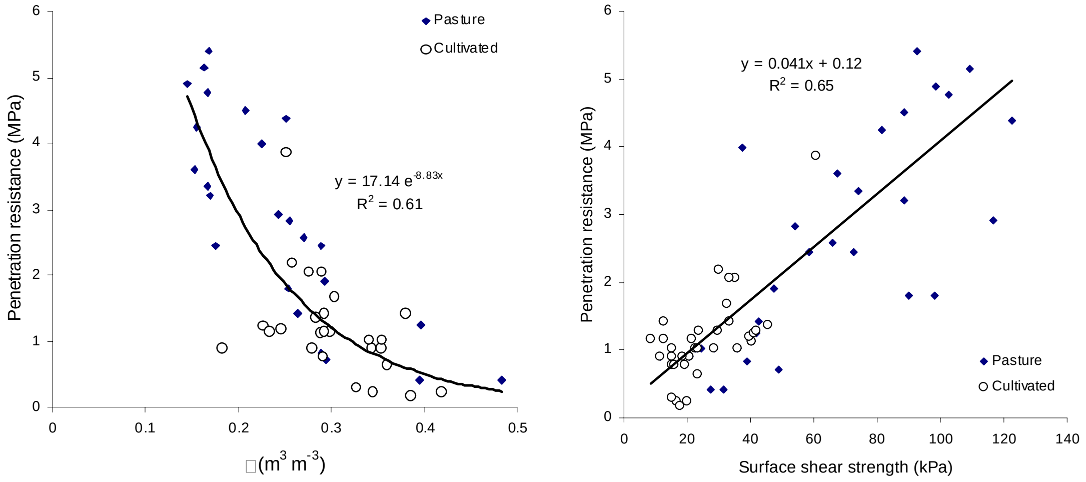
Within a soil type, penetration resistance is affected by the water content, bulk density and structure of the soil (Bengough *et al*. 2002). The relationship between the penetration resistance and two other soil physical properties is shown in Fig. 6. Both graphs show the relationship with penetration resistance and landuse quite readily. The difference in the shear strength is not as pronounced as the penetration resistance, because the penetrometer compounds shear, compressive and tensile strength and friction.

There is an exponential relationship observed between with moisture content and penetration resistance. This can be attributed to water molecules decreasing the cohesion between the particles as well as acting as a lubricant between the clay particles, thus reducing the frictional forces that need to be overcome to shear the soil.



(a) **(b)**

Figure 5. (a) Cumulative energy density for soil under cultivation and pasture. (b) Predicted profile penetration resistance.



(a) **(b)**

Figure 6. Relationship between penetration resistance and (a) moisture content, (b) surface shear strength.

Conclusions

We looked at various ways to extract information from soil penetration resistance. Our analysis can translate the data into penetration profiles, which may be useful for discerning hard pans or compacted layers. The dynamic penetrometer proved valuable because it enabled us to envisage the differences in soil structure at field capacity as a function of depth and soil management history.

With our current state of knowledge and technology, the data produced by the dynamic penetrometer must be interpreted semi-qualitatively because differences in strength at field capacity are difficult to separate from effects of water content. Comparisons with other more established measurements, such as the static penetrometer, need to be made. However, as with other penetrometers, it is essential to specify the characteristics of the rod and cone of the dynamic penetrometer as well as the formulae used to calculate the soil resistance.

Acknowledgement

The authors would like to acknowledge the surveying efforts of the Soil Physics 2004 students at the University of Sydney. Interested readers may visit their website at www.usyd.edu.au/su/agric/web04.

References

Bengough AG, Campbell DJ, O'Sullivan, MF (2001) Penetrometer techniques in relation to soil compaction and root growth. In Soil and Environmental Analysis. Physical Methods. 2nd Edition. Eds. KA Smith, CE Mullins. pp. 377-403. Marcel Dekker: New York.

Cassan M (1988) Les essais in situ en méchanique des sols, Volume 1 réalisation et interpretation. 2ème edition, pp 146 – 151. Eyrolles: Paris.

Herrick JE, Jones TL (2002) A dynamic cone penetrometer for measuring soil penetration resistance. *Soil Science Society of America Journal* **66**, 1320-1324.

Lowery B, Morrison JE (2002) Soil penetrometers and penetrability. In 'Methods of Soil Analysis, Part 4, Physical Methods'. Eds. JH Dane, GC Topp pp. 363-388. Soil Science Society of America, Inc.: Madison, WI.

Meshalkina JL, Stein A, Dmitriev YeA (1995) Spatial variability of penetration data on Russian plots in different land use. *Soil Technology* **8**, 43-59.

Parker ER, Jenny H (1945) Water infiltration and related soil properties as affected by cultivation and organic fertilization. *Soil Science* **60**, 353–376.

Sanglerat G (1972) The Penetrometer and Soil Exploration. Developments in Geotechnical Engineering 1. Elsevier Publishing: New York.

Scala AJ (1956) Simple method of flexible pavement design using cone penetrometers. Proceedings of the 2nd Australian and New Zealand Conference on Soil Mechanics and Foundation Engineering, pp. 73-83 New Zealand Society of Soil Mechanics and Foundation Engineering: Christchurch.

Vaz CMP, Hopmans JW (2001) Simultaneous measurement of soil penetration resistance and water content with a combined penetrometer–TDR moisture probe. *Soil Science Society of America Journal* **65**, 4-12.