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The effects of compaction and soil drying on penetrometer resistance

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ABSTRACT

Penetrometer resistance is widely used as a measure of the mechanical impedance that roots experience in either drying or compacted soil. However, there are relatively few models to predict penetrometer resistance that can be applied without detailed knowledge of soil texture, organic matter content, soil water status, density or other soil variables. Few models allow the effects of management on penetrometer resistance to be predicted in a simple way. It would be useful if it were possible to predict the effects of structure, compaction, and soil drying on penetrometer resistance. We designed a laboratory experiment to explore how compaction and subsequent soil drying affected the penetrometer resistance of three soils: a loamy sand and two silty clay soils with very different organic carbon contents. By assuming that penetrometer resistance is proportional to the small strain shear modulus, G, we were able to develop an empirical model to explain the effects of compaction and soil drying on penetrometer resistance. The parameters of the model were determined by fitting it to experimental data collected in the laboratory. The model was tested on field data using sensed matric potential data and measured soil density data. Model predictions were compared with those obtained with an earlier model. Both approaches explained approximately 60% of the variance in the measured penetrometer data. The future application of this approach is discussed.

1. Introduction

Lower root elongation is almost always associated with lower shoot growth and hence yields (Whalley et al., 2008). While the mechanistic explanation for the effects of high soil strength on lower yields is not fully understood (Dodd et al., 2010), there is a widely reported association between strong soil and lower yields (Masle and Passioura, 1987; Lipiec and Hatano, 2003; Whalley et al., 2006, 2008). Interpreting the effects of abiotic stresses on both root and shoot elongation can be complicated because they (water stress and soil strength in particular) are highly correlated and it can be unclear which stress (or stress combination) is limiting growth (Whitmore and Whalley, 2009; Bengough et al., 2011). Penetrometer resistance is widely used as a measure of the mechanical impedance that roots experience in either drying or compacted soils (Whalley et al., 2007). The resistance of a standard penetrometer tends to be higher than that experienced by roots, mainly due to the effects of soil to metal friction that is higher than root to soil friction (Bengough et al., 1997; Whalley et al., 2005). However, penetrometer resistance is closely correlated with both root and crop growth.

It would be useful to have a simple model to relate soil physical conditions and the effects of soil management to penetrometer resistance. The soil factors that affect penetrometer resistance are known, for example: bulk density, soil water status, soil depth and compaction episodes (Aggarwal et al., 2006; Whalley et al., 2007; Whitmore et al., 2011). It is also the case that many approaches to predict soil penetrometer resistance from a number of soil characteristics including particles size distribution, organic matter content, bulk density, and water content have been published. Recent examples have been described by To and Kay (2005), Stock and Downes (2008), and Vaz et al. (2011) and these are often referred to as pedotransfer functions (PTF). While they are useful in a descriptive sense and can give direct predictions of the effect of soil drying on penetrometer resistance, their usefulness for developing a soil management strategy is limited. An interesting approach is described by Dexter et al. (2007), who used the slope of the water release characteristic at the point of inflexion to predict penetrometer resistance. The advancement made by Dexter et al. (2007) was to relate a soil property that can be manipulated by a soil management strategy to penetrometer resistance. The approach of Dexter et al. (2007) is more sophisticated than the conventional PTF because more subtle aspects of soil structure can be considered. Another important limitation of the conventional PTF approach is that they require too many soil variables to be measured and many of these (e.g. particle size distributions) vary

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around fields and are not easily determined. Progress has been made at reducing the number of variables required by PTF models of penetrometer resistance, mainly by defining soil water status as the product, $S\psi$, where S is the degree of saturation and ψ is the matric potential (Whalley et al., 2007). For a wide range of loose soils penetrometer resistance was simply found to be proportional to $S\psi$ (Whalley et al., 2005). In recent work, Gao et al. (2012) developed an empirical model for penetrometer resistance, which was based on the compression characteristic of soil. For relatively moist and hence compressible soils, they were able to predict the penetrometer resistance of five soils compressed to different degrees and drained to high matric potentials (i.e. very moist soils). The advantage of this model was that it used only three parameters and was independent of soil type within the range of soils studied. An application of this model would be to relate the mechanical impedance to seedling growth to ground pressures due to trafficking. It would be useful if it were also possible to predict the effects of soil drying on the increase in penetrometer resistance as a function of soil structure and previous compaction episodes. Ultimately, this would allow us to predict how compaction and soil management affect yield.

In this paper our objective is to explore the effects of applied stress, density, matric potential, and soil structure (as summarized by the air entry potential) on penetrometer resistance. We develop a model for penetrometer resistance with relatively few fitted parameters. This model is based on the simple idea that penetrometer resistance is proportional to the shear modulus. The model was tested using penetrometer measurements from the field, sensed matric potential data, and measured soil density data. Model predictions were also compared with those obtained with an earlier empirical model of Whalley et al. (2007). The utility of the model developed is that it can be used to explore the effect of relatively complex interactions between applied pressure, void ratio, air entry potential and matric potential on penetrometer resistance.

2. Materials and methods

2.1. Lab experiments

2.1.1. Soil samples

Three soils with contrasting physical and mechanical properties were used in our experiments (Table 1). They were collected from the top 20 cm of two Rothamsted Research experimental fields: Highfield (Harpenden) and Butt Close (Woburn). The soil textures were silty clay loam that had grassland and fallow soil management (Watts and Dexter, 1997) and loamy sand that was from an arable site (Whalley et al., 2008). The soils will be referred to as: arable loamy sand (A_{LS}), Fallow, silt clay loam (F_{ZCL}), and Grassland, silt clay loam (G_{ZCL}). Soil samples were gently broken up by hand under field moist conditions before being air dried and sieved through a 2-mm sieve.

2.1.2. Consolidation behaviour

We determined the water content θ_m at which these soils were most compressible with the method described by Gregory et al. (2010). The air-dried soil samples were slowly wetted to a range of water contents. The moist soils were stored in plastic bags at 4 °C for 48 h before being packed into plastic tubes (64 mm in diameter, 50 mm height) using a pneumatic soil press fitted with a 60-mm diameter piston. The press was set to give soil an axial stress of 200 kPa. There were three replications for each soil and water content. During the compaction process, there was no visible water drainage from the soil cores. The wetted soil samples were packed into the tubes in layers approximately 10-mm deep. The soil cores were weighed before the samples were oven-dried at 105 °C for 24 h for the determination of dry bulk density and water content.

2.1.3. Soil water release characteristic curve and penetrometer resistance measurement

The complete experimental regime is summarized in Fig. 1. Air-dry soil samples were wetted to the water contents θ_m, where the soil was most compressible. The soil samples were then compressed with an axial pressure of 30, 200, and 1000 kPa, respectively. These axial pressures were selected to represent low, moderate, and high axial pressures covering the range that might be experienced in the field (e.g. Kim et al., 2010). The cylindrical plastic tubes (64 mm in diameter, and 50 mm height) were packed in layers approximately 10 mm deep. The final height of soil in the cores was typically 46 mm. In the case of the soil compacted with an axial stress of 1000 kPa there was some water drainage from the soil during compaction.

The compressed soil samples were then equilibrated on a tension table at 0 kPa. Water retention characteristics were determined by equilibrating the saturated cores to a range of water potentials; −1, −3, −5, −7, −10, and −30 kPa with a tension table and −100, −300, and −500 kPa, with a pressure plate apparatus. At each water potential, the new weight and height of soil cores were recorded. The measurements at −1, −3, −5, and −7 kPa were used solely to determine the shape of the water release characteristic at high matric potentials and not used in subsequent measurements. The penetrometer resistance was measured on all the other samples. The method of measuring soil penetrometer resistance, Q, was described by Gao et al. (2012). Briefly, a small cone penetrometer with a cone-base diameter of 2 mm and 60° cone angle was driven into the soil at a rate of 20 mm/min using a universal test frame (Davenport–Nene Test Frame DN10, Wigston, UK). The force required to push the cone

Table 1
The properties of soil used in the experiments.

Property	Rothamsted		Woburn
Soil abbreviation	F_{ZCL}	G_{ZCL}	A_{LS}
Land use	Fallow	Grass	Arable
Location	Highfield Rothamsted	Highfield Rothamsted	Butt Close, Woburn
Latitude	51.80420°N	51.80402°N	52.01220°N
Longitude	0.36140°W	0.36182°W	0.59665°W
Soil type FAO[a]	Chromic Luvisol	Chromic Luvisol	Cambic Arenosols
Sand ($g\,kg^{-1}$ dry soil)	178	179	876
Silt ($g\,kg^{-1}$ dry soil)	525	487	55
Clay ($g\,kg^{-1}$ dry soil)	297	333	70
Texture, SSEW[b] class[a]	Silt clay loam	Silt clay loam	Loamy sand
Particle density ($g\,cm^{-3}$)	2.614	2.464	2.660
Organic matter ($g\,kg^{-1}$ dry soil)	20	54	10

[a] Avery (1980).
[b] Soil Survey of England and Wales.