Open Research Online

The Open University's repository of research publications
and other research outputs

Estimating penetrometer resistance and matric potential from the velocities of shear and compression waves

Journal Item

How to cite:

Gao, W.; Watts, W. R.; Ren, T.; Shin, H.; Taherzadeh, S.; Attenborough, K.; Jenkins, M. and Whalley, W. R. (2013). Estimating penetrometer resistance and matric potential from the velocities of shear and compression waves. *Soil Science Society of America Journal*, 77(3) pp. 721–728.

For guidance on citations see [FAQs](#).

© 2013 Soil Science Society of America, Inc.

<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.2136/sssaj2012.0394>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Estimating Penetrometer Resistance and Matric Potential from the Velocities of Shear and Compression Waves

W. Gao

Dep. of Soil and Water Sciences
China Agricultural Univ.
Beijing, China 100193

C.W. Watts

Rothamsted Research
West Common
Harpenden, St Albans, AL5 2JQ, UK

T. Ren

Dep. of Soil and Water Sciences
China Agricultural Univ.
Beijing, China 100193

H.-C. Shin

S. Taherzadeh

K. Attenborough

Open Univ.
Walton Hall
Milton Keynes, MK7 6AA, UK

M. Jenkins

Delta-T Devices
130 Low Road
Burwell, Cambridge, CB25 0EJ, UK

W.R. Whalley*

Rothamsted Research
West Common
Harpenden, St Albans, AL5 2JQ, UK

Recently there has been interest in using the velocity of elastic waves to deduce soil physical properties. We wanted to validate the suggestion that the small strain shear modulus has a relatively simple linear relationship with penetrometer resistance. We were also interested in testing published equations for predicting shear wave velocity with an independent data set. Three soils were investigated in this study: a loamy sand soil and two silty clay loam soils. The soils were packed into cores with vertical axial stresses of 30, 200, or 1000 kPa. Following saturation, they were drained to a range of matric potentials between -10 and -500 kPa. After equilibration, we measured the velocities of shear (S wave) and compression (P wave) waves as well as the penetrometer resistances. Our data confirmed a previous proposal that the penetrometer resistance was an approximately linear function of the small strain shear modulus but tested the relationship by direct measurement. The relationships were found to have some sensitivity to soil type. Nevertheless, we show for the first time that there is considerable potential for using S wave velocity to deduce penetrometer resistance with a calibration that is relatively insensitive to soil type. Although estimation of the matric potential with either shear or compression wave velocity was found not to be very accurate, the possibility for estimating the matric potential from an elastic wave velocity given a priori knowledge of the void ratio is an interesting opportunity.

It would be useful if the velocity of elastic waves (Lu et al., 2004; Lu and Sabatier, 2009; Whalley et al. (2011, 2012) could be used to deduce soil physical properties that can be directly related to root growth. Of these, in drying soil, penetrometer resistance and matric potential are among the most important (Whalley et al., 2007; Whitmore and Whalley, 2009; Bengough et al., 2011; Whitmore et al., 2011). In this study, we explored the use of either shear waves (S waves) or compression waves (P waves) in soil as a tool for deducing soil physical properties, particularly matric potential and penetrometer resistance.

The velocity of an S wave, V_s , is given by

$$V_s = \sqrt{\frac{G}{\rho}} \quad [1]$$

where G is the small strain shear modulus and ρ is the soil bulk density. The velocity of a P wave is given by

$$V_p = \sqrt{\frac{B+4G/3}{\rho}} \quad [2]$$

where B is the coefficient of incompressibility (Nakagawa et al., 1997; Santamarina et al., 2001).

Soil Sci. Soc. Am. J.
doi:10.2136/sssaj2012.0394
Received 21 Nov. 2012.

*Corresponding author (Richard.whalley@rothamsted.ac.uk).

© Soil Science Society of America, 5585 Guilford Rd., Madison WI 53711 USA

All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Permission for printing and for reprinting the material contained herein has been obtained by the publisher.

Earlier work (Whalley et al., 2012) has shown that the velocity of an S wave in soil, V_s , is given by the following empirical relationship:

$$V_s = A \frac{(F - e)^2}{1 + e} \left[\sigma_s^r - \psi \left(\frac{\psi}{\psi_{ac}} \right)^{-0.55} \right]^\gamma \quad [3]$$

where e is the void ratio, ψ is the matric potential (kPa), ψ_{ac} is the air-entry potential (kPa), and σ_s is the net stress applied to the soil (kPa); A , F , r , and γ are adjustable empirical parameters but for a relatively wide range of soils their values do not depend on soil type. Thus, provided e , σ_s , and ψ_{ac} are known, in principle, it should be possible to estimate ψ from measurements of V_s .

Previously, Gao et al. (2012a) proposed that the penetrometer resistance, Q , is a linear function of the small strain shear modulus G (from Eq. [1], $G = \rho V_s^2$) such that

$$Q = kG \quad [4]$$

Gao et al. (2012b) estimated shear wave velocity with Eq. [3]; however, the validity of Eq. [4] has not been tested with measurements of both V_s and Q made on the same soil sample.

In this study, our objectives were (i) to provide an independent assessment of the ability of Eq. [3] to predict shear wave velocity in soils, (ii) for the first time to compare Q and G , determined from V_s , with measurements on the same soil cores, and (iii) to evaluate the scope for using shear and compression wave velocity data to predict matric potential.

MATERIALS AND METHODS

Soils and Sample Preparation

The three soil samples used in this study included one loamy sand soil and two silt clay loam soils (Table 1). The loamy sand soil was collected from an arable field located at Butt Close, Woburn, UK, as described by Whalley et al. (2008). The silty clay loam soils were collected from the Rothamsted Research

long-term experimental field located at Highfield, Harpenden, UK. The land uses of these silty clay loams were continuous fallow and grassland (Watts and Dexter, 1997). All of the soil samples were collected from the top 0- to 20-cm soil layer. Soils were collected from the three replicated treatment locations within both experiments. The three subsamples from each treatment were then bulked, forming a representative sample. The soil samples in this study were an arable loamy sand (A_{LS}), a fallow silty clay loam (F_{ZCL}), and a grassland silty clay loam (G_{ZCL}).

Following collection from the field, the soils were air dried and sieved through a 2-mm sieve. The sieved soil was wetted to a water content at which it was most compactable (Gregory et al., 2010; Gao et al., 2012a). The wetted soils were stored in a plastic bag for 48 h at 4°C and then packed into a plastic tube (50 mm high and 64 mm in diameter) using a pneumatic press. Three axial compression stress levels were used (30, 200, and 1000 kPa) to consolidate the soil samples. 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 packed soil cores were equilibrated at 0 kPa on a tension table and then drained to five matric potentials: -10 and -30 using a tension table and -100, -300, and -500 kPa using pressure plate equipment. Nine samples (3 axial stresses $\times$ 3 treatments) of each soil were placed randomly on one of nine predetermined locations within the pressure vessel or tension table. Following equilibration, the samples were taken off for measurement in a predetermined random order.

The penetrometer resistance and the velocity of S and P waves (see below) were measured in the equilibrated soil samples. The final water content and void ratio were also determined. The experiment had 3 replications $\times$ 3 compression levels $\times$ 5 matric potentials = 45 treatment combinations for each of the three soils.

Penetrometer Resistance Measurement

The penetrometer resistance was measured with the method used by Gao et al. (2012a, 2012b). A 2-mm-diameter and 60° cone angle penetrometer was inserted into the soil core at a constant speed of 20 mm min⁻¹ from the surface to the 30-mm depth using a universal test frame (Davenport-Nene Test Frame DN10). An electronic balance was used to record the force that was experienced by the penetrometer in each soil. Three vertical penetrometer measurements were made on each soil core.

Measurement of Compression and Shear Wave Speeds

Shear wave (S wave) velocity, V_s , and compression wave (P wave) velocity, V_p , were measured using piezo-ceramic devices at the top and bottom of the cylindrical samples as shown in Fig. 1. The electrical input signal was a single cycle of a sine wave with a 0.2-ms period. This signal was converted into an elastic wave by one

Table 1. The properties of soil used in the experiments.

Property	Rothamsted		Woburn
	F_{ZCL}	G_{ZCL}	A_{LS}
Land use	fallow	grassland	arable
Location	Highfield, Harpenden, UK	Highfield, Harpenden, UK	Butt Close, Woburn, UK
Latitude	51.80420° N	51.80402° N	52.01220° N
Longitude	0.36140° W	0.36182° W	0.59665° W
Soil type			
USDA†	Paleudalf	Paleudalf	Udipsamment
FAO†	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‡ classt	silty clay loam	silty 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

† Avery (1980).

‡ Soil Survey of England and Wales classification.

of the devices, which was then detected by the second device. The time taken for the P or S wave to travel the length of the core was determined by comparing the signal input to the soil core with the detected wave (Whalley et al., 2011). The sensors, related electronics, and software are available commercially (GDS Instruments).

RESULTS AND DISCUSSION

Soil Water Content and Density

The water release characteristics of the soil samples were consistent with those in the earlier data of Gao et al. (2012b) and are not shown here. The soil bulk densities resulting from the initial compression pressures (30, 200, and 1000 kPa) for three soil samples were: 1.53, 1.64, and 1.71 g cm⁻³ for the A_{LS} soil; 1.16, 1.50, and 1.77 g cm⁻³ for the F_{ZCL} soil; and 0.94, 1.16, and 1.34 g cm⁻³ for the G_{ZCL} soil. In soils consolidated to a given pressure, the soil water content for A_{LS} was lower than that of F_{ZCL} and G_{ZCL}. The G_{ZCL} soil retained more water than F_{ZCL}. Soil compaction decreased the water content at higher matric potentials, which was consistent with the data of Gao et al. (2012b) for these soils.

Soil Penetrometer Resistance

An ANOVA indicated that, for each soil type, the soil penetrometer resistance varied with matric potential and initial compression stress ($P < 0.001$). Generally, for each soil type, the penetrometer resistance increased with increasing initial compression stress and decreasing matric potential (Fig. 2). An exception to this was in the grassland soil (G_{ZCL}), where penetrometer resistance was not very sensitive to matric potential. No simple relationship was found between the initial soil compression, matric potential, and soil type and penetrometer resistance (Fig. 2). This observation is supported by previous studies (e.g., To and Kay, 2005; Vaz et al., 2011).

Compression and Shear Wave Speeds

The travel time of P and S waves was determined from the time delay between the first peak of the input signal and the first peak of the signal detected after it had traveled through the soil sample, as described by Whalley et al. (2011). Shear wave velocity, V_s , and compression wave velocity, V_p , are plotted against matric potential and void ratio for the three soils in Fig. 3 and 4, respectively.

The shear and compression wave velocities were influenced by the matric potential and void ratio (achieved by the initial soil compression). The velocities of the shear and

Fig. 1. (A) The geometry of a core to measure penetrometer resistance and (B) the arrangement of the piezoelectric sensors to measure shear and compression wave speeds.

Fig. 2. Penetrometer resistance of the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils plotted against initial compression stress and soil matric potential.

Fig. 3. Shear (S) wave velocity plotted as a function of matric potential and void ratio for arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils in various consolidation states.

compression waves could be described by a simple nonlinear function with matric potential, as reported by Lu and Sabatier (2009) (Table 2); however, each soil type and soil compaction treatment required a separate fit to the data. For the G_{ZCL} soil, the effects of matric potential on the shear wave velocity and compression wave velocity were small in comparison with the effects on the A_{SL} and F_{ZCL} soils, particularly for the low initial soil compaction treatments (30 and 200 kPa).

Shear wave velocity V_s and compression wave velocity V_p were related to each other by

$$V_p = m V_s + c \quad [5]$$

where m is the slope and c is the intercept, but different values of m and c were needed for the three different soils (Fig. 5; Table 3). Strictly, the relationship between the velocities of P and S waves is determined by Poisson's ratio, ν , where

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \quad [6]$$

and if V_p and V_s are both known, then Poisson's ratio can be calculated as

$$\nu = \frac{1/2(V_p/V_s)^2 - 1}{(V_p/V_s)^2 - 1} \quad [7]$$

(Santamarina et al., 2001). The ratio V_p/V_s was constant only for the grassland soil (G_{ZCL}) because the intercept, c , in Eq. [5] was not significantly different from zero ($P = 0.194$). Thus for this soil, the applied treatments did not have any effect on Poisson's ratio. For the other two soils (A_{LS} and F_{ZCL}), Poisson's ratio depended on the applied compaction and matric potential treatments, but no pattern could be identified. The range of values of Poisson's ratio (0.15–0.44 with a mean of 0.34) is similar to values reported in the literature (e.g., Nakagawa et al., 1997).

Compression and Shear Wave Speeds and Effective Stress

Assuming that in the packed soil cores σ_s in Eq. [3] was zero, and with the values of parameters reported by Whalley et al. (2012), we were able to predict the shear wave velocity of the soils in this study (Fig. 6). In general, the degree of saturation is more easily estimated than the air-entry potential, thus the suction stress was calculated by replacing $(\psi/\psi_{ae})^{-0.55}$ with the degree of saturation S . If $S < 0.5$, then it was fixed at 0.5 (Whalley et al., 2012). The use of S to scale the matric potential to give a suction stress is likely to make this work easier to apply. With the exception of the G_{ZCL} soil, the measured shear wave velocities agreed well with the predicted values (Fig. 6; Table 4), although there was a tendency for Eq. [3] to overestimate V_s . The greater degree of aggregation in the G_{ZCL} soil may have resulted in V_s and V_p be-

ing less sensitive to matric potential, especially in the low compaction treatments (30 kPa) (Fig. 3 and 4). In aggregated soil, there is a dual pore structure, and simple models for elastic wave velocity such as Eq. [3] do not take this into account (Bagherieh et al., 2009), which may be responsible for the overestimation of V_s .

Both P and S wave velocities (V) could be described by a modified form of Eq. [3]:

$$V = A \frac{(F - e)^2}{1 + e} (\psi S^*)^{\gamma_1} \quad [8]$$

where $S^* = S$ for $S > 0.5$; otherwise $S^* = 0.5$ (Fig. 7; Table 5).

Estimation of Matric Potential

There is no doubt that V_s and V_p correlate well with the matric potential (Lu and Sabatier, 2009; Whalley et al., 2012; Yang et al., 2008) and can account for a high percentage of the variance (Table 2); however, these relationships are calibrations that apply to a given soil type packed to a given condition. It would be useful if the void ratio data could be used to develop calibrations that needed only different parameters to distinguish between soil types. Provided that the void ratio, e , the degree of saturation, S , and the elastic wave velocity, V , are known, then in principle, Eq. [8] can be solved for the matric potential (Table 5; Fig. 8) for a given soil. The use of V_s appeared to give a better estimation of soil moisture than V_p . This may, in part, be because compression waves are less sensitive than shear waves to changes in matric potential when the soil is tension saturated. In saturated soils, the P wave velocity is determined by the bulk modulus of water and only increases when air enters the soil (Mitchell and Soga, 2005). In contrast, S waves are very sensitive to changes in the matric potential of the saturated soil (Whalley et al., 2012). The relationship between fitted and experimental $\log_{10}(S\psi)$ values for the grassland soil were poor in comparison with the other two soils (Fig. 8), explaining only about 50% of the variance compared with >80% for A_{LS} and F_{ZCL} . As already noted, the grassland soil has a strong dual-porous structure, which may re-

Fig. 4. Compression (P) wave velocity plotted as a function of matric potential and void ratio for arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils in various consolidation states.

quire a more complex model than Eq. [8] for shear or compression wave velocity (Bagherieh et al., 2009).

Compression and shear wave velocity data could be combined to eliminate the need for a priori void ratio data when the soil moisture status is predicted. Assuming a common value of F in Eq. [8] allows the ratio of shear and compression wave speeds to be written as

$$\frac{V_s}{V_p} = \frac{A_s}{A_p} (S\psi)^{\gamma_s - \gamma_p} \quad [9]$$

and, following inversion, $S\psi$ is given as

Table 2. Relationships between shear wave velocity, V_s , or compression wave velocity, V_p , and soil matric potential for the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils presented in Fig. 3 and 4.

Soil	Initial compression stress kPa	Relationship between V_s or V_p and matric potential, ψ	R^2
A_{LS}	30	$V_s = 55.476\psi^{0.2461}$	0.86
		$V_p = 175.69\psi^{0.1576}$	0.88
	200	$V_s = 64.627\psi^{0.2468}$	0.87
		$V_p = 183.88\psi^{0.1759}$	0.85
	1000	$V_s = 92.37\psi^{0.1913}$	0.81
		$V_p = 230.44\psi^{0.1423}$	0.77
F_{ZCL}	30	$V_s = 40.848\psi^{0.2464}$	0.97
		$V_p = 87.471\psi^{0.256}$	0.97
	200	$V_s = 66.715\psi^{0.2728}$	0.92
		$V_p = 179.41\psi^{0.208}$	0.89
	1000	$V_s = 150.44\psi^{0.1742}$	0.78
		$V_p = 513.85\psi^{0.101}$	0.55
G_{ZCL}	30	$V_s = 33.363\psi^{0.1119}$	0.63
		$V_p = 80.264\psi^{0.1014}$	0.62
	200	$V_s = 73.528\psi^{0.062}$	0.85
		$V_p = 125.71\psi^{0.0874}$	0.86
	1000	$V_s = 113.53\psi^{0.1402}$	0.96
		$V_p = 198.57\psi^{0.1495}$	0.78

Fig. 5. A comparison of compression (P) and shear (S) wave velocities (V) for the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils subject to a range of initial stresses and matric potentials. The curves are fitted to Eq. [5] and the fitted parameters are listed in Table 3.

Table 3. Parameter values of Eq. [5] relating compression (P) and shear (S) wave velocities to each other with a linear function, where m is the slope and c is the intercept. The fitted curves are shown in Fig. 5.

Soil†	Parameter	
	m	c
		$m s^{-1}$
A_{SL}	1.394 ± 0.126	126.6 ± 4.71
F_{ZCL}	2.019 ± 0.075	48.8 ± 19.7
G_{ZCL}	1.744 ± 0.123	23.0 ± 17.6 NS‡

† ALS, arable loamy sand; FZCL, fallow silty clay loam; GZCL, grassland silty clay loam.

‡ NS, not significant ($P > 0.05$).

Fig. 6. Prediction of shear (S) wave velocity with the model described by Eq. [3] for the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils. A net stress (s_s) of zero was used and the suction stress ($S\psi$) was computed using the degree of saturation. The values of the parameters were those suggested as a general solution for a wide range of soils by Whalley et al. (2012). A statistical comparison of the predicted and measured values is given in Table 4.

$$S\psi = \left(\frac{A_p V_s}{A_s V_p} \right)^{1/(\gamma_s - \gamma_p)} \quad [10]$$

where the subscripts s and p refer to parameters for S and P waves, respectively, in Eq. [8]. To test the feasibility of this approach, we plotted $\log_{10}(V_s/V_p)$ against $\log_{10}(S\psi)$. We found a significant relationship only for the A_{LS} soil (Fig. 9), and $\log_{10}(S\psi)$ accounted for 66% of the variance in $\log_{10}(V_s/V_p)$. Again, the difficulty is that Eq. [10] is highly nonlinear (Fig. 9), and the variance increases with the mean value of $S\psi$. The most appropriate approach for developing a calibration function that can be applied generally remains to be determined.

Relationship between Penetrometer Resistance and the Small Strain Shear Modulus

Penetrometer resistance was closely correlated to the small strain shear modulus (Fig. 10). This is consistent with the findings of Gao et al. (2012b). The implicit assumption is that the penetrometer resistance in these soils is dominated by elastic failure because the small strain shear modulus is a measure of

Table 4. Predicted and measured shear wave velocities (V_s) compared as V_s predicted = kV_s measured in Fig. 6.

Soil†	k	Variance accounted for
		%
A_{SL}	1.3007 ± 0.0361	81.6
F_{ZCL}	1.1383 ± 0.0282	89.8
G_{ZCL}	1.3395 ± 0.0725	49.7

† ALS, arable loamy sand; FZCL, fallow silty clay loam; GZCL, grassland silty clay loam.

Fig. 7. Fitted (A) shear wave velocity V_s , and (B) compression wave velocity, V_p , determined using Eq. [8] plotted against the measured data from the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils. The values of the parameters used to fit the wave speeds are listed in Table 5.

the soil elastic properties. The empirical relationships in Fig. 10 are linear (Table 6) but differ between different soil types; however, they do provide a promising basis for inferring penetrometer resistance from shear wave velocity. We found that an improved fit between the penetrometer resistance (Q , kPa) and the small strain shear modulus (G , kPa) for soils could be

Table 5. Values of adjustable empirical parameters in Eq. [8] fitted to estimate the compression (P) and shear (S) wave velocities in the three soils used in this work.

Soil†	Parameter	S wave	P wave
A_{SL}	A	7.77	13.54
	F	4.59	5.68
	γ	0.25	0.17
F_{ZCL}	A	5.74	51.43
	F	5.70	3.75
	γ	0.25	0.16
G_{ZCL}	A	9.28	66.64
	F	3.88	3.08
	γ	0.34	0.18

† A_{LS} , arable loamy sand; F_{ZCL} , fallow silty clay loam; G_{ZCL} , grassland silty clay loam.

Fig. 8. Calculated values of $\log_{10}(-S\psi)$, where $S\psi$ is the suction stress, determined with an inverted form of Eq. [8] using the parameter values listed in Table 5 plotted against the measured data: (A) results calculated from the shear wave velocity V_s , and (B) results calculated from the compression wave velocity, V_p , for the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils.

obtained for two of the soils (F_{ZCL} and G_{ZCL}) by including a constant term such that

$$Q = mG + c \quad [11]$$

Regressions against penetrometer resistance based on the P wave velocity were less successful than those that used the shear wave velocity.

Table 6. The parameters of a linear fit of penetrometer resistance (kPa) against the small strain shear modulus (kPa) Eq. [11], where m is the slope and c is the intercept.

Soil†	Parameter	
	m	c
		kPa
A_{SL}	0.0286 ± 0.0013	-53.00 ± 12.9 NS‡
F_{ZCL}	0.0159 ± 0.0006	694.32 ± 10.8
G_{ZCL}	0.03377 ± 0.0013	439.57 ± 54.6

† A_{LS} , arable loamy sand; F_{ZCL} , fallow silty clay loam; G_{ZCL} , grassland silty clay loam.

‡ NS, not significant ($P > 0.05$).

Fig. 9. The $\log_{10}(V_s/V_p)$, where V_s is the shear wave velocity and V_p is the compression wave velocity, plotted against $\log_{10}(-S\psi)$, where $S\psi$ is the suction stress. Only data for the arable loamy sand (A_{LS}) is shown; for the other soils, the fits were not significant.

CONCLUSIONS

There is potential for using the S wave velocity to deduce penetrometer resistance with a linear calibration that has some sensitivity to soil type. Prediction of the matric potential from P or S wave speeds with a general calibration function was found to be not very accurate because the variance was a function of the mean value and a logarithmic transformation was required. It may be possible to estimate the matric potential in soil from elastic wave speeds with more accuracy, provided a calibration for each soil at a given density is determined.

ACKNOWLEDGEMENTS

Rothamsted Research is grant-aided by the Biotechnology and Biological Sciences Research Council (BBSRC) of the UK. C.W. Watts and W.R. Whalley are funded by the 20:20 Wheat project at Rothamsted Research. This work was funded by EPSRC Grant EP/H040617/1.

REFERENCES

- Avery, B.W. 1980. Soil classification for England and Wales (higher categories). Tech. Monogr. 14. Soil Surv. England Wales, Harpenden, UK.
- Bagherieh, A.R., N. Khalili, G. Habibagahi, and A. Ghahramani. 2009. Drying response and effective stress in a double porosity aggregated soil. *Eng. Geol.* 105:44–50. doi:10.1016/j.enggeo.2008.12.009
- Bengough, A.G., B.M. McKenzie, P.D. Hallett, and T.A. Valentine. 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Exp. Bot.* 62:59–68. doi:10.1093/jxb/erq350
- Gao, W., T. Ren, A.G. Bengough, L. Auneau, C.W. Watts, and W.R. Whalley. 2012a. Predicting penetrometer resistance from the compression characteristic of soil. *Soil Sci. Soc. Am. J.* 76:361–369. doi:10.2136/sssaj2011.0217
- Gao, W., C.W. Watts, T. Ren, and W.R. Whalley. 2012b. The effects of compaction and soil drying on penetrometer resistance. *Soil Tillage Res.* 125:14–22. doi:10.1016/j.still.2012.07.006
- Gregory, A.S., N.R.A. Bird, W.R. Whalley, G.P. Matthews, and I.M. Young. 2010. Deformation and shrinkage effects on the soil water release characteristic. *Soil Sci. Soc. Am. J.* 74:1104–1112. doi:10.2136/sssaj2009.0278
- Kim, H., S.H. Anderson, P.P. Motavalli, and C.J. Gantzer. 2010. Compaction effects on soil macropore geometry and related parameters for an arable

Fig. 10. The relationship between penetrometer resistance and the small strain shear modulus calculated from the shear wave velocity for the arable loamy sand (A_{LS}), fallow silty clay loam (F_{ZCL}), and grassland silty clay loam (G_{ZCL}) soils. The slope and intercept of the fitted lines (Eq. [11]) are given in Table 6.

- field. *Geoderma* 160:244–251. doi:10.1016/j.geoderma.2010.09.030
- Lu, Z., C.J. Hickey, and J.M. Sabatier. 2004. Effects of compaction on the acoustic velocity in soils. *Soil Sci. Soc. Am. J.* 68:7–16. doi:10.2136/sssaj2004.0007
- Lu, Z., and J.M. Sabatier. 2009. Effects of soil water potential and moisture content on sound speed. *Soil Sci. Soc. Am. J.* 73:1614–1625. doi:10.2136/sssaj2008.0073
- Mitchell, J.K., and K. Soga. 2005. *Fundamentals of soil behavior*. 3rd ed. John Wiley & Sons, New York.
- Nakagawa, K., K. Soga, and J.K. Mitchell. 1997. Observation of Biot compressional wave of the second kind in granular soils. *Geotechnique* 47:133–147. doi:10.1680/geot.1997.47.1.133
- Santamarina, J.C., K.A. Klein, and M.A. Fan. 2001. *Soils and waves*. John Wiley & Sons, Chichester, UK.
- To, J., and B.D. Kay. 2005. Variation in penetrometer resistance with soil properties: The contribution of effective stress and implications for pedotransfer functions. *Geoderma* 126:161–276.
- Vaz, C.M.P., J.M. Manieri, I.C. de Maria, and M. Tuller. 2011. Modeling and correction of soil penetration resistance for varying soil water content. *Geoderma* 166:92–101. doi:10.1016/j.geoderma.2011.07.016
- Watts, C.W., and A.R. Dexter. 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. *Soil Tillage Res.* 42:253–275. doi:10.1016/S0167-1987(97)00009-3
- Whalley, W.R., M. Jenkins, and K. Attenborough. 2011. The velocity of shear waves in saturated soil. *Soil Sci. Soc. Am. J.* 75:1652–1657. doi:10.2136/sssaj2010.0449
- Whalley, W.R., M. Jenkins, and K. Attenborough. 2012. The velocity of shear waves in unsaturated soil. *Soil Tillage Res.* 125:30–37. doi:10.1016/j.still.2012.05.013
- Whalley, W.R., J. To, B.D. Kay, and A.P. Whitmore. 2007. Prediction of the penetrometer resistance of agricultural soils with models with few parameters. *Geoderma* 137:370–377.
- Whalley, W.R., C.W. Watts, A.S. Gregory, S.J. Mooney, L.J. Clark, and A.P. Whitmore. 2008. The effect of soil strength on the yield of wheat. *Plant Soil* 306:237–247. doi:10.1007/s11104-008-9577-5
- Whitmore, A.P., and W.R. Whalley. 2009. Physical effects of soil drying on roots and crop growth. *J. Exp. Bot.* 60:2845–2857. doi:10.1093/jxb/erp200
- Whitmore, A.P., W.R. Whalley, N.R.A. Bird, C.W. Watts, and A.S. Gregory. 2011. Estimating soil strength in the rooting zone of wheat. *Plant Soil* 339:363–375. doi:10.1007/s11104-010-0588-7
- Yang, S.-R., H.-D. Lin, J.H.S. Kung, and J.-Y. Liao. 2008. Shear wave velocity and suction of unsaturated soil using bender element and filter paper method. *J. GeoEng.* 3:67–74.