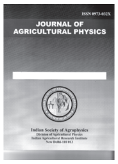
Vol. 20, No. 1, pp. 22-29 (2020)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in



Research Article

Exploring the Relationships between Penetration Resistance, Bulk Density and Water Content in Cultivated Soils

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ABSTRACT

Subsurface compaction impairs the exchange of water and air and adversely affects the root growth. Penetration resistance (PR) is often used as an indicator of soil compaction and is related to the difficulty of roots to move through soil layers. It is a dynamic property and directly related to bulk density (BD) and inversely to soil water content (WC). Two long-term fertilizer experiments at IARI, New Delhi (maize-wheat rotation in a sandy loam soil under; LTE-1) and at Birsa Agricultural University, Ranchi (soybean-wheat rotation in a sandy clay loam soil; LTE-2), and two conservation agriculture experiments at ICAR-IARI, New Delhi (maize-wheat rotation in a sandy loam soil, CA-1; and rice-wheat rotation in a clay loam soil, CA-2) were selected to explore the PR-BD-WC relationships. A linear model was the best suitable for direct PR-BD relations (R^2=0.22 and 0.25 for LTE-1 and LTE-2, respectively) but no such relation was recorded either for CA-1 or CA2. The PR-WC association was better explained through an exponential relationship in all the experiments. Results suggested WC may better explain the variation of PR in the soil than the BD. Linear and logarithmic regression equations were developed from the pooled dataset using a five-fold validation technique to quantify the PR-BD-WC relationships. The R^2 and the RMSE were 0.75, 0.42 for the linear model and 0.61, 0.34 for the logarithmic model.

Key words: Penetration resistance, bulk density, soil water content, relationship

Introduction

Subsurface mechanical impedance is a major physical constraint affecting crops globally (Ahmad *et al.,* 2018). Penetration resistance (PR) to soil is a reliable predictor of the ease with which roots can penetrate through the soil. High PR leads to a reduction in root growth, and PR>2 MPa has been suggested to severely restrict the growth and development of roots (Silva *et al.,* 2008; Lima *et al.,* 2012). Studies describe how the PR relates to ephemeral soil properties such as water content, soil bulk density and matric potential (Whalley *et al.,* 2007; Vaz *et al.,* 2011).

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In some cases, soil properties that change slowly with time like particle size and organic matter content have been included (To and Kay, 2005). Most of these relationships with a few exceptions (Hernanz *et al.,* 2000) exclude the effect of soil depth, thereby disregarding the fact that increasing depth results in greater PR due to overburden pressure and internal soil friction (Whitmore *et al.,* 2011). Soil management practices including tillage and organic inputs impact the soil strength down the profile. Conservation tillage, which involves minimum soil disturbance modifies soil BD compared to conventional tillage practices which require frequent tilling of the soil. The former also maintains a relatively higher soil water content (WC), thereby reducing the strength in the subsurface layer (Mondal *et al.,* 2019). Integrated nutrient management practices where a part of the recommended dose of fertilizer is replaced by organic inputs improve soil structural condition and therefore, alters the soil bulk density and water retention in the soil (Chakraborty *et al.,* 2019). The apparent strength of a subsurface compact layer must reduce with an increase in water content in the layer. There have been attempts to quantify the impact of BD and WC on the PR in isolation or tandem mostly through laboratory measurements (Constantini *et al.,* 1997; Whalley *et al.,* 2007), except a few through field observations (Uusitalo *et al.,* 2019). In this paper, we have attempted to model the PR with BD and WC through simultaneous measurements in the field under a variety of soil management practices in different soils.

Materials and Methods

Site characteristics

Two long-term fertilizer experiments and two short-term conservation agriculture experiments were selected for the study. The long-term fertilizer experiments are located at IARI, New Delhi (sandy loam soil with maize-wheat rotation; LTE-1) and Birsa Agricultural University, Ranchi (sandy clay loam with soybean-wheat rotation; LTE-2). Both the conservation agriculture experiments are located at IARI, New Delhi. One experiment was conducted between 2004 and 2011 in a sandy loam soil under maize-wheat rotation (CA-1), while the other is an ongoing experiment in a clay loam soil under rice-wheat rotation since 2010 (CA-2) (Table 1 in details).

Table 1. Selected properties of the soils under the All India Coordinated Research Project (AICRP) on long-term fertilizer experiments in Delhi (LTE-1) and Ranchi (LTE-2) and conservation agriculture experiments, IARI-Institute project(CA-1) and ICAR Consortium Research Platform on Conservation Agriculture (CA-2) in Delhi

Property	LTE-1	LTE-2	CA-1	CA-2
Project	AICRP	AICRP	IARI	CRP-CA
Location	IARI, New Delhi	BAU, Ranchi	IARI, New Delhi	IARI, New Delhi
Continuing since	1971	1972	2004*	2010
Latitude	28.63° N	23.35° N	28.63° N	28.64° N
Longitude	77.16° E	85.33° E	77.15° E	77.15° E
US Soil Taxonomy	Typic Haplustept	Typic Haplustalf	Typic Haplustept	Typic Haplustept
Cropping system	Maize-Wheat	Soybean-Wheat	Maize-Wheat	Rice-Wheat
Sand, %	71.7	66.2	74.8	25.9
Silt, %	12.0	8.4	9.5	39.7
Clay, %	16.3	25.4	15.7	34.5
Texture, USDA	Sandy loam	Sandy clay loam	Sandy clay loam	Clay loam
Soil organic C#, g $100g^{-1}$	0.44	0.45	0.13	0.52

*terminated in 2011; # at the time of sampling

Observations

Bulk density: Undisturbed soil samples were collected from 0-15, 15-30 and 30-45 cm layers by using a core sampler. Soil samples were dried in an oven at 105° for 48 h. Bulk density (g cm^{-3}) was calculated by dividing the weight of oven-dry soil by the volume of core (Veihmeyer and Hendrickson, 1948).

Soil water content

Soil samples were also collected at the time of BD sampling to measure the soil water content (WC) using the gravimetric method. Samples were carried in polythene bags quickly to the laboratory, weighed and oven-dried at 105° for 24 h, and dry soil weights were taken. The WC (%, g/g) was the difference in wet and dry soil weights divided by the weight of dry soil, and expressed in percentage.

Penetration resistance

The soil PR was measured simultaneously in each plot (4 readings $plot^{-1}$) by using a Rimik cone penetrometer (model no. CP20). The maximum value of penetration resistance that can be measured by this instrument was 5000 kPa for a maximum depth of 600 mm. The diameter of the base of the cone, and the slant height is 12 and 24 mm, respectively and the angle of the cone is 30°. The capacity of the load cell is 60 kg. The instrument has a data logger system attached to it for the automatic recording. Data retrieval on PC using CP20V2 software gives the recorded PR data at an interval of 20 mm soil depth in tabular form (details may be obtained from the hardware manual of 'Rimik cone penetrometer CP20). The penetrometer gives a continuous reading up to the specified depth (45 cm in our case) with a depth resolution of 20 mm. These readings were averaged for 0-15, 15-30, 30-45 for all sites. The variability of PR, BD and WC is depicted in the box-and-whisker plot (Fig. 1).

Predicting penetration resistance

Models were developed independently for LTEs and the CAs and the pooled data (combining values of all). In all, 95, 48, 20 and 141 observations from LTE-1, LTE-2, CA-1 and CA-2 respectively were used to develop the models. Total observations were split randomly into training and testing data using the "Caret" package of R software. The function was used in such a way that 75% of total observations were used for creating training data and the remaining 25% as testing data.

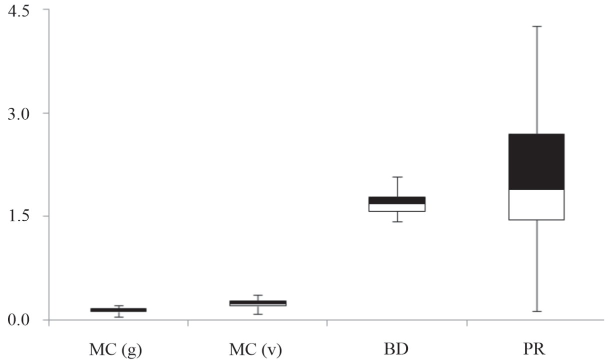

Fig. 1. A box plot of soil water content [g g^{-1}, WC(g) and v v^{-1}, WC(v)], soil bulk density (BD) and soil resistance to penetration (PR) data (pooled from selected sites; Table 1 or details)

The predicted values were compared, and prediction accuracy was evaluated using the coefficient of determination (R^2), root mean square error (RMSE) and plots of residuals with observed PR data.

Results and Discussion

Soil penetration resistance-bulk density-water content relations: Partial dependencies of soil resistance to penetration on bulk density and water content

The relations between PR, BD and WC were studied for each site with the pooled data using scatter plots (Fig. 2).

The logarithmic model was best-fitted with PR-BD relation, which showed significant direct relationships in both LTEs (R^2= 0.22 and 0.25, $p<0.01$), while in CA experiments, relations were non-significant (R^2= 0.02). The R^2 of the pooled data was 0.23 ($p<0.01$). Bulk density could not explain much of the variations in the PR values,

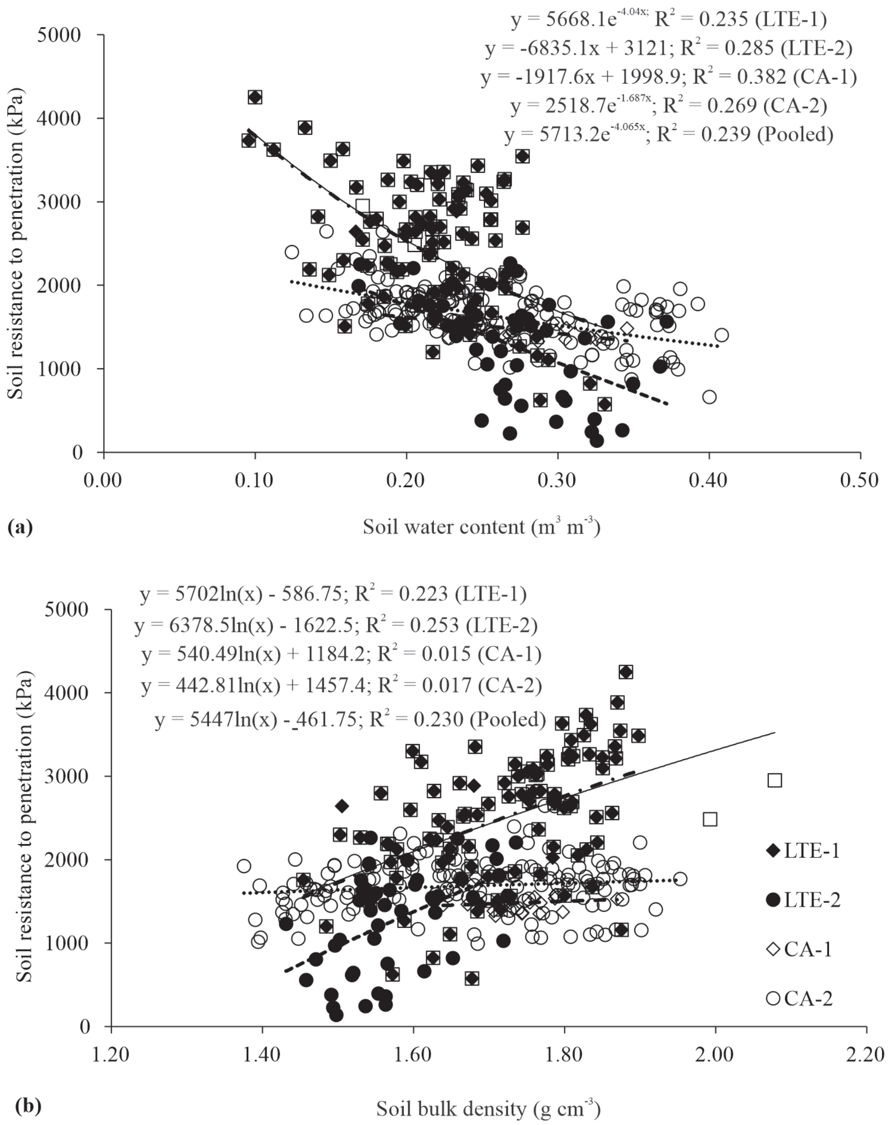

Fig. 2. Fitted relationships between soil resistance to penetration and soil bulk density (a) and soil water content (b) for selected experimental sites (See Table 1 for details)

more so in CA experiments. The exponential relationship explained the best for the PR-WC association and was inversely related to all sites. The R^2 values were 0.24, 0.29, 0.38 and 0.27 for LTE-1, LTE-2, CA-1 and CA-2, respectively, and for pooled data, R^2 was 0.24. The WC, therefore, could better explain the variation in PR compared to the BD.

Prediction of soil resistance to penetration from bulk density and water content data

Linear and logarithmic regression equations were developed from four experimentations and the pooled dataset using a five-fold cross validation technique, and the coefficients of these models along with their significance are shown in Table 2. Although the coefficients were not always significant in the case of a single site, strong predictability was obtained with the pooled data. The R^2 and the RMSE were 0.75, 0.42 for linear (Fig. 3) model and 0.61, 0.34 for the logarithmic model, respectively (Fig. 4). Residuals (observed-predicted) values when plotted with the observed values, these were closer to zero line (no residual; observed-predicted=0) in linear model, but away from zero

Table 2. Coefficients of linear and non-liner model for prediction of soil resistance to penetration (Table 1 for details of experimental sites; '*' and '**' refer to significance at 5% and 1% levels)

	Linear			Non-Linear		
	A	b	C	log a	b	C
LTE-1	-1.06	3.17**	-14.89**	-2.24**	2.5**	-0.84**
	(1.1)	(0.59)	(2.31)	(0.37)	(0.56)	(0.15)
LTE-2	-0.75	2.6**	-12.06**	-4.56**	3.76*	-1.66**
	(1.62)	(0.94)	(2.44)	(1.01)	(1.77)	(0.45)
CA-1	1.03	0.71	-4.87**	-0.86*	0.69	-0.47**
	(0.84)	(0.49)	(0.95)	(0.35)	(0.52)	(.09)
CA-2	2.25**	0.06	-4.4**	-0.31*	0.04	-0.42**
	(0.3)	(0.17)	(0.66)	(0.15)	(0.17)	(0.06)
Pooled	1.34**	1.34**	-11.59**	-1.94**	1.24**	-0.95**
	(0.48)	(0.25)	(0.98)	(0.2)	(0.28)	(0.09)

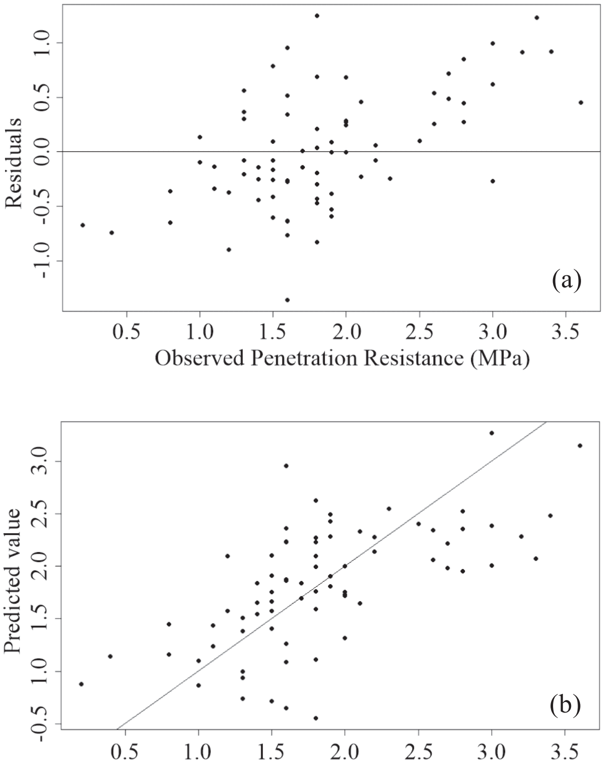

Fig. 3. Residual (Observed – Predicted) values of soil resistance to penetration plotted against the observed values (a) and comparison of PR estimated with observed values (b) in linear model

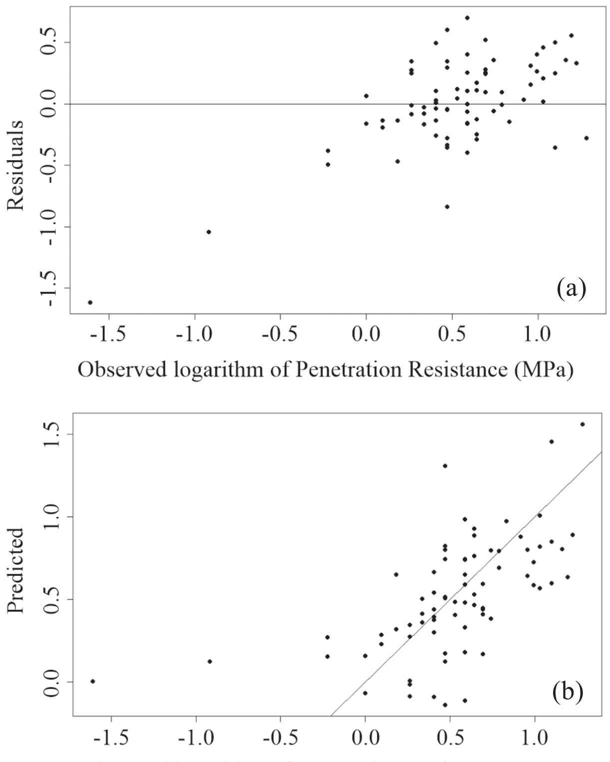

Fig. 4. Residual (Observed – Predicted) values of soil resistance to penetration (PR) plotted against the measured values (a), and comparison of PR estimated with observed values (b) in a non-linear Model

line while in the logarithmic model. In the linear model, values are randomly distributed unlike the case in the logarithmic model.

Soil BD and PR are the two most common parameters to characterize the soil strength (or the level of compaction), which influenced the structural characteristics and functions of soils (Hakansson and Lipiec, 2000). The PR in a given soil is directly related to BD, and inversely to the WC. However, PR is a composite variable, and both BD and WC should be considered concurrently. The WC had a larger influence on PR than BD in uncultivated soils, but at higher WC, PR was more sensitive to BD (Constantini, 1997). In cultivated soils, PR was more sensitive to BD at low soil water, and also the rate of change in PR with soil water was greater at higher BD. In the present study, PR values were lower in LTE-2 (Ranchi) compared to LTE-1 (Delhi), which may be due to the higher soil water content and correspondingly lower BD values. Variations in PR were higher with increasing depth for both the sites (data not presented). Constantini (1997) observed greater variation of PR values at lower soil water status in the clayey soil, possibly due to higher cohesion and adhesion forces with lesser water content (Fermino and Kümpf, 2006). With the increase in water content, the lubricating effect makes the soil more plastic, and facilitated ease of penetration (Assis *et al.,* 2009). Furthermore, an increase in water content caused a reduction of friction as well as cohesion forces between soil particles and aggregates, resulting in a decrease in PR (Ros *et al.,* 2011).

BD is an important indicator of soil compaction (Abu-Hamdeh, 2003). Studies showed that organic components had a dilution effect in lowering the bulk density (Martin and Stephens, 2001; Bronick and Lal, 2005). The lowest PR and BD were obtained in manure-plus-mycorrhiza treated plots, which also increased soil organic carbon and improved aggregate stability (Celik *et al.,* 2010).

Among the different models, Mirred and Ketcheson (1972) and Whalley *et al.* (2007) used BD (Mg m^{-3}) and matric potential (MPa) as the main predictor variables. However, the non-linear model used by Busscher and Sojka (1987) and tested by Busscher (1990), related BD and gravimetric water content with PR as controlling variables, has been mostly used (Tormena *et al.,* 1998; Chen *et al.,* 2014; Goncalves *et al.,* 2014; Moreira *et al.,* 2014). Most of the studies found the relation between BD and soil WC to be linear or exponential. Stock and Downes (2008) on the contrary observed the sigmoidal relationship between the two parameters.

In the present study for all the models developed, PR was positively correlated with BD and negatively correlated with WC, similar to the trends obtained by Ehlers *et al.* (1983) and Da Silva *et al.* (1994). However, Sojka *et al.* (2001) found a strong correlation for soil strength, expressed as cone index, with WC when data for the whole profile was analyzed, but not with BD. He attributed the variation in soil strength to the strong cementation effects due to the presence of high calcium carbonate content in these soils.

Conclusions

Soil penetration is an important indicator that indicates the easiness of soils towards the growing roots of the plant. It primarily depends on two soil physical parameters viz. bulk density and soil water content. The PR was directly and inversely related to soil BD and water content, respectively. The current study revealed that PR has a significant linear relation with BD under conventional tillage practices while conservation agriculture yielded no relation. The PR and water content was more strongly related and may better explain the variation in PR than explained when soil BD was taken as a predictor. The soil PR can be successfully predicted from bulk density and water content through both linear and logarithmic models.

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Received: April 16, 2020; Accepted: June 30, 2020