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Model for calculation of penetration resistance from easily measurable soil physical properties

P MAITY[1], P AGGARWAL[2] and P DEY[3]

Indian Agricultural Research Institute, New Delhi 110 012

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ABSTRACT

Higher cost of equipment and requirement of trained human power often limit the direct measurement of soil penetration resistance (PR) in developing countries. Hence, in this paper, we present an indirect measurement of PR from easily measurable soil physical properties in surface (0-15 cm) and subsurface (15-30 cm) layer. Experiments conducted on 12 hectare area of IARI main farm under two texturally different soils, viz sandy loam and loam showed highly significant differences in the values of PR, soil water content (SWC) and bulk density (BD) both before and after ploughing. Although the average PR and BD values of 15-30 cm layer were reduced after ploughing, they remained above critical limits which confirmed the presence of permanent plough pan between 15-30 cm. The BD registered a significant positive correlation to PR, while SWC followed a significant negative correlation. Stepwise regression analysis of PR, BD and SWC of both soils showed that among all soil physical parameters, SWC exerted maximum influence on PR both before and after ploughing. While SWC alone contributed up to 40-65% variation in PR, it accounted for 60-80% of variations in combination with BD. However, addition of clay (%) and sand (%) in the regression model did not improve the coefficient of determination. The study conclusively proved that the researchers have yet another tool and dimension to use SWC, BD, clay (%) and sand (%) as an index for calculation of PR value.

Key words: Bulk density, Clay, Penetration resistance, Regression model, Sand, Soil water content

As a consequence of progressive increase in mechanization of farm operations, the problem of soil subsurface compaction is very severe in alluvial soils of Indo Gangetic plains. The subsurface compaction adversely affects the root penetration into the soil, leading to limited nutrient and water availability to the plants and consequently reduces crop production. The level of compaction can be measured by determining the bulk density (BD), saturated hydraulic conductivity or penetration resistance (PR) of the soil. Generally, PR increases with compaction or bulk density (Lowery and Schuler 1994), decreases with increase in soil moisture and increase in sand (%) (Puppala *et al.* 1995, Gajri *et al.* 1991). A penetrometer measurement of 2.0 MPa is generally regarded as sufficient to hinder the growth and developments of crops (Kay and Anger 2002). Soil penetration resistance at field capacity moisture content can be treated as a measure of compaction status of the soil (Aggarwal *et al.* 2006). Automatic penetrometers with data loggers are generally more reliable, accurate, easy to operate in field, have greater range of measurement (5 MPa) and depth of penetration (60 cm). Pedotransfer functions (multiple regression equations) were developed by Grunwald *et al.* (2001) to describe the relationship between cone index and soil texture, BD and SWC and depth to evaluate the sensitivity of each of the above input parameter used in computing PR. Such relationships could be used in predicting critical bulk densities and critical soil water contents corresponding to critical soil penetration resistance values (2–3 MPa for most of the crops) Since, measurement of PR in field condition is difficult, time consuming and requires costly equipments as well as skilled personnel, there is a need to be able to predict PR from basic soil physical properties such as soil composition, bulk density and water content. Hence, an experiment was conducted to develop a regression model for predicting soil PR from easily measurable soil physical properties.

MATERIALS AND METHODS

The study area is situated at 28.38° N, 77.20° E and is at an altitude of 228.7 m above the mean sea level in the

[1] Scientist Division of Environmental Science (email: pragati.kiran7682@gmail.com), [2] Principal Scientist, Division of Agricultural Physics (email: pramila.iari@gmail.com), [3] Principal Scientist, Central Soil Salinity research Institute, Karnal (email: pdey@cssri.ernet.in)

Table 1 Descriptive statistics of soil samples taken from sandy loam field in two depths (0-15 cm, 15-30 cm)

Statistical	PR (kPa)		BD (Mg/m^3)		SWC (%)		Clay (%)	Sand (%)
parameters	0-15	15-30	0-15	15-30	0-15	15-30	0-15	0-15
Sandy loam soil before ploughing								
Mean	1 610.60	2 631.70	1.46	1.69	16.98	15.71	17.75	60.45
Maximum	1 906.60	3 100	1.53	1.83	18.82	20.25	19.80	72.60
Minimum	1 200.90	2 100	1.38	1.55	14.60	12.83	15.80	53.80
Std deviation	1.77E+02	2.41E+02	4.17E-02	9.64E-02	1.16E+00	1.71E+00	1.13E+00	5.60E+00
CV%	10.98	9.15	2.85	5.97	6.88	10.87	6.38	9.26
Sandy loam soil after ploughing								
Mean	1 623.10	2 258.20	1.34	1.59	17.50	16.06		
Maximum	1 850.75	2 750.56	1.44	1.65	20.40	18.13		
Minimum	1 090.63	1 800.25	1.34	1.51	14.50	13.41		
Std deviation	3.01E+02	2.80E+02	5.34E-02	3.65E-02	1.69E+00	1.01E+00		
CV%	18.53	12.41	3.99	2.29	9.62	6.31		

Table 2 Descriptive statistics of soil samples taken from loam field in two depths (0-15 cm, 15-30 cm)

Statistical	PR (kPa)		BD (Mg/m^3)		SWC (%)		Clay (%)	Sand (%)
parameters	0-15	15-30	0-15	15-30	0-15	15-30	0-15	0-15
Loamy soil before ploughing								
Mean	1 914.60	2 880.00	1.34	1.56	18.28	16.12	25.70	35.80
Maximum	2 205.90	3 201.80	1.45	1.61	20.48	17.86	38.40	44.60
Minimum	1 600	2 504.50	1.30	1.51	15.20	13.53	15.20	22.60
Std deviation	1.33E+02	1.61E+02	3.86E-02	2.74E-02	1.45E+00	9.90E-01	5.90E+00	6.27E+00
CV%	6.93	5.61	2.80	1.75	7.94	6.15	22.90	17.47

IARI Research Farm, New Delhi, India. The climate of the area is semiarid and subtropical with hot summer and cool winters. Data on soil penetration resistance (PR) and other soil physical parameters such as bulk density (BD), soil water content (SWC), clay and sand content of two texturally different soils of sandy loam (Main Block VIII; size- 300 m × 200 m; soil type- sandy loam; class- Typic Ustocrepts) and loam soils (Main Block XI; size- 300 m × 200 m; soil type- loam; class- Typic Ustocrepts) were collected from 0-15 cm and 15-30 cm soil depth. Soil samples were collected in 27 sampling points in a block on a rectangular grid at 33.3 m × 50 m interval. Samples were collected from 1 m × 1 m plot. Before collection of samples, the area thus marked was bunded for impounding of water and allowed to drain for 48 hours to reach to field capacity level. The first sampling was done before plowing for winter sowing and the second sampling was done immediately after plowing and sowing of winter crop. This enables creating two states of compaction. All the data were collected during 2005-06. During rainy season maize was grown in the field by ridge and furrow methods and during winter season wheat was grown by conventional method. In loamy field, where wheat was sown under no tillage condition, soil physical parameters after plowing could not be collected.

Soil penetration resistance for each sampling point up to 30 cm soil depth was measured by using a Rimik cone penetrometer (model no.CP20) (automatic penetrometer with data logger) at field capacity (2nd day after watering a bunded plot of 1 m x 1 m size). Bulk densities (BD) of 0-15 cm and 15-30 cm soil layer both before and after plowing were measured at each sampling point using a core sampler (Blake and Hartge 1986). Soil water content (SWC) was measured simultaneously along with penetration resistance using gravimetric method. Sand, silt and clay percentages of 0-15 cm soil layer at each site of the field were determined by Bouyoucos hydrometer method (Bouyoucos 1962) from same BD samples and soil textural classes were determined by USDA textural triangle. Descriptive statistical analysis was carried out to predict mean, range, variance and CV of all the measured parameters, i e PR, BD, SWC, sand (%) and clay (%) for surface (0-15 cm) and subsurface (15-30 cm) layers of both loam (Block XI) and sandy loam (Block VIII) soils. To examine whether the data of different soil parameters of the two soils are significant or not, t - test was performed. A stepwise multiple regression model was developed for predicting PR as a function of BD, SWC, clay (%) and sand (%) for both soil layers of sandy loam and loam field using "Statistica 6.0" software package. If the value of t parameter

Table 3 Test of significance between data set of soil physical parameters of sandy loam and loam soil in two depths before ploughing

Parameters	PR (kPa)		BD (Mg/m^3)		SWC (%)	
	Sandy loam	Loam	Sandy loam	Loam	Sandy loam	Loam
			0-15 cm			
Average	1 610.50	1 914.60	1.46	1.37	16.98	18.35
t value	–7.15		7.85		–3.61	
p value			5.00E-05		6.80E-04	
Significance	Highly significant		Highly significant		Highly significant	
			15-30 cm			
Average	2 631.60	2 880.00	1.69	1.56	15.70	16.10
t value	–4.45		6.79		1.08	
P value	3.00E-05		1.00E-05		2.84E-01	
Significance	Highly significant		Highly significant		Non significant	

at $P < 0.05$ (ratio of coefficient of the parameter to its standard error) was found >2, then parameter was considered to have significant effect on PR.

RESULTS AND DISCUSSION

Descriptive statistics of soil physical parameters

Statistical analysis of penetration resistance (PR), bulk density (BD) and soil water content (SWC) data for 0-15 cm soil layer in sandy loam field showed that value of PR ranged between 1200-1900 kPa before ploughing and 1090-1850 kPa after ploughing, but their average values remained non-significantly different and well below the critical limit of 2000 kPa (Table 1). PR of 15-30 cm depth ranged between 2100-3100 kPa before ploughing and ranged between 1800-2700 kPa after ploughing. The PR after ploughing showed significant reduction but remained still higher than its critical limit indicating the continuous presence of compact 15-30 cm plow pan. PR increase with depth due to overburden pressure and the moving average property in force measurement over the length of the cone must have contributed to the increase in cone index with depth (Kumar *et al*. 1996). Similarly, average BD of 0-15 cm and 15-30 cm soil layers were 1.46 Mg/m^3 and 1.69 Mg/m^3 before ploughing and it was reduced by 6-8% after plowing, but the BD of subsurface layer still remained higher than its critical limit of 1.60 Mg/m^3 which again confirmed the presence of plough pan. Average SWC of both layers two days after watering (presumed to be the soil water content at field capacity) increased by 1 % after plowing. In loamy field, where wheat was sown under no tillage condition, soil physical parameters after plowing could not be collected. Comparison of PR, BD, and SWC of both layers before ploughing showed similar trends to that for sandy loam soil (Table 2).

Regarding the coefficient of variation in both soils, BD had lowest coefficient of variation, which ranged from 1.7-4.0%, followed by SWC with a range from 6.15-9.60%. Similar low value of CV for BD of two fluvents in Turkey was also reported by Kilic *et al.* (2004). The CV of PR was marginally higher with range between 5.60-18.50%. The CV of clay differed from 6.38-22.90% and sand varied from 9.26-17.47%. The use of t- test between the data sets of both soils showed highly significant differences in values of PR, SWC and BD of loam and sandy loam field as indicated by high t values at p values less than 0.05 (Table 3). However, SWC of 15-30 cm soil layer was an exception where values were nonsignificantly different for both soils.

Values of coefficient of correlation between BD and PR ranged from 0.25 to 0.72 for sandy loam soil and 0.34 to 0.78 for loam soil. Between SWC and PR, it ranged from 0.48 to –0.69 for sandy loam and –0.79 to –0.80 for loam (Table 4). It is clear from the above results that in general for both soils, average PR increased with BD, whereas average SWC showed appreciable reduction with increase in BD. The relations are true for both depths. Again for both soils, PR was positively correlated to BD and negatively correlated to SWC, which is in accordance with results from other studies (Laboski *et al.* 1998, Utset and Cid 2001, Veronese *et al.* 2005). However, the values of PR, BD and SWC were significantly different for both soils. Similar results have been reported by Grunwald *et al*. (2001) and Kilic *et al*. (2004). Mulqueen *et al*. (1977) suggested that the mode of soil failure due to a penetrometer is a function of soil water content.

Multiple regression analysis of PR with BD, SWC, sand (%) and clay (%)

In the first step of regression model for 0-15 cm of sandy loam before ploughing, the independent variable, which has most significant effect on the dependent variable, is chosen to develop the regression equation (Table 5). Here in this case SWC was found to have maximum influence on PR, the developed regression equation is given as under:

$$\text{PR (kPa)} = 3\,677.69 - 121.67 * \text{SWC (\%)} \quad \text{..........(1)} \quad r^2 = 0.65$$

As evident from Table 5, the value of t parameter which is the ratio of coefficient of parameter divided by its standard error value was always higher than 2.0 at $P < 0.05$ which

Table 4 Correlation coefficients of multiple regression equation models for predicting PR as a function of BD and SWC for surface soil (0-15 cm) and subsurface soil (15-30 cm) soil before and after ploughing

Parameter	BD (Mg/m^3)		SWC (%)		PR (kPa)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Sandy loam- before ploughing						
BD (Mg/m^3)	1.00	1.00	0.26	– 0.11	0.32	0.61**
SWC (%)	0.26	– 0.11	1.00	1.00	– 0.48*	–0.63**
PR (kPa)	0.32	0.61**	– 0.48*	– 0.63**	1.00	1.00
Loam- before ploughing						
BD (Mg/m^3)	1.00	1.00	– 0.55**	0.27	0.78**	0.34
SWC (%)	0.55**	0.27	1.00	1.00	– 0.80**	–0.79**
PR (kPa)	0.78**	0.34	– 0.80**	– 0.79**	1.00	1.00
Sandy loam- after ploughing						
BD (Mg/m^3)	1.00	1.00	– 0.28	0.20	0.72**	0.25
SWC (%)	0.28	0.20	1.00	1.00	– 0.64**	–0.69**
PR (kPa)	0.72**	0.25	– 0.64**	– 0.69**	1.00	1.00

*Significant at P<0.05, **significant at P<0.01

again confirms that the effect of SWC was highly significant. The results of second step of forward analysis revealed that SWC along with BD contributed nearly 70.85% towards the variation of PR. Both these parameters significantly affected PR as shown by their computed t at $P < 0.05$.

The developed relationship was

PR (kPa) = 2 252.26–131.73 * SWC (%) + 1 090.09 * BD (Mg/m^3) ……. (2) $r^2 = 0.71$

The results of analysis in step 3 showed that inclusion of sand in the regression equation did not improve the r^2 value. The computed t value was less than 2 at $P < 0.05$, which indicated that effect of sand (%) on variation of PR was nonsignificant. The analysis of results in step 4 showed that like in the previous step 3, the inclusion of clay (%) along with BD, SWC and sand (%) did not improve the r^2 value further. Again, the computed t value for clay (%) and sand (%) indicated that they have nonsignificant effect on variation of PR. Hence from the above analysis it can be concluded that out of all parameters used in analysis, only SWC and BD

Table 5 Forward stepwise linear regression equation to predict PR of the surface horizons (0-15 cm) a sandy loam and loam soils before and after ploughing

Method/no of steps	Parameters	Intercept	BD (Mg/m^3)	SWC (%)	Sand (%)	Clay (%)	R^2
Sandy loam soil before ploughing							
Forward- Step-1	Coefficient	3 677.69		–121.68			0.65
	Standard error	306.13		17.98			
Forward- Step-2	Coefficient	2 252.26	1 090.08	–131.73			0.71
	Standard error	693.72	484.06	17.26			
Forward- Step-3	Coefficient	2 645.61	876.00	126.56	–2.77		0.71
	Standard error	942.17	597.58	19.33	4.42		
Forward- Step-4/	Coefficient	2 565.57	816.08	–124.08	–3.12	8.28	0.72
final step	Standard error	975.56	622.84	20.44	4.57	18.53	
loam soil before ploughing							
Forward- Step-1	Coefficient	3 252.47		–73.17			0.64
	Standard error	201.11		10.96			
Forward- Step-2	Coefficient	492.76	1 674.49	–48.47			0.80
	Standard error	632.72	372.77	9.92			
Sandy loam soil after ploughing							
Forward- Step-1	Coefficient	– 3 778.54	4 041.94				0.51
	Standard error	1 050.96	785.81				
Forward- Step-2	Coefficient	– 1 271.21	3290.31	85.54			0.70
	Standard error	990.32	625.37	19.75			

Table 6 Forward stepwise linear regression equation to predict PR of subsurface horizons (15-30 cm) a sandy loam and loam soils before and after ploughing

Method/no of steps	Parameters	Intercept	BD (Mg/m^3)	SWC (%)	R^2
Sandy loam soil before ploughing					
Forward- Step-1	Coefficient	4 036.05		– 89.39	0.40
	Standard error	344.34		21.79	
Forward- Step-2/step final	Coefficient	1 577.81	1371.41	– 81.16	0.69
	Standard error	561.94	281.04	15.84	
Loam soil before ploughing					
Forward- Step-1	Coefficient	4 969.39		129.59	0.63
	Standard error	317.39		19.65	
Forward- Step-2/step final	Coefficient	2 701.80		141.16	0.70
	Standard error	1 030.19		18.84	
Sandy loam soil after ploughing					
Forward- Step-1	Coefficient	5 236.42		191.03	0.47
	Standard error	647.24		40.22	
Forward- Step-2/step final	Coefficient	694.68	3 133.71	214.05	0.60
	Standard error	1 535.37	969.50	34.99	

significantly affected PR. Reason for such a finding could be that for prediction of a dependent variable as a function of several input variables, the chosen input variables should be relatively independent of each other. But in this case both BD and SWC are dependent on sand and clay content (Kumar *et al.* 2009). Agodzo and Adama (2003) proved that being a sandy clay loam, *Kumasi* series has clay content of 26.6% and a sand content of 63.6%. Its clay content is highest among the test soils and sand content, the least in the group. This suggests that it has the highest water holding capacity and at the same time the least dry bulk density values. Hence it is not advisable to use sand (%) and clay (%) along with SWC and BD in the model. Step wise regression model of PR, BD and SWC of 15-30 cm of sandy loam and both depths of loam soil before and after ploughing showed that SWC alone contributed up to 40-65% variation in PR and SWC along with BD contributed 60-80 % towards its variation (Table 5 and 6). Other researchers also observed significant contribution of SWC for explaining variation of PR (Kumar *et al.* 1996, Grunwald *et al.* 2001).

CONCLUSIONS

Out of all parameters used in analysis, only SWC and BD significantly affected PR. Such research is needed to accurately characterize the soil hardpan through quantification of soil penetration resistance and how it is influenced by soil moisture, soil texture and bulk density on landscape level for site specific tillage applications leading to precision agriculture. PR value obtained from cone penetrometer at field capacity can be taken as an index of compaction instead of BD and SWC. Empirical relationships obtained in this study could further be used in managing soil quality and tillage and simulating crop growth models. The premise of this study was that a measurable change in soil water content and bulk density still will account for the major effect on penetration resistance. Model presented in this study are empirical, the transferability to landscapes with contrasting characteristics in soils, climate and management needs separate calibration and validation. Performance of our approach could be improved in the future when more experimental data and a better quantitative expression of the role of the different factors in penetration become available. The study conclusively proved that the researchers have yet another tool and dimension to use SWC, BD, clay (%) and sand (%) as an index for calculation of PR value.

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