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MODELING AND CORRELATION OF SOIL CONE INDEX FOR BULK DENSITY, MOISTURE CONTENT AND PENETRATION DEPTH LEVELS IN A SANDY LOAM SOIL

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ABSTRACT

Soil cone index (CI) is as criteria for representing soil strength. Itis a useful tool to evaluate the impact of tillageprocess and predicting draft force of tillage implements. The current research investigated modeling and correlation of CIfor bulk density, moisture content and penetration depth levels in a sandy loam soil. CI datawere gathered and analysed. Regression models for correlatingCIwith independent parameters were developed and compared with the most promising models which selected from literature.Statistical analysis indicated that soil moisture content (MC), soil bulk density (BD) and penetration depth(PD) had significant effect (P=0.01) on CI. The all interactions among variables (BD, MC and PD) had alsosignificant effect (P=0.01) on CI. It is found that BD and PD are linearly and directly proportional to CI. However, MC is quadratic curve (second degree) and inversely proportional to CI. The results showed thatmaximum value of CI (5153 kPa) was recorded at BD (1.82 g/cm^3), MC (4.6%) and PD (15 cm). But, minimum value of CI (346 kPa) was recorded at BD (1.36 g/cm^3), MC (8.8%) and PD (5 cm).Two equations developed by regression analysis (linear and polynomial) for estimating of CI were obtained. The polynomial equation (R^2=95.6%) was more precision compared with linear equation (R^2=93.3%). The obtained two regression models (linear and polynomial) were compared with other regression models (exponential and power) from literature. It can be concluded that the linear and polynomial equations were exhibiting the closest match to measured CI. The polynomial equation was also the best matching equation for estimating of CI (highest R^2 of0.968 and lowestroot mean squared error of 127.2kPa).

INTRODUCTION

Soil strength is an important characteristic affecting many aspects of agricultural soils, such as the performance of plowing implements, root growth, least-limiting water range and the traffic ability (Moraes *et al.*,2012). Soil strength can be defined as the resistance of the soil to withstand the external forces without failure. Besides, penetration resistance is an important property of soils, and can be expressed as cone index (Bengough et al., 2001).

Characterization of soil strength is usually made by measuring the response of a soil to a range of applied forces. Soil cone index (CI) is generally regarded as one of the best tools to assess soil strength (Bengough and Mullins, 1991). CI is as criteria for representing soil strength andcan be used to identify areas where soil physical characteristics are negatively impacting yield (Hummel *et al.,* 2004). It has been used by several researchers to quantify the soil quality and to identify the layers with increased degree of compaction (Ayers and Bowen, 1987; Vazquez et al., 1991;Perumpral, 1987;Unger and Jones, 1998;Grumwald et al., 2001; Tavares-Filho and Ribon, 2008;Moraes et al., 2014). It also indicates characteristic index of soil cultivability, which shows the effect of soil taken against cultivation implement and expressed as force per unit cross-sectional area of the cone-base.

Soil cone index (CI) could be measured and obtained by a simple and inexpensive device (penetrometer). It can be done relatively quickly and easily, and can provide valuable data about soil conditions. Different types of penetrometers have been developed to measure soil penetrability that operates on static or dynamic principles (Lowery and Morrison 2002).The scientific literature contains a considerable number of studies which examine the dependence of soil strength on factors such as soil bulk density (BD), soil texture and soil moisture content (MC) (Wells and Treesuwan, 1978;Busscher, 1990; Mielke et al., 1994;Materechera and Mloza-Banda, 1997;Busscher et al., 2000; To and Kay, 2005; Dexter et al., 2007; Gubiani et al., 2011; Sun et al., 2012;Lina et al., 2014). Most of these studies have been carried out on idealized soils or on remolded soil samples. Also, it is found that MCand BD are considered the most significant parameters that determined the soil properties for penetration studies (Moraes et al., 2014).

Several researchers have worked on the relationship between Cland MC. However, MC is considering an important factor affecting CI (Yasin et al., 1993;Saad, 2003;Hummelet al., 2004). Ayers and Perumpral (1982) found an inverse relationship between Cland squared MC for various mixtures of sand and clay.On the other hand, Ohu et al. (1988) found an exponential relationship between Cland MC for loam and clay soils. But Ley et al. (1993) found a linear correlation between Cland MC. Carlos et al. (2011) showed that CI and MC interactions were found to be complex.

Soil bulk density (BD) is often regarded as the most useful parameter of soil structure and is used as an indicator of soil compaction in engineering construction works (Hernanz et al., 2000). BD is also used as an indicator of problems of root penetration, soil aeration and water infiltration. However, CI has a directly correlated to BD (Ayers and Perumpral, 1982;Hemanz et al., 2000). Their experiments conducted with various soils clearly reveal that this relationship is not linear over a wide range of MCand BD. At high MC, the CI is practically insensitive to changes in MCand BD has little effect in cohesionless soils.

Several empirical models are found in the literature. They are commonly used to estimate CI as a function of BDand MC. As example, in Upadhyaya et al. (1982) model, Clwas a linear function of MC. Moreover, Ayers and Perumpral (1982) proposed CI as a polynomial function of BD and MC. Besides, Canarache (1990) proposed an exponential model relating BD and MC.Meanwhile, Gubiani et al. (2011) developed a linear model in which CI was considered to be the dependent variable, with MC, BD and depth being the independent variables.

Elbanna and Witney (1987) developed an empirical equation based on the tieory of the bearing capacity of the soil under a continuous footing, in which CIwas a function of the type of soil, cohesion, angle of internal friction and MC. The empirical equation accurately estimated CI in a wide variety of soils, from loamy sand to a heavy clay soils with MC of 10-65%.

Dexter et al. (2007) predicted a new equation of CI. The equation contained two terms; the first was a measure of the degree of compactness of the soil and the second was the contribution of pore water to the soil strength. They compared predictions CI from new equation with predictions from two other published equations. It was shown that the performance of the proposed equation is superior to the other two.

Carlos et al. (2011) utilized obtained data of CI to parameterize 23 previously applied regression models. They measured CI within soil textures ranging from loamy sand to clay for a wide range of MCand BD. A total of 23 employed regression equations; CI was expressed either as a function of a combination of independent variables MC and BD or only as a function of a single variable. They found that the best matching model equations were identified based on the root mean square deviation (RMSD) and coefficients of determination (R^2). The exponential function proposed by Jakobsen and Dexter (1987) and Ohu et al. (1988)that expresses CI as function of MC and BD showed lowest RMSD and highest R^2. The same result of CI from the power function proposed by Busscher (1990) was satisfied.

Gubiani et al. (2011) found that the parameterized regression models are not general and cannot be readily applied to other soils because of significant variations in MC and BD among different soils properties due to disparities in texture, pore size distribution or particle density.

Santos et al. (2012) employed anartificial neural networks model for predicting the penetration resistance produced by the soil's basic properties, such as BD and MC. They showed that CI is associated with BD and MC.

The objectives of this study were to (1) correlate and fit CI data which measured in sandy loam soil at different levels of MC, BD and PD, (2) develop regression equations for correcting CI values, (3) validate the regression equations using field data collected in this study, (4) compare the prediction model with the most promising models which selected from literature.

MATERIALS AND METHODS

Experimental arrangements

Field experiments were conducted on an 18 by 22 m site located in the Educational Farm of the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia (Fig. 1). The soil of the study field was classified as sandy loam (75.6 % Sand, 12.4% Silt and 12 % Clay). In this plot, a sprinkler with fixed installation is used as an irrigation system.

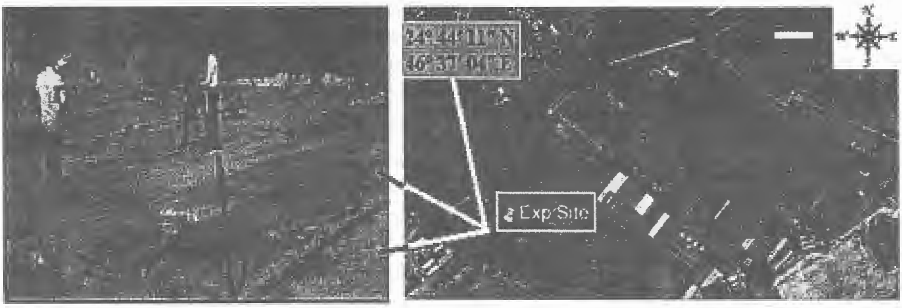

Fig. 1.Locationof field study in the Educational Farm of King Saud University

The experimental design was a split-split plot design randomized within four replicates. The experiment treatments were four levels of soil moisture content (MC) as main plots and four levels of soil bulk density (BD) as sub-main plots. Three penetrated depth (PD)were selectedin tillage zone (plowing layer) as sub-sub plots as shown in Table (1).

Table (1).Levels of experiment treatments

Main plots	Sub-main plots	Sub-sub plots	Replicates
Soil moisture content (%)	**Soil bulk density (g/cm^3)**	**Penetrated depth (cm)**	
MC1=4.62	BD1=1.36	PD1=5	R1
MC2=6.43	BD2=1.54	PD2=10	R2
MC3=7.41	BD3=1.68	PD3=15	R3
MC4=8.82	BD4=1.82		R4

Plate compactor

A TOKU, Malaysia, Vibratory Plate Compactor (model: 5.0 Robin EY 20-3) (Fig. 2) was used for the purpose of obtaining different levels of soil compaction; it means different levels of soil bulk density.

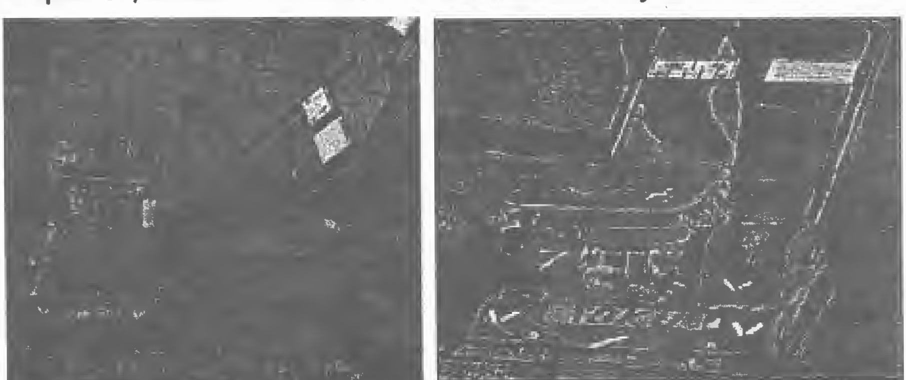

Fig. 2. Plate compactor

Soil compaction meter (Cone Index)

A Spectrum Technologies (Fig. 3), soil compaction meter was used to measure soil compaction in terms of soil resistance (Cone Index). The compaction meter consisted of an electronic penetrometer and a built-in datalogger for storage and processing of the penetration resistance measurements. The device was equipped with an ultrasonic sensor located at the base of the meter which was used to measure the depth of penetration.

The used Field Scout SC 900 compaction meter featured a measuring range of 0 to 45 cm and a cone index range of 0 to 7000 kPa.

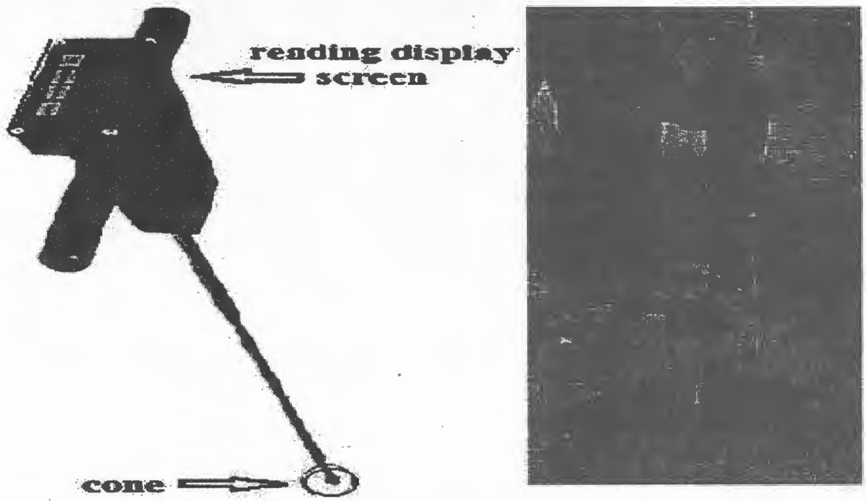

Fig. 3. The compaction meter

Test procedure

The experimental site was prepared before running test by using chisel plow and leveling soil surface by using Land Leveler. The experimental site has been divided into four main plotsfor each level of soil moisture content (MC) and four sub-main plots for each level of soil bulk density (BD).The size of the main plot was 8 m × 10 m and one meter between plots was considered to separate the plots.Different MC were obtained by applying different drying periods after site irrigation by using the sprinkler system.The size of the sub-main plot was 1 m × 10 m and one meter between plots was considered to separate the plots. Different soil bulk densities were obtained by applying different passes of the compactor on the soil surface as shown in Fig. 4.At each MC and BD level, four data points of were recorded by the soil compaction meter to represent replicates (R1, R2, R3 and R4).

Soil bulk density and soil moisture content determination

At each replicate,thesoil samples were collected at three depths 5, 10and 15cm using the soil cores and the soil sampler (Auger). The cylindrical sampling cores, 5cm diameter and 6cm height with sharp cutting edges were used to collect samples at 5 and 10cm depth. The volumetric sampler (Auger), 8cm diameter and 16cm height were used to collect samples at 15cm.Each soil sample which collected from the field was placed in a polythene bag andweighted. The samples were transferred to the laboratory and placedin an electric ovento dry at 105 °C for 24 h. The dry mass of the soil divided by the cylinder volume gave the soil bulk density (g/cm^3). The soil moisture content, MC (%, db) was calculated as the mass of water in the soil sample divided by the mass of the dry soil.

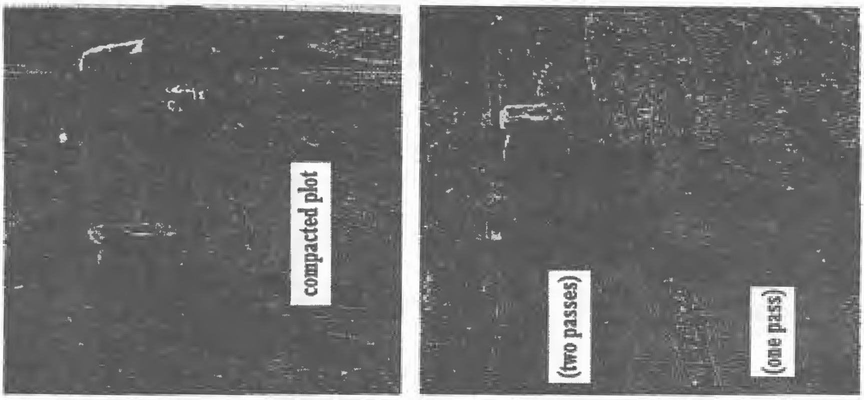

Fig. 4.Plate compactor was compacted soil during experiments

Statistical analysis

CI data were statistically analysed, using analysis of variance (ANOVA) for the split-split plot design with four replicates. The used software was COSTAT. Comparisons among treatment means, when significant, were conducted using least significant difference (LSD) at F test level of 0.05.

Predictionregression model of soil cone index

Regression analyses were performed on data obtained from field experiments in order to establish regression model for estimating the variation in the CI. It was used to predict CI relate to BD, MC and PD levels. Two equations of regulation model were obtained from the analysis, linear model (Eq. 1) and polynomial model (quadratic curve)(Eq. 2).

$$CI = a_{11} + b_{11}*MC + b_{12}*BD + b_{13}*PD \quad (1)$$

$$CI = a_{21} + b_{21}*MC + b_{22}*BD + b_{23}*PD + b_{24}*MC^2 + b_{25}*BD*PD \quad (2)$$

Where: CI Soil cone index, kPa, MC is soil moisture content, % , BD sis oil bulk density, kg/cm^3, PD ispenetration depth, cm, a_{11}, b_{11},b_{12}, $b_{13}$are regression coefficients in Eq. 1 and a_{21},b_{21}, b_{22}, b_{23},b_{24}, $b_{25}$are regression coefficients in Eq. 2

The model equations (Eq.1 and Eq.2) were compared with the most promising model equations from research study by Carlos et al (2011). The exponential (Eq.3) and power (Eq.4) functions proposed by Jakobsen and Dexter (1987) and Busscher (1990).

$$CI = \exp(a_{31}+b_{31}*BD + b_{32}*MC) \quad (3)$$

$$CI = a_{41}\, BD^{b_{41}} * MC^{b_{42}} \quad (4)$$

Where: a_{31},b_{31}, $b_{32}$are regression coefficients in Eq. 3, a_{41},b_{41}, $b_{42}$are regression coefficients in Eq. 4

Validation of regression models for estimating CI

The validation of results can be carried out by analyzing the errors.When the differences between measured (CI) and estimated (CI) values are smaller, the fitting data is considered good correlation. Also, the best model has lower root mean square error (RMSE) which could be determined as follows:

$$RMSE = \sqrt{\frac{\sum (CIM - CIP)^2}{N}} \quad ....(5)$$

Where CIM is measured soil cone index, CIP is predicted soil cone index and N is number of observations.

RESULTS AND DISCUSSION

Evaluating the influence of MC on CI

The relationships between CI and MC at different levels of BD and PD were quadratic curve (second degree) as shown in Fig. (5). The trend, similar to all previous studies, was found that CI decreased as MC increased. This phenomenon is due to reduced pressure of the liquid that fills empty spaces between soil particles and due to the reduced spacing between particles in some soils (Bengough et al., 1997). The rate of CI reduction with the increase in the MC is greater with higher BD values (such as result byHummel et al., 2004 and Moraes et al., 2012). Data were well represented by the model selected ($p<0.05$) in all cases, although there was a slight deal of random variability around regression line fitted. This random variability tended to be lower for low MC than for high MC and for 15cm depth than for 5cm depth.

Evaluating the influence of BD on CI

The relationships between CI and BD at different levels of MC and PD were linear regression as shown in Fig. (6). The trend, similar to all previous studies, was found that CI increased as BD increased because of soil strength increased (such as result by Ayers and Bowen, 1987). It was reported to increase soil strength with BD increased due to a higher number of contacts between particles per unit volume of soil (Ley et al., 1993). The rate of change in CI with BD levels was slight low.

Evaluating the influence of PD on CI

CIwas depended to a greater extent on penetration depth than it did on its MC orBD.The relationships between CI and PD at different levels of MCand BD were linear regression.The effect of penetration friction componentwas increased when penetrating soil (it mean that CI values increased when penetration depthsincreased).

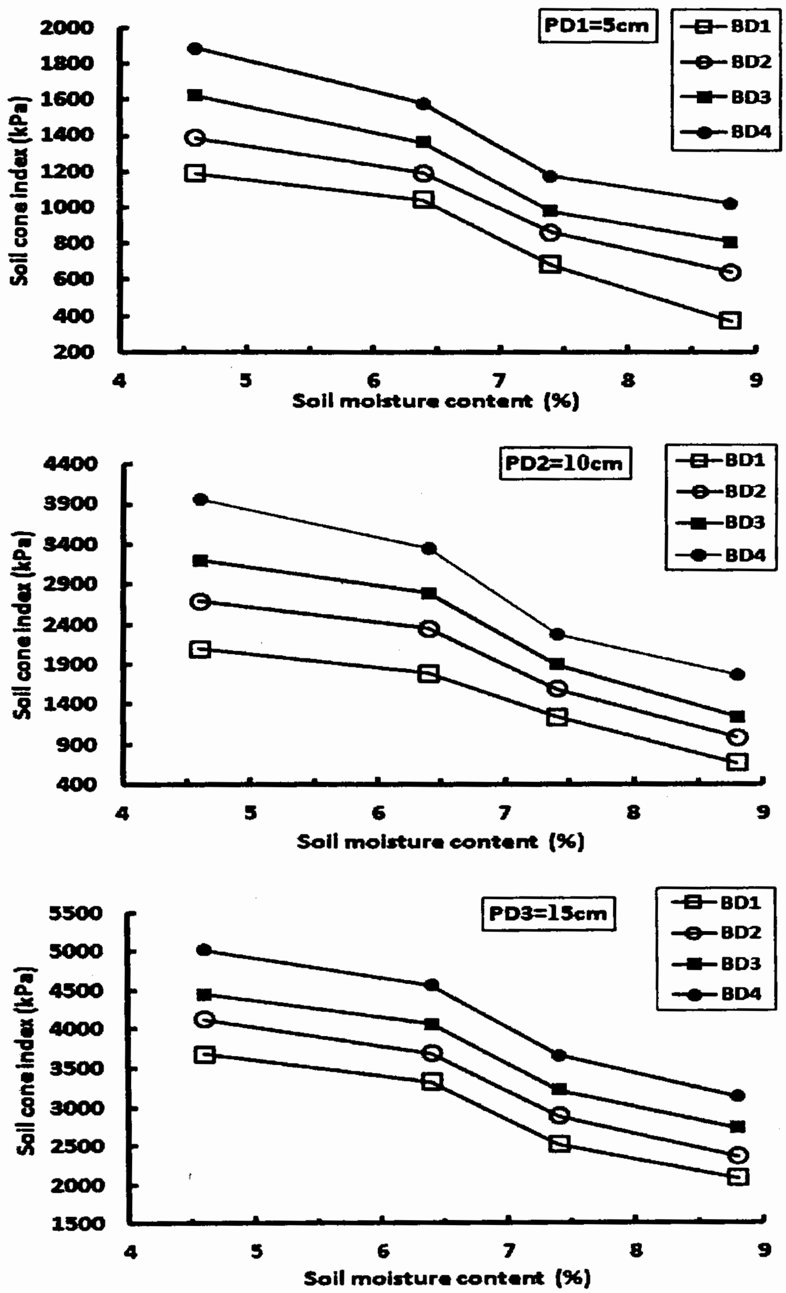

Fig.5. Effect of soil moisture content onmeasured soil cone index at different soil bulk densities (BD) and penetrated depths (PD)

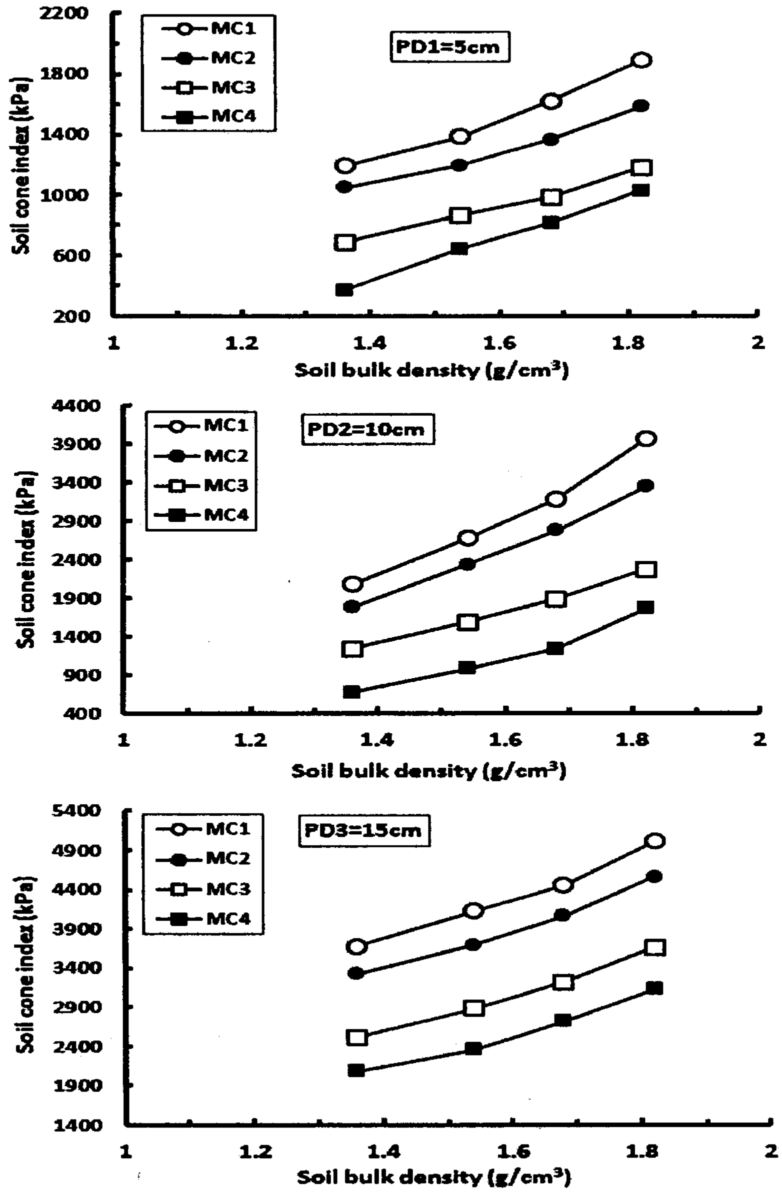

Fig.6. Effect of soil bulk density onmeasured soil cone index at different soil moisture contents (MC) and penetrated depths (PD)

Establishing regression models for estimating CI

$$CI = -1298.04 + 2273.65BD-361.8MC + 235.37P ....(6)$$

$$CI = -4440.05+2421.77BD+624.91MC+189.4PD-31.24MC^2-210.2BD*MC+128.12BD*PD-23.39MC*PD ....(7)$$

Regression statistics of model equations are shown in Table (2) for Eq.6 and Eq.7.The $R^2$of Eq. 6 and Eq. 7 were equal 93.3% and 95.6%, respectively. The standard error in Eq. 7 was reducing by 19.5% from Eq. 6. It means that polynomial function (quadratic curve) (Eq. 7) was more accuracy to estimate CI in sandy loam soil than linear function (Eq. 6).

Table (2). Regression statisticsof establishmodel equations for estimating CI .

	Regression statistics	
	Eq.6	Eq.7
Multiple R	0.972	0.985
R Square	0.933	0.956
Adjusted R Square	0.942	0.966
Standard Error	293.982	236.655
Observations	192	192

Comparison of regression models for estimating soil CI

The exponential model (Eq.3) by Jakobsen and Dexter (1987) and the power model (Eq.4) by Busscher (1990) were selected from literature to compare with two new equations of regression model.Table (3) summarized the coefficients of determination (R^2) and the root mean square error (RMSE) for each four regression models. The best matching equation of regression model to measured CI was identified based on the low value of RMSE and the high level of R^2. The levels of R^2 and the values RMSEfor all models were distinctly different. In general, both R^2 (≥0.92) and RMSE (≤127kPa) of two model of current study(linear and polynomial) were better than those of the other models from literature (exponent and power). For exponent model, the R^2 (≥0.88) and RMSE (≤324kPa) were low accuracy at PD 10cm. Also, the R^2 (≥0.84) and RMSE (≤336kPa) were low accuracy at PD 10cm for power model. It could be notice that data of exponent and powermodels were taken in soil types ranging from loamy sand to clay (Carlos et al., 2011). The linear and polynomial equations of this study were exhibiting the closest match to measured CI. The polynomial equation was the best matching equationfor estimating of soil CI (high R^2of0.968 and low RMSE of 127.2kPa). However, Fig. (7) shows correlation between the measured CI and CI estimated from establishmodel equations (Eq.1 and Eq.2).

Table (3).The $R^2$and RMSE of four regression models for estimating CI.

	Linear model		Polynomial model		Exponent model		Power model	
	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
PD=5cm	146.7	0.924	127.2	0.944	148	0.885	161.5	0.847
PD=10cm	280.9	0.928	246.3	0.956	324.7	0.921	336.7	0.884
PD=15cm	282.5	0.946	209.9	0.968	232.9	0.931	293.7	0.882

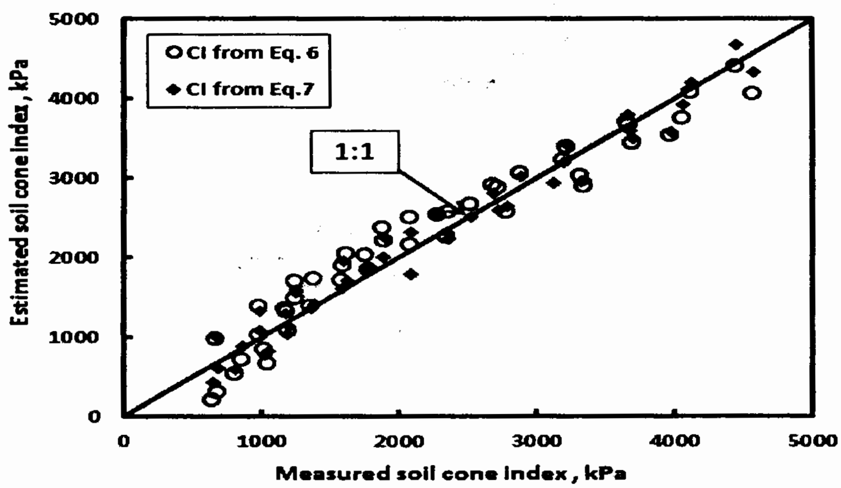

Fig. 7.Relationship between the measured Cland CI estimated from establishmodel equations (Eq.6 and Eq.7).

The ANOVA analysis (Table 4) indicated that BD, MC and PD had significant effect (P=0.01) on CI.This finding was in agreement with the results of Whalley et al. (2007). The all interactions among dependent variables (BD, MC and PD) had significant effect (P=0.01) on CI.Moreover, comparison between the mean of BD, MC and PD by LSD test (Table 5) showed that there are significant among all variables means. The highest values of CI were observed at BD (1.82 g/cm^3), MC (4.6 %) and PD (15 cm). But, the lowest values of soil CI were observed at BD (1.36 g/cm^3), MC (8.8 %) and PD (5 cm).

Table (4). Summary of the analysis of variance for the effect of soil bulk density, soil moisture content and penetrated depth on the soil cone index.

Source of variation	DF	Mean Square	F Value	P> F
		Main plots		
Blocks (replicates)	3	225800.24	33.989	0.00001***
MC	3	21578376	3248.14	0.00001***
Main plot error	9	6643.30		
BD	3	8506720.7	889.13	0.00001***
BD * MC	9	102369.26	10.699	0.00001***
Subplot error	36	9567.47		
PD	2	92694346	8248.5	0.00001***
PD * MC	6	1079233.5	95.829	0.00001***
PD * BD	6	477150.76	42.368	0.00001***
PD * BD * MC	18	38065.91	3.38	0.00001***
Error	96	11261.97		

DF: Degree of freedom, BD: soil bulk density, MC: soil moisture content, PD: penetrated depth.

Table (5). Mean* soil cone index as affected by bulk density, moisture content and penetrated depth

Bulk density levels	Mean CI	Moisture content levels	Mean CI	Penetrated depth levels	Mean CI
g/cm^3	kPa	%	kPa	cm	kPa
1.36	1769.45d	4.62	2983.72a	5	1105.79c
1.54	2075.22c	6.43	2559.14b	10	2113.98b
1.68	2364.62b	7.41	1972.45c	15	3505.17a
1.82	2757.29a	8.82	1451.27d		
LSD+ (5%)	40.493	LSD+ (5%)	37.636	LSD+ (5%)	37.238

***Means followed by different letters in each column are significantly different at P = 0.05.**
+LSD = least significant difference

CONCLUSION

Statistical analysis indicated that soil moisture content (MC), soil bulk density (BD) and penetration depth (PD) had significant effect (P=0.01) on soil cone index (CI). The all interactions between variables (BD, MC and PD) had significant effect (P=0.01) on CI. Moreover, there were significant among all variables means (BD, MC and PD).In sandy loam soil, BD and PD are linearly and directly proportional to CI. However, MC is quadratic curve (second degree) and inversely proportional tol CI. The maximum value of CI (5153 kPa) was recorded at BD (1.82g/cm^3), MC (4.6%) and PD (15 cm). The minimum value of CI (346kPa) was recorded at BD (1.36g/cm^3), MC (8.8%) and PD (5 cm).Two equations of regression model (linear and polynomial) for estimating of soil CI were predicted. The polynomial equation (R^2=95.6%) was more accuracy from linear equation (R^2=93.3%). It was compared two regression models (exponential equation by Jakobsen and Dexter (1987) and power equation by Busscher (1990)) with two established equations of regression model (linear and polynomial). The linear and polynomial equations were exhibiting the closest match to measured CI.The polynomial equation was the best matching equation for estimating of CI as value of high R^2(0.968) and low RMSE (127.2kPa).

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نمذجة وارتباط دليل اختراق التربة لمستويات كثافة ظاهرية ومحتوى رطوبة وعمق اختراق في تربة رملية طميية

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دليل اختراق التربة (CI) هو معيار يبين قوة وصلابة التربة. هو أداة مفيدة لتقييم تأثير عملية الحراثة والتنبؤ بقوة الشد للمحاريث.الهدف من الدراسة الحالية هو نمذجة وارتباط دليل اختراق التربةلمستويات كثافة ظاهريةومحتوى رطوبةوعمق اختراقفي تربة رملية طميية . تم جمع وتحليل بيانات مقاومة اختراق التربة(CI) إحصائيا عند أربع مستويات لكل من محتوى الرطوبةوالكثافة الظاهرية وثلاثة أعماق اختراق. تم تطوير نموذجين للانحدار (خطي ومتعدد) لتقدير مقاومة اختراق التربة (CI) ومقارنة هذه النماذج مع نماذج انحدار من الدراسات السابقة. أظهر التحليل الإحصائي أن CI تأثر معنويا بمستويات المتغيرات الثلاثة والتداخل بينهم. وأن الكثافة الظاهريةوعمق الاختراقيرتبطا مع CI بعلاقة خطية وتناسب طردي. لكن محتوى الرطوبة يرتبط مع CI بعلاقة منحنى وتناسب عكسي.وأظهرت النتائج أننموذج الانحدار كثير الحدود (R^2=95.6%) أكثر دقة من نموذج الانحدار الخطي (R^2=93.3%) في تقدير مقدار CI. وخلاصة النتائج أوضحت أن نموذجي الانحدار المستنتجين (خطي وكثير الحدود) يعطيا أقرب تطابق مع القيم المقاسة لـ CI من نموذجين مختارين من الدراسات السابقة (النموذج الأسي والنموذج الوغاريتمية).بينما في هذه الدراسة وجد أن معادلة نموذج الانحدار كثير الحدود (Polynomial) تكون أفضل معادلة لتقدير قيمة CIوأكثر تطابق للقيم المقاسة مع القيم المقدرة (أعلى قيمة R^2(0.968) و أقل مقدار (RMSE=127.2kPa).