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ORIGINAL PAPER

Unconfined Compressive Strength (UCS) and Compressibility Indices Predictions from Dynamic Cone Penetrometer Index (DCP) for Cohesive Soil in Kurdistan Region/Iraq

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Abstract Uniaxial Compressive Strength (UCS) and compressibility indices are essential tests for calculation of bearing capacity and settlement of cohesive soil in the foundation of building construction. These tests are time-consuming and demand significant effort. Therefore, the Dynamic Cone Penetrometer Index (DCP) can be utilized as an alternative method to predict UCS and compressibility indices such as compression index (Cc) and recompression index (Cr). In this study, the DCP is used to evaluate the UCS, Cc and Cr using the simple regression analysis. One hundred test pits were conducted in thirty-five locations, 150 DCP were tested at different depths and 150 samples were collected and tested for Natural water content, Dry density and Consolidation. The useful empirical equation between DCP and UCS was proposed. The obtained results prove the reliability of the proposed equations and for the first time, compressibility indices (Cc and Cr) were reasonably correlated with DCP. In addition, dry density of tested samples was studied and correlated with DCP.

Keywords UCS · Compression index · Recompression index · Dynamic cone penetrometer · Dry density

1 Introduction

Undrained shear test is crucially required to calculate the shear strength parameters of cohesive soils for the foundation of structures so as to calculate their bearing capacity. Usually, Uniaxial Compression Strength (UCS) test is used to predict the undrained shear strength parameters of cohesive soils. However, this test is time consuming and demand significant effort. The simple alternative method is to use the Dynamic Cone Penetrometer Index (DCP). This method is extensively studied and used for quality control of compaction of granular materials for earthwork and road construction and significant empirical equations were developed to predict the CBR, modulus subgrade reaction and dry density (Amini 2003); however, there are few study about prediction of UCS using DCP. McElvaney and Bundadidjatnika (1991) correlated the DCP with the laboratory uniaxial compressive strength (UCS) results for various types of lime stabilized soils in pavement engineering; however,

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they used compacted cohesive subgrade materials in their work and the proposed correlation may not reflect the real situation in the field under foundation of structures as well as the number of samples were limited. Similar correlations were developed by other researcher (Chai and Roslie 1998; Du et al. 2016; Gabr et al. 2000; Patel and Patel 2012; Ranasinghe et al. 2017; Salgado and Yoon 2003; White et al. 2009; Zumrawi 2014) but for quality control of pavement layers. The literature review clearly reveals the need of empirical equation to estimate UCS, Cc and Cr from DCP based on the field and laboratory works. Also, the literature review indicated that there is no universal standard method of utilizing DCP test to predict undrained shear strength of cohesive clay. In addition, according to authors' knowledge, there is no information about predicting compression index and recompression index of cohesive soils from DCP index. This study presents a correlation between UCS and DCP for cohesive soil available in Sulaimani governorate in Kurdistan region of Iraq. Approximately one hundred boreholes were conducted in thirty-five locations, 150 DCP tests were performed at different depths and 150 samples were collected and tested for determining the Natural water content, Dry density and. The UCS and compressibility tests were performed on undisturbed samples whereas DCP test were achieved at depths where the undisturbed samples were taken.

2 Previous Correlations

McElvaney and Bundadidjatnika (1991) proposed Eq. (1) to predict UCS from the DCPI for cohesive soils mixed with different percent of lime (0–8%) for pavement engineering. The coefficient of determination (R^2) was 0.68. However, the DCP test was performed on cohesive soil in compaction mould and this may not represent the field situation. Also, the number of tests was less than 100.

$$\log \mathrm{UCS} = 3.56 - 0.809 \log \mathrm{DCP} \tag{1}$$

White et al. (2009) proposed Eq. (2) which is similar to Eq. (1) with R^2 of 0.58. The DCP was achieved on compacted cohesive soil in the field. However, the number of tested samples (23 samples) was limited and this may not represent the real situation in the field. Again, this study was achieved for pavement engineering.

$$\log S_u = 2.95 - 0.67 \log \mathrm{DCP} \tag{2}$$

where S_u is the undrained shear strength in kPa.

Patel and patel (2012) used DCP to predict UCS. About 29 tests were performed on remoulded soaked soil samples in the laboratory for each of DCP and UCS. They developed the following equation:

$$\mathrm{UCS}\left(\frac{\mathrm{N}}{\mathrm{mm}^2}\right) = 3.1237 * (\mathrm{DCP})^{-0.865} \tag{3}$$

Patel et al. (2013) used DCP to predict the subgrade strength parameters and as a result of their study, they proposed the Eq. (4) to predict UCS of clay soils using remoulded clay in the laboratory. They utilized multiple regression analysis in the proposed equation incorporating Moisture Content (M.C.) and modified Liquid Limit (W_{LM}).

$$\mathrm{UCS}\left(\frac{\mathrm{kg}}{\mathrm{cm}^2}\right) = 0.07904 * \mathrm{DCP} - 0.05686 * W_{LM} - 0.07359 * \mathrm{M.C.} + 3.223091 \tag{4}$$

It should be noted that the above equations are suitable for values of DCP greater than 20 mm/blow (low strength soils) because those equations overestimates the value of UCS especially for DCP of less than 20 mm/blow as shown in Fig. 1.

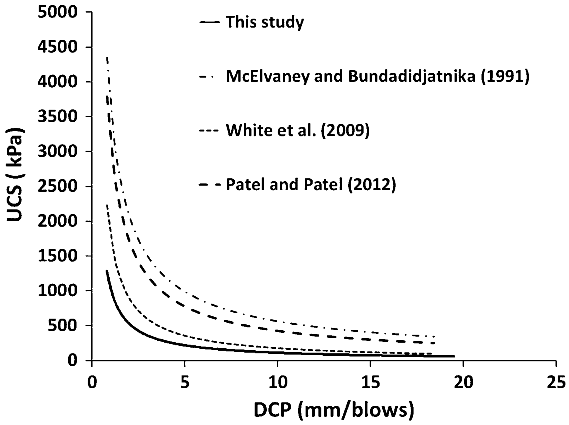

Fig. 1 Comparison between the previous developed correlations and current study

3 Materials and Methodology

3.1 Cohesive Soil Materials

In this study, we selected brown clay with carbonates because large area of sulaimani city is covered with cohesive soils. About 35 locations were selected in Sulaimani city in Kurdistan of Iraq. Samples of 150 were collected from boreholes at different depths ranging from 1 m to 4 m using hand augur method. To obtain undisturbed samples of cohesive soils Shelby tube sampler was used. The classifications of soils used in this study are presented in Fig. 2. It should mention that tests and the procedures were conducted according to ASTM standard as presented in Table 1.

3.2 Dynamic Cone Penetrometer

The dynamic cone penetration (DCP) test, has been widely used in geotechnical investigations for the last three decades (Mohammad et al. 2007). The in situ dynamic cone penetration (DCP) was conducted in this study because the test which is a simple, fast, and economical geotechnical test. The sketch of the apparatus is shown in Fig. 3. The test consists of 8 kg weight having a drop of 575 mm, fitted to the end of the shaft is a 20 mm diameter cone. The length of DCP penetration rod is about 1 m, but it can be extended by extension rods (each 1 m) to the desired depth in the boreholes. The DCP can be carried out to depths of about 6 m. In this study a new methodology was adopted to carry out the DCP test, the new procedure is as follows:

(1) The DCP setup was held vertical and positioned at the preferred location.
(2) The hammer was lifted and dropped so as to initiate the test.
(3) Following 10 blows of the hammer, the depth of penetration was computed and then the penetration depth was divided by 10 blows and recorded as the DCP value (mm/blow).

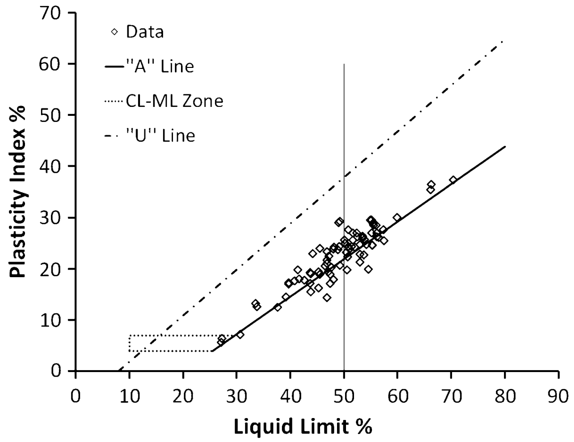

Fig. 2 The plasticity chart shows the classification of soils used in the study

It should be mentioned that one the most important features in this study is that all DCP tests were conducted in the field for 150 points at different depths of 35 locations and all UCS tests were conducted on undisturbed samples.

The length is approximately 1 m, but it can be extended by extension rods (each 1 m) to desired depth in the boreholes. The DCP can be carried out to depths of about 6 m.

3.3 Uniaxial Compressive Strength Test

Undisturbed soil samples of 150 points were collected from brown clay of 35 locations by small diameter of thin wall tubes (38 mm), which are suitable for conducting unconfined compression tests. Also, the natural moisture content, bulk and dry density were conducted for these samples as presented in Table 2. The results indicate that the range of UCS, natural water content, and dry densities are (13.9–1058.9 kPa), (6.2% and 57.5%), and (1.31–1.91 gr/cm^3), respectively. These values indicate that the cohesive soil layers are soft to hard cohesive brown soils.

3.4 Consolidation Test

Consolidation tests were performed only on 80 undisturbed cohesive samples by using consolidation ring 50-mm diameter by 19-mm thick. The applied pressure used is in the range of 25 to 800 kPa. Casagrande's method is used to determine preconsolidation pressure (Pc) (Das and Sobhan 2013). The values of compression Index (Cc) were between (0.0570 and 0.5867) and the values of recompression index were between 0.0109 and 0.1609.

Table 1 Test methods and procedures utilized in the paper

Test description	Test procedure
Description and classification of cohesive soils	ASTM D2488
Soil sampling	Undisturbed samples were collected according to ASTM D1587 for Unconfined compression and Consolidation tests whereas disturbed samples were collected for classification tests according to ASTM D4220
Moisture content of cohesive soils	ASTM D2216
Density of soils	ASTM D7263
Atterberg limits	ASTM D4318
Unconfined compressive strength	ASTM D2166
Consolidation tests	ASTM D2435
Unified Soil classification system	ASTM D2487

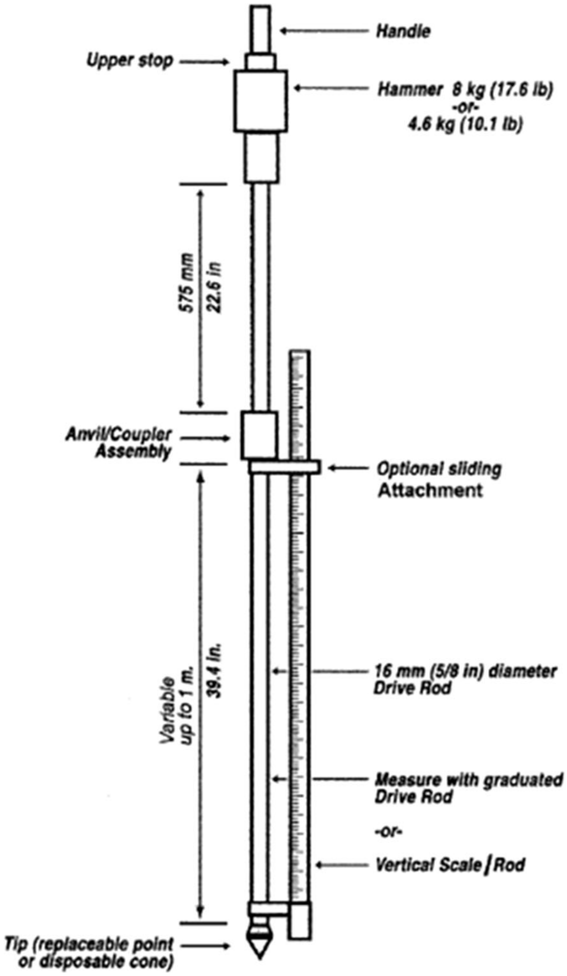

Fig. 3 Dynamic cone penetrometer apparatus (ASTM 2003)

4 Results and Discussions

The results of DCP, natural moisture content, dry density, UCS, Recompression Index (Cc) and Compression Index (Cr) are represented in Table 3. In this study the simple regression analysis using Microsoft Excel 2010 was utilised and the coefficient of correlation (R) is used to determine the goodness of fit and it describes the relative correlation between the predicted and actual results. The guide proposed by Smith (1993) was utilised as follows: (a) **|R| = 0:8:** strong correlation exists between two sets of variables; (b) **0:2 < |R| = < 0:8**: correlation exists between two sets of variables; **(c) |R| = 0:2**: weak correlation exists between two sets of variables.

In this paper, the collected undisturbed samples from different locations of brown clay were brought to the laboratory and UCS was performed. The UCS (kPa) values obtained in laboratory were correlated with in situ DCP (mm/blow) using simple regression analysis. Figure 4 shows the correlation between DCP and UCS. The nature of the data suggests that as DCP increases the UCS value decrease. As can be seen, there is a power relationship between DCP and UCS with correlation coefficient (R) of 0.91 which suggests that there is a good correlation between the two variables. The correlation Eq. (5) can be used to predict the undrained shear strength parameter of cohesive soils. A general relationship between shear strength of cohesive materials and DCP values is possible because shear strength of cohesive materials

Table 2 The results of DCP, natural moisture content, dry density and UCS

Location name	Test Pit no.	Depth (m)	Natural water content (%)	Dry density	DCP (mm/blows)	UCS (kPa)
Saed-Sadiq-Sulaimani	1	1	20.81	1.634	10	176.8
		2	19.54	1.727	9.2	191.4
		3	32.14	1.4368	13.2	83.52
		4	32.31	1.401	11.4	92.52
		5	22.35	1.60’/	10.8	132.54
	2	2	16.73	1.726	4.7	204.02
		3	29.27	1.488	13.2	81.65
		4	30.67	1.465	7.7	134.43
	3	2	19.11	1.745	5.9	174.05
		3	29.67	1.51	8.5	134.09
		4	29.57	1.444	8.5	140.98
	4	2	20.43	1.693	7.5	193.91
Gapelon-Sulaimani	1	1.7	26.96	1.609	15.9	44.19
		2.7	23.74	1.679	7.1	146.16
		4	29.95	1.545	6.2	126.7
	2	1.5	57.46	1.36	19.5	83.1
		3	26.57	1.633	6.5	184.1
	3	1.2	19.23	1.644	15.7	28.3
		2.3	23.11	1.62	7.1	120.94
		3.4	26.22	1.648	6.3	182.5
	4	2.2	22.52	1.61	5.3	267.2
	5	2.5	26.74	1.669	9.1	182.5
	6	2.4	26.78	1.649	6.8	104.99
	7	2	34	1.475	8.4	81.31
		3	24.26	1.363	11.8	49.71
Darbandv-khan-Sulaimani	3	3	20.1	1.576	7.2	255.2
Bakrajo-Sulaimani	1	1	15.74	1.6774	2.8	451.9
		3	19.16	1.606	2	497.7
	2	1.5	15.8	1.724	1.5	686
		2	19.38	1.626	2	460.3
		3	16.04	1.6449	1.5	712.97
AUS (American University)	3	1	15.73	1.686	4.6	267.4
Hajv Awa-Sulaimani	3	3.2	17.19	1.71	3.1	390.2
Rap areen-Sulaimani	1	1.3	16.36	1.726	4.1	321.02
	1	2	10.5	1.809	1.9	441.82
	1	4	20.93	1.589	2.5	505.51
	2	3	22.96	1.612	2	508.07
	3	2.6	21.52	1.591	2.4	442.52
Kany Speka-Sulaimani	1	1.5	16.67	1.622	5.8	269.08
	2	1.5	17.71	1.702	3	440.1
		2.4	28.97	1.434	9	168.9
	3	4	28.44	1.443	14.4	60.2
	4	3.4	29.31	1.432	6.4	153.5
		5	34.52	1.356	9.6	70.6

Table 2 continued

Location name	Test Pit no.	Depth (m)	Natural water content (%)	Dry density	DCP (mm/blows)	UCS (kPa)
Dormitory Building-University of Sulaimani	1	1	20.3	1.5988	9	131.68
		2	19.68	1.6397	4	313.09
		3	16.06	1.7247	2.4	397.75
	2	2.3	14.61	1.7605	3.3	390.27
		3.5	13.28	1.819	1.8	517.22
	3	0.5	19.62	1.7935	4.5	247.17
		1	18.6	1.8269	4.1	316.65
Kirkuk (K1)	1	4	9.97	1.7664	0.8	1058.9
	2	4	19.13	1.7295	4.7	319.3
	3	3	10.33	1.6628	1.8	466.94
	4	1	10.94	1.7923	1.2	700.6
		4	15.34	1.568	4.4	178.68
Raniya	1	1	14.59	1.6451	5	230.21
	3	1	19.83	1.769	5	152.95
		2	18.49	1.614	4	214.23
Zaetton show-Kirkuk	1	3	15.93	1.571	2.9	335.9
Wahid Azar -Kirkuk	1	3.6	17.93	1.708	3.8	308.97
Hay-Askary-Kirkuk	1	4.8	17.45	1.7006	5.1	254.2
M aasker Khalid-Kirkuk	1	4	15.01	1.716	1.5	666.54
Peramerd p ark-Sulaimani	1	2.5	22.01	1.613	5.4	289.49
		3.3	22.15	1.607	5.3	226.6
	2	1.7	21.61	1.652	7.1	128.4
		2.5	20.54	1.649	5.9	140.5
	3	2.4	23.03	1.612	9	180.2
		3.4	25.53	1.531	9.6	152.9
		5.4	24.94	1.55	3.5	239.14
	4	2	19.39	1.689	7.7	209.5
		3	26.1	1.521	5.6	174.2
		5	25.76	1.487	4.6	191.1
	5	2	24.13	1.551	9.7	132.8
		3	20.23	1.67	5.3	221.1
		4	23.1	1.583	4.3	283.4
	6	3	24.37	1.579	3.4	304.5
	7	2	20.08	1.667	9.7	98.37
	8	3	24.14	1.568	7.2	154.5
		4	30.06	1.439	5.5	162.6
		5	26.37	1.511	3.9	219.7
	9	4	24.32	1.529	4.5	216.5
		5.1	36.84	1.43	7	174
		6.5	35.68	1.313	4.3	220.9
	10	3.2	1332	1.759	6	165.7
		5	32.06	1.402	8.1	148.99
Halabja-Sulaimani	1	3	26.63	0.517	5.8	144.4

Table 2 continued

Location name	Test Pit no.	Depth (m)	Natural water content (%)	Dry density	DCP (mm/blows)	UCS (kPa)
	2	2	26.28	0.529	10	77.43
	4	1	23.14	1.633	3	300.8
	4	2	21.68	1.591	4.9	201
	5	1.2	21.61	1.613	9.7	142.5
	9	1.5	22.24	1.657	3.8	276.6
Halabia-Sulaimani	4	2.5	22.08	1.614	6	290.6
Hamon citv-Kova	6	1.2	6.17	1.9089	3	274.2
Bakraio-ARC-Sulaimani	3	1.5	16.43	1.758	1.5	591.7
Suse-Sulaimani	1	1	13.44	1.831	7	171.9
	2	2	43.18	1.319	18.4	13.91
Bazyan-Sulaimani	1	1.3	18.08	1.664	7.2	137.9
		4	16.73	1.752	4	230.4
	2	1.3	18.23	1.684	7.9	146.9
	3	1.3	17.9	1.697	2.7	457.9
	5	1.3	25.11	1.507	12.3	81.85
		2.5	21.3	1.633	2.8	412.7
		4	18.72	1.632	3.7	256.8
	7	4	19.43	1.725	4.3	253.43
	8	1.3	14.29	1.72	6.7	241.8
Daya City-Sulaimani	7	1	20.98	1.696	3.9	344.9
		2	24.01	1.628	4	323.2
		3.3	22.11	1.66	3.7	288.6
Kurd City2-Sulaimani	10	1	12.79	1.689	5.2	295.3
Ranya-Sulaimani	1	3	19.81	1.616	2.7	413.9
Halabja-Sulaimani	1	2	21.54	1.641	2.4	521.7
Ranya-Sulaimani	1	1	27.2	1.509	12.7	118.9
	2	1	26.6	1.532	10	124.77
		3	22.3	1.657	4	270.8
	5	1	23.9	1.601	10	101.8
	6	3	20.77	1.623	3.1	266.04
	8	0.5	22.19	1.696	7.8	147.1
Diya Ciy2-Sulaimani	1	1	20.09	1.734	4.2	342.4
		3	16.24	1.821	2.5	490.6
	2	2.5	19.43	1.752	3	333.8
	4	2	20.63	1.696	3.7	225.3
		3	22.41	1.64	4	252.6
		4	22.71	1.622	3.6	313.5
	5	2.5	31.6	1.425	7.3	161.99
		3.5	28.21	1.576	3.4	366.6
	6	3.2	20.93	1.646	2.4	482.7
	8	1	21.99	1.677	6.7	111.53
		2	23.49	1.618	6	181.6
Qaladeza-Sulaimani	1	1	23.67	1.569	16	122.08
		2	21.76	1.563	4.2	316.9

Table 2 continued

Location name	Test Pit no.	Depth (m)	Natural water content (%)	Dry density	DCP (mm/blows)	UCS (kPa)
	3	1	19.27	1.655	15.1	46.51
	4	1	20.96	1.65	15.9	95.9
		2	22.02	1.624	4.8	238.4
	6	1	27.2	1.558	8.1	187.51
	8	1.2	28.32	1.499	12.6	79.7
		4.3	27.79	1.563	4.8	208.3
	10	3	37.71	1.513	2.7	406.4
	11	1	18.59	1.669	17.3	68.01
		2	17.92	1.765	3.1	377.7
		4	22.32	1.65	2.6	359.4
	12	1	23.69	1.613	14.2	125.96
		2	22.48	1.612	5.1	184.1
		3	23.21	1.623	6.5	262.9
Wolloba-Sulaimani	2	2	22.71	1.668	2.9	424.3
		3	19.06	1.757	2.2	462.8
	3	2.6	20.06	1.71	3.1	325.6
	5	1	18.32	1.765	2.5	443.5
Qolarasy-Sulaimani	5	4	17.31	1.693	2.5	402.2

is not affected by confining pressure (Das and Sobhan 2013).

$$\mathrm{UCS} = 1033.6 * (\mathrm{DCP})^{-0.968} \tag{5}$$

4.1 Correlation Between DCP and Dry Density

Figure 5 presents the correlation of DCP with dry density of clay samples. As can be seen, there is a linear relationship between DCP and dry density with correlation coefficient of R = 0.50. The correlation is given in Eq. (6). The value of R can be increased by incorporating water content using multiple regression analysis; however, only simple regression analysis was used here so as to predict the studied parameters by simple and rapid test such as DCP.

$$\rho_d = 1.7702 * \mathrm{DCP}^{-0.055} \tag{6}$$

4.2 Correlation Between UCS and Dry Density

Figure 6 presents the correlation between UCS and dry density. There is an exponential relationship between UCS and dry density with correlation coefficient of R = 0.53. As can be predicted that this correlation is not strong because UCS depends on other parameters such as water content and liquidity index; therefore, to get a strong relationship, a multiple regression analysis is crucially required and this will not be studied here because the focus of this study is rapid determintation of strength parameters using DCP.

$$\mathrm{UCS} = 18.282 * \rho_d^{5.099} \tag{7}$$

4.3 Correlation Between DCP and Compressibility Indices

In this study an attempt was made to predict compression and recompression indices of consolidation test from DCP. The results are presented in Fig. 7. From the results, it can be concluded that the indices may be predicted using DCP and it should be mentioned that the correlation coefficient of DCP with compression index is 0.91 and with recompression index is 0.52.

$$\mathrm{Cc} = 0.0119 * (\mathrm{DCP}) + 0.1011 \tag{8}$$

Table 3 The results of DCP, natural moisture content, dry density, Recompression Index (Cc) and Compression Index (Cr)

Location name	Test Pit no.	Depth	Recompression index (Cc)	Compression index (Cr)	Natural water content (%)	Dry density (Gr/cm^3)	DCP (mm/blows)
Saed-Sadiq-Sulaimani	1	4	0.0355	0.2634	30.56	1.5146	11.4
	2	3	0.047	0.2411	29.59	1.6107	13.2
	3	3	0.0372	0.2131	28.75	1.498	8.5
Gapelon-Sulaimani	1	2.7	0.0334	0.1765	24.81	1.7088	7.1
	2	3	0.0405	0.2095	25.4	1.7009	6.5
	3	3.4	0.0304	0.1668	24.62	1.6105	6.3
	4	2.2	0.0269	0.1727	22.58	1.6132	5.3
	5	1.3	0.0346	0.206	26.49	1.5125	8.6
	3	0.0367	0.1622	24.7	1.7103	5.2	
Darbandikhan-Sulaimani	1	1	0.0301	0.1967	21.58	1.6374	7.5
	3	1	0.0221	0.1462	15.78	1.4534	3.5
	4	5	0.019	0.1136	15.39	1.99	0.9
Kalar-Sulaimani	2	3	0.0181	0.1364	18.59	1.7103	4
Bakrajo-Sulaimani	2	3	0.0319	0.1097	15.3	1.7219	2.7
Rap areen-Sulaimani	1	4	0.0324	0.1317	19.35	1.6007	2.5
	3	2.5	0.0351	0.1144	21.26	1.8119	2.4
Kany Speka-Sulaimani	2	1.4	0.0319	0.1336	20.29	1.8321	2
	2.3	0.0286	0.2342	27.3	1.5554	9	
	3	4	0.0274	0.2346	33.04	1.4682	9
	5	0.0318	0.243	32.91	1.5039	11	
	4	3.4	0.0368	0.1953	30.84	1.4335	6.4
Dormitory Building-University	3	2.8	0.016	0.127	17.44	1.6967	1.3
Kirkuk (K1)	1	2	0.0191	0.1285	9.55	1.8136	1.1
	2	3	0.0227	0.1667	16.38	1.63	6.8
Raniya-Sulaimani	1	1.5	0.0296	0.1503	18.49	1.6867	3.5
	3	2	0.0331	0.1261	18.17	1.7758	3
	4	1.5	0.0193	0.1457	18.34	1.8349	3.5
Zaetton show-Kirkuk	1	2	0.0262	0.1029	14.42	1.871	2
		4	0.0224	0.1505	16.84	1.6786	1.7
Peramerd park-Sulaimani	1	2	0.0364	0.1445	18.26	1.6313	1
	2	4.3	0.0358	0.1606	21.41	1.6573	2.7
	4	4	0.0375	0.1575	25.64	1.5141	5.8
	6	2.25	0.0316	0.1301	23.82	1.3979	4.4
	9	6.5	0.0485	0.1698	32.58	1.4126	4.3
	10	3.2	0.0308	0.1622	17.01	1.6808	6
Halabja-Sulaimani	8	1	0.0205	0.1286	16.83	1.9012	3.3
	10	3	0.03	0.1652	24.17	1.5688	3.2
Hamon city-Koya	9	1.4	0.0225	0.1667	16.52	1.7844	2.9
Bakrajo-ARC-Sulaimani	1	2.5	0.0184	0.1066	17.04	1.8715	1.9
	3	1.5	0.0227	0.137	15.16	1.8952	1.5
	4	1.5	0.0217	0.1416	15.49	1.834	1.7
Suse-Sulaimani	2	2	0.0486	0.3112	53.89	1.2188	18.4
Qaladiza2-Sulaimani	3	1	0.0198	0.1662	24.2	1.892	5

Table 3 continued

Location name	Test Pit no.	Depth	Recompression index (Cc)	Compression index (Cr)	Natural water content (%)	Dry density (Gr/cm^3)	DCP (mm/blows)
Bazyan-Sulaimani	5	2.5	0.0298	0.1281	22.24	1.6615	2.8
	7	2.5	0.0237	0.1655	15.66	1.8046	4.1
	8	1.3	0.0264	0.1606	18.01	1.653	6.7
HalabjaBC-Sulaimani	1	1.4	0.019	0.1327	17.78	1.6152	4
	2	1	0.0183	0.1557	13.88	1.6399	3
Daya City-Sulaimani	6	0.5	0.024	0.1234	16.8	1.865	3.3
	2.6	0.0331	0.1392	17.95	1.8059	3.3	
	7	3.3	0.0353	0.1482	22.59	1.7836	3.7
Kurd City2-Sulaimani	6	3	0.0325	0.1536	21.39	1.7901	5.3
	11	1	0.0285	0.1515	18.7	1.7449	6.3
Halabja-Sulaimani	1	2	0.0318	0.1146	20.05	1.6806	2.4
	2	4	0.0394	0.1154	22.61	1.6522	1.9
Ranya-Sulaimani	2	1	0.0329	0.2304	25.97	1.5421	10
	5	1	0.032	0.2018	24.49	1.6572	10
	9	2	0.0285	0.1551	20.18	1.7802	4.2
	4	0.0282	0.1359	17.41	1.6237	1.7	
Diya Ciy2-Sulaimani	3	3	0.0221	0.1301	16.7	1.7874	3.1
	4	3.1	0.0277	0.1433	22.78	1.7786	4
	1	0.0431	0.2056	21.6	1.7738	6.7	
	6	1	0.0288	0.1249	23.82	1.7864	3.8
	3.1	0.024	0.1111	19.12	1.8692	2.4	
	8	2	0.0395	0.1691	26.34	1.5588	6
Qaladeza-Sulaimani	4	2	0.0384	0.1336	21.04	1.781	4.8
	8	4.3	0.0255	0.1392	26.09	1.6308	4.8
	9	4.2	0.0339	0.1372	20.57	1.7457	2.7
	10	2	0.0217	0.132	17.34	1.6006	3.9
	11	2	0.0241	0.1321	15.82	1.867	3.1
Wolloba-Sulaimani	4	2	0.0226	0.1046	20.25	1.8271	2.1
	5	4	0.0263	0.115	19.58	1.8262	2.1
	9	1.5	0.0205	0.1898	16.89	1.6664	4.6
Qolarasy-Sulaimani	1	1.5	0.0196	0.1236	16.04	1.748	2.7
	3	2.5	0.0191	0.1181	16.93	1.8584	2.4
	4	4	0.0283	0.134	18.34	1.5759	2.2
	5	1.5	0.0167	0.1261	15.15	1.7126	3.1
	14	2.5	0.0185	0.1271	17.66	1.7398	3.3
	15	2.5	0.0194	0.137	19.2	1.7399	2.8
	16	2.5	0.0204	0.1413	16.4	1.6459	2.3

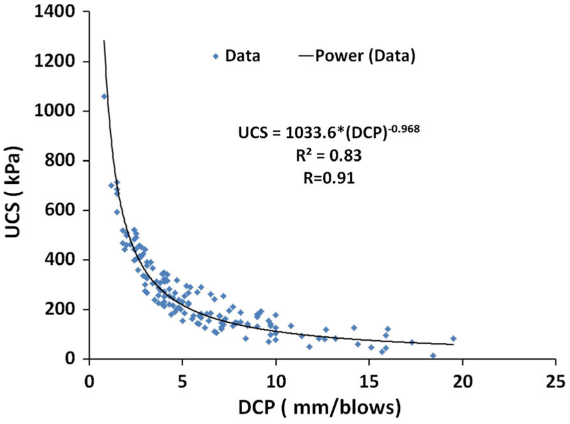

Fig. 4 Relationship between DCP and UCS

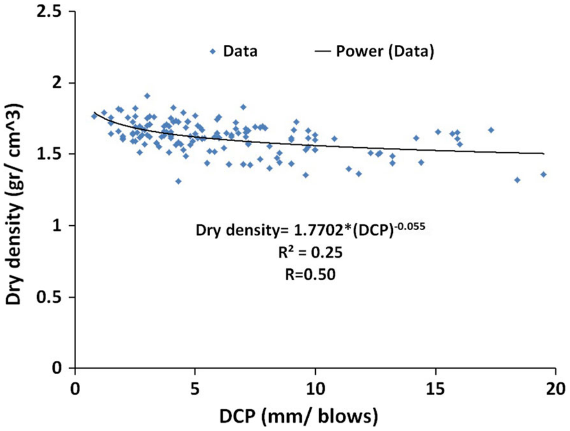

Fig. 5 Relationship between DCP and dry density of tested soils

$$\mathrm{Cr} = 0.0013 * (\mathrm{DCP}) + 0.0225 \tag{9}$$

5 Predicted Versus Measured Parameters

5.1 Uniaxial Compressive Strength (UCS)

To check the reliability of DCP the predicted UCS using Eq. (5) was plotted versus measured UCS of undisturbed samples. The results are presented in Fig. 8. As can be seen there is a good distribution of data around equity line which indicates that the DCP can be correlated with UCS and the correlation coefficient of this relationship is 0.95. It should be noted that the Root Mean Square Error (RMSE) = 52.4 kPa.

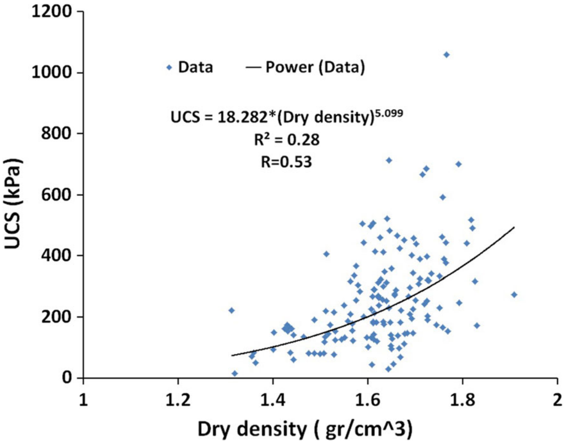

Fig. 6 Relationship between Dry density and UCS

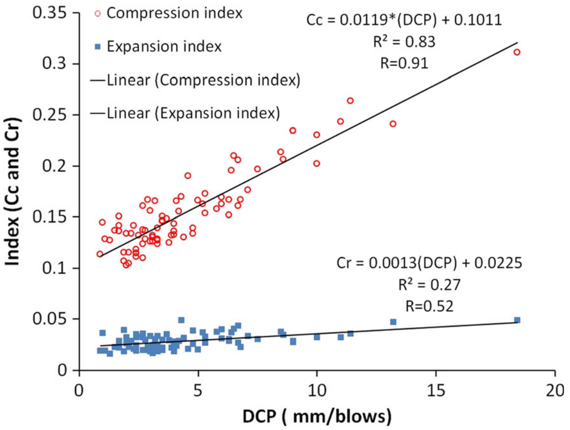

Fig. 7 Relationship between DCP and indices (compression and recompression)

5.2 Compression Index (Cc) and recompression Index (Cr)

The measured compression index was plotted against predicted compression index. The results are presented in Fig. 9. The correlation coefficient of this relationship is 0.91 which indicates a strong relationship between the proposed prediction equations with measured value. The RMSE was 0.01644. The relationship between measured recompression index and predicted recompression index shows a satisfactory correlation (R = 0.52) with RMSE of 0.00653 as presented in Fig. 10; however, this relationship is not strong as in Cc since the variance in recompression index values are small in comparison with Cc.

Finally, we should remark that the practical implication of this study is to find some geotechnical properties of cohesive soils such undrained shear strength and soil compressibility utilizing the DCP method in the field which can be used to rapid predict of the bearing capacity of the cohesive soils as well as the consolidation settlement of foundation of structures.

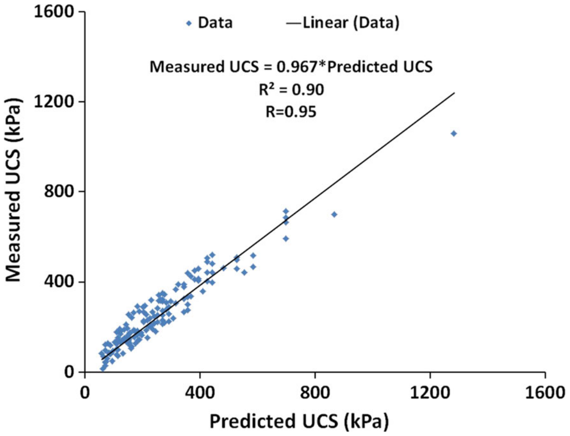

Fig. 8 Measured UCS versus Predicted UCS

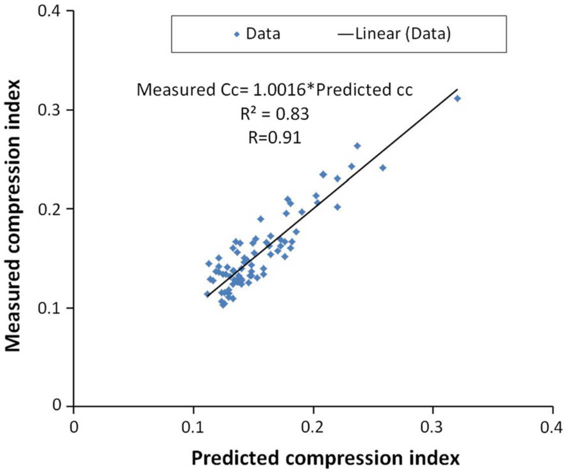

Fig. 9 Measured Cc versus predicted Cc

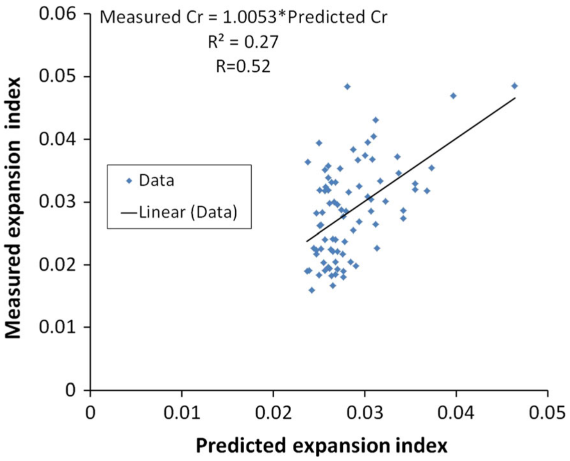

Fig. 10 Measured Cr versus predicted Cr

6 Conclusion

In this study an attempt was made to correlate the DCP value with undrained shear strength parameter of cohesive soils collected from some parts of Kurdistan region, Iraq. Also, dry density, compression and recompression indices were predicted using the DCP value. As a result of this study the following conclusion can be concluded:

(1) A new methodology was adopted to calculate the rate of penetration using DCP which can be used as a standard to predicted shear strength parameter for bearing capacity of cohesive soils.
(2) A reasonable correlation was developed between DCP value and UCS with correlation coefficient of R = 0.91 for cohesive soils.
(3) An acceptable relationship was found between DCP and compression index for cohesive soils with correlation coefficient (R) of 0.91.
(4) A correlation was found between DCP value and dry density of cohesive soils.

It should be noted that the results of this study should only be used with caution and for estimating the Unconfined Compressive Strength (UCS) and compressibility Indices for lightly loaded structures constructed on cohesive soils Also, the DCP can be used as a verification tool for an economical foundation analysis.

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References

Amini F (2003) Potential applications of dynamic and static cone penetrometers in MDOT pavement design and construction. Princeton, Citeseer

ASTM (2003) Standard test method for use of the dynamic cone penetrometer in shallow pavement applications. ASTM D 6951-03. ASTM International, West Conshohocken, PA

Chai G, Roslie N (1998) The structural response and behaviour prediction of subgrade soils using the falling weight deflectometer in pavement construction. In: Paper presented at the 3rd international conference on road and airfield pavement technology, proceedings volume 2

Das BM, Sobhan K (2013) Principles of geotechnical engineering. Cengage Learning, Boston

Du Y-J, Jiang N-J, Liu S-Y, Horpibulsuk S, Arulrajah A (2016) Field evaluation of soft highway subgrade soil stabilized with calcium carbide residue. Soils Found 56(2):301–314. https://doi.org/10.1016/j.sandf.2016.02.012

Gabr M, Hopkins K, Coonse J, Hearne T (2000) DCP criteria for performance evaluation of pavement layers. J Perform Constr Facil 14(4):141–148

McElvaney J, Bundadidjatnika I (1991) Strength evaluation of lime-stabilised pavement foundations using the dynamic cone penetrometer. Aust Road Res 21(1):1

Mohammad LN, Herath A, Abu-Farsakh MY, Gaspard K, Gudishala R (2007) Prediction of resilient modulus of cohesive subgrade soils from dynamic cone penetrometer test parameters. J Mater Civ Eng 19(11):986–992

Patel MA, Patel H (2012) Experimental study to correlate the test results of PBT, UCS, and CBR with DCP on various soils in soaked condition. Int J Eng (IJE) 6(5):244

Patel MA, Patel H, Dadhich G (2013) Prediction of subgrade strength parameters from dynamic cone penetrometer index, modified liquid limit and moisture content. Procedia-Soc Behav Sci 104:245–254

Ranasinghe RATM, Jaksa MB, Kuo YL, Pooya Nejad F (2017) Application of artificial neural networks for predicting the impact of rolling dynamic compaction using dynamic cone penetrometer test results. J Rock Mech Geotech Eng 9(2):340–349. https://doi.org/10.1016/j.jrmge.2016.11.011

Salgado R, Yoon S (2003) Dynamic cone penetration test (DCPT) for subgrade assessment. Jt Transp Res Program 73:1–90

Smith M (1993) Neural networks for statistical modeling. Wiley, New York

White DJ, Vennapusa PK, Gieselman H, Johanson L, Siekmeier J (2009) Alternatives to heavy test rolling for cohesive subgrade assessment. In: Paper presented at the Bearing Capacity of Roads, Railways and Airfields. 8th International Conference (BCR2A'09)

Zumrawi MM (2014) Prediction of in situ CBR of subgrade cohesive soils from dynamic cone penetrometer and soil properties. Int J Eng Technol 6(5):439