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Prediction of some geotechnical properties of deltaic clays: using regression analysis models

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ABSTRACT

Establishment of any engineering structure on a compressible clay leads to settlement and/or failure through this clay. The amount of this settlement is controlled mainly by the compressibility parameters, while the failure by the undrained strength. The measuring of compressibility parameters and undrained strength are expensive, cumbersome, and time-consuming; therefore several attempts have been made to predict these geotechnical parameters by using simple, cheap, and time-saving index properties of the soil. In this study, the performance of applying empirical equations for the estimation of these critical geotechnical parameters was assessed by using a database including 551 undisturbed samples of the Nile Delta clay. The regression analysis results depict statistically moderate to strong correlations exist between both compression index and recompression index and the bulk density, Atterberg limits, initial void ratio, and effective overburden pressure. The precompression stress, overconsolidation ratio, and undrained shear strength parameters have no remarkable correlations with these index properties, except the effective overburden pressure parameter that has moderate to strong correlations with these properties. The compressibility and strength parameters depend on the in-situ effective stress, stress during geological history, diagenesis and cementation process, mineralogy, microstructure, and texture of clay, therefore they provide meaningful relationships. The developed empirical equations in this study, which derived from various linear and multi-variables regression models, are reliable and capable to predict the geotechnical design parameters with high prediction performance.

1. Introduction

The onshore part of the Nile Delta covers an area of about 25000Km^2 and it is one of the most well know world's earliest recognized deltaic systems. It is the main hydrocarbon providence in Egypt with potential gas reserves that attract the attention of many petroleum companies and geologists.

The development of these gas industries and the new gas discoveries in the northern regions of the Nile Delta as well as the construction of ports along these regions motivated the need for geotechnical investigation and characterization of the Nile Delta deposits for design and construction of major projects.

A vital stage in the selection decision of any megaproject site as well as the design of an appropriate and reliable foundation system depend mainly on the types and properties of the soil layers encountered in the geotechnical soil profile. The main issues in this vital geotechnical investigation stage are the evaluation of the compressibility and strength parameters of the geotechnical soil profile under the megaproject infrastructures [1,2].

Owing to the clay composition of the majority areas in the Nile Delta, the present study is addressed to determine the applicable empirical relationships between index properties, undrained shear strength, and compressibility parameters of the Nile Delta high plastic clays Fig. 1. These empirical relationships can provide a great aid for geotechnical engineers and engineering geologists to estimate the main geotechnical parameters in continuous geotechnical profiles for a project site in a relatively short time with high accuracy and perform fewer expensive, time-consuming, and complicated tests.

The compression index (c_c) and recompression index (c_r) are the two soil parameters that required to unravel for the safety of the proposed structures after construction and during their lifetime as expressed in settlement calculations. On the other hand, the main parameter in the ultimate limit state design or stability assessment of these structures is the undrained shear strength (s_u).

The compressibility and undrained strength parameters are obtained by performing laboratory tests on undisturbed soil samples that are expensive, cumbersome, time-consuming, and required a lot of experience for obtaining undisturbed soil samples from the field. To mitigate these complexities, several attempts have been made in the past to predict these critical soil parameters by using simple, cheap, and time-saving index properties of the soil such as Atterberg limits, bulk density, moisture content, and initial void ratio as well as pocket penetrometer and laboratory torvane.

In the last decade, few studies were performed to correlate the physical properties with the mechanical characteristics of the Nile Delta clay, essentially to evaluate the delta deposits [1,3,4]. **Abbas *et al.*** [1] studied the relationships between the in-situ tests as flat dilatometer (DMT), mechanical cone penetration (CPT), and vane shear (VST) as well as the laboratory tests as Atterberg limits, consolidation, unconfined compressive strength, and torvane of clay deposits in northeast Nile Delta. They revealed that, the overconsolidation ratio (OCR) can be estimated by reasonable correlations based on liquidity index and undrained shear strength from vane shear test $S_{u(VST)}$, in addition to the undrained shear strength values $S_{u(VST)}$ which estimated using the correlations with plasticity index reasonable agree with the measured values of $S_{u(VST)}$. Finally, they suggested that the published correlations usually need to be validated to the local geological soil conditions, and each specific area shall be having specific developed correlations. **Masoud** and **Masoud *et al.*** [3,4] studied the deltaic clay soils in Nile Delta region and revealed that, the relationships between the physical properties and compressibility parameters from consolidation test are mostly fair with correlation coefficient less than ±0.3 and several moderately correlations with maximum correlation coefficient less than ±0.5. They also disclosed the physical properties have moderately to strong correlations between them and also in the same manner the compressibility parameters have moderately to strong correlations between them. The most researches that carried out on the Nile Delta clay soils are mostly concerned with the evaluation of their geotechnical characteristics by using in-situ tests, therefore we can believed that the addition of the data presented in this paper to the previous studies provides a better knowledge that can be used as a first approximation of the main geotechnical soil parameters for use in the preliminary design of civil projects and later as a mean to validate the results of expensive, cumbersome, and time-consuming laboratory tests.

2. Geological Setting of Nile Delta

The geology of the Nile Delta was studied by many authors [5 - 13]. In general, the onshore sedimentary sequence of the Nile Delta is divided into three sedimentary cycles [7,9,10,11]:

(1) The Miocene cycle: comprises largely shallow marine deposits of Sidi Salem, Qawasim, and Rosetta Formations;

(2) The Pliocene -Pleistocene cycle: comprises the Abu Madi Formation, the open marine Kafr El Sheikh Formation, and the deltaic El Wastani and Baltim Formations; and

(3) The Pleistocene - Holocene cycle: comprises the Mit Ghamr/ Bilqas Formations and topmost deposits.

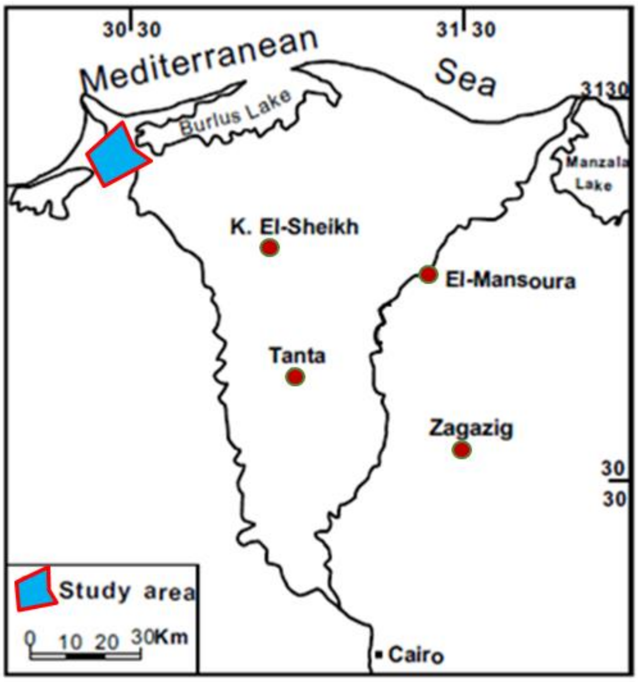
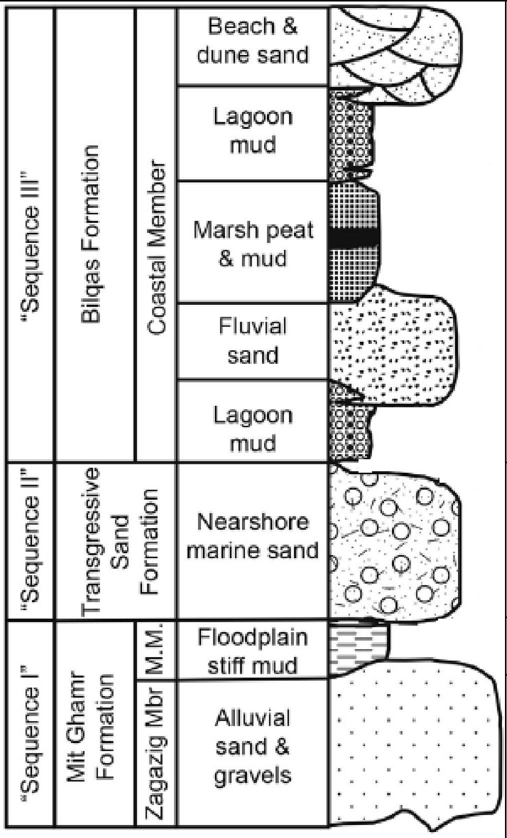


Fig.1 Location map of the studied area in the northwestern part of Nile Delta

The Miocene cycle starts with shallow marine deposits and ends with an evaporitic sequence. Sidi Salim Formation belongs to Middle-Late Miocene. It is composed mainly of predominant green-grey shale intercalations and streaks of quartzose sandstone, with calcareous cement as well as with occasional anhydrite and sandy limestone at its top [9]. The Qawasim Formation overlies the Sidi Salem Formation and it composed of a thick complex sequence of sandstones and shale interbedded with conglomerates. The Rosetta Formation of the Messinian age is represented by thick anhydrite deposits interbedded with thin claystone and limestone layers [7].

The Pliocene-Pleistocene section in the northern part of the Nile Delta is a mega-sequence of marine sediments with thickness up to more than 3000m [10]. Early Pliocene Abu Madi Formation includes fluvio-marine to shallow marine deltaic deposits [7]. This formation is composed mainly of sandstone with siltstone and shale intercalations. The clay content increases up-section and finally converts into Kafr El Sheikh Formation. Kafr El Sheikh Formation (Early-Middle Pliocene, outer shelf depositional environment) composes mainly of claystone and siltstone sequences with thin sandstone units [7]. Its top is defined by the first appearance of the overlying El Wastani sand sheets [10]. El Wastani Formation is of the Late Pliocene age and is composed of thick quartzose sands with argillaceous interbeds. The Baltim Formation (Early Pleistocene) overlies El Wastani Formation and composes of intercalations of clay, sand, shale, with thin bioclastic limestones. El Wastani and Baltim Formations are considered shallow marine deposits [11]. The Pleistocene – Holocene deposits in the Nile Delta divided from base to top into Mit Ghamr and Bilqas Formations. Mit Ghamr Formation overlies El Wastani Formation and it is a typical fill-up of a basin with shelly sand, coquina beds, clay, and peat. This formation grades into the overlying Bilqas Formation by the increase of interbedded clays with sands, rich in peat, fossiliferous, and with a coastal or lagoonal fauna. The depositional environment of Mit Ghamr and Bilqas Formations are shallow marine to fluvial and lagoonal to brackish swamps intermittent with beach sand, respectively.

Pennington *et al.* [12] studied the fluvial evolution of the Pleistocene-Holocene Nile Delta deposits and suggested that the general sedimentary sequence of the coastal region of the Nile Delta is composed of three sequences as shown in Fig. 2. The lower sequence is Late Pleistocene iron-stained quartz sands and stiff muds (Sequence I deposits, Mit Ghamr Formation) that represent terrestrial sedimentation on a partially vegetated braided river-plain [13], and it is divided into two members that are Zagazig and Munif Members. Quartz sands with shallow marine fauna (Sequence II deposits or Transgressive Sands Formation) are unconformable above the Sequence I deposits that represent the Early to Middle Holocene transgression. These deposits were probably originally fluvial sediments that incorporated a littoral signature during retrogradation of the shoreline and major reworking by waves and other coastal processes. The upper sequence, Sequence III deposits or Bilqas Formation, is another depositional hiatus and composed of a variety of lithologies that record a range of marine, semi-terrestrial, coastal, estuarine, lagoonal, and in some cases fluvial deltaic environments. Bilqas Formation of the coastal region of Nile Delta renamed as Coastal Member to distinct from the Bilqas Formation of a fluvial zone of Nile Delta.



This unit represents all sediments interpreted as having being deposited in a coastal, nearshore, or marine setting, and contains marine, semi-terrestrial, coastal, estuarine, lagoonal and occasionally sabkha deposits.	Alluvial mud of the delta plain
Coarse, poorly sorted, olive-grey to yellowish-brown quartzose sands which contain a high percentage of heavy minerals, as well as mollusca and echinoderm fragments, mica and lithic clasts, plus pelecypods, gastropods, ostracods, and foraminifera [15,16,17,18,19].	
Calcareous white palaeoso l[20].	Medium-coarse quartzose sands, containing pebbles of quartzite, chert, and dolomite [24], some authigenic carbonate nodules [25], rare gastropod shells [26], as well as some finer layers (silt and clay).
Sub-delta formation" [21] or the "Lower Buried Channel" [22]. It composed of "coarse and fine sands interfingering with pebbly or gravelly beds" [23].	

Fig.2 A representative log through the coastal zone of the Nile Delta M.M.: Minuf Member [12]

3. Material and Methods

3.1 Sample Location

The geological and geotechnical data of the clay soils were collected from 132 boreholes (from the soil investigation laboratory and foundation department of HA Engineering Consulting, Hamza Associates). The borehole drilling was carried out at the northwestern part of the Nile Delta Fig. 1, and the boreholes are filtered according to a detailed lithologic description, a continuous coring up to a depth of 60 m from the surface with complete in-situ and laboratory tests, and statistically homogeneous with the whole data above 95% confidence level. These boreholes represented the main stratigraphic units that composed the study area, Fig. 2.

The stratigraphy of the study area is very much in accordance with the published model of the Pleistocene-Holocene stratigraphy of this part of the Nile Delta, Table 1.

3.2 Database Compilation

In order to build the database, 551 undisturbed clay soil samples were collected. To achieve the present investigation, the 129 consolidation tests (to measure initial void ratio, compression index, recompression index, precompression index, overconsoildation ratio, and effective overburden pressure), 521 bulk density, 465 dry density and 551 natural water content tests, and 383 Atterberg limits tests (liquid and plastic limits, and plasticity index), as well as 473 pocket penetrometer tests, 275 torvane tests, 211 unconsolidated-undrained triaxial tests, and 277 laboratory vane shear tests (to measure undrained shear strength), were carried out (according to ASTM standard test methods, Table 2) on the studied clay soil samples which represented the different foundation clay layers distributed all over the study area. The testing program of laboratory works is carried out in soil investigation laboratory, HA Consulting, the authors are thankful to HA Engineering Consulting for allowing the use of some data (data of 400 clay samples), as well as for the facilities provided during the authors laboratory works for the other data of 551 samples.

In this study, the tests must be conducted under similar conditions and using the same techniques. Almost all of the studied clay soil samples are classified according to USCS as high plasticity inorganic/organic clay (CH/OH) as shown in the plasticity chart, Fig. 3, and most of these clay soils are considered as normally consolidated to overconsolidated clays [14], (overconsolidation ratio, OCR, < 4.0).

The soil parameters used in this database were natural water content (w_n), bulk density (γ_b), dry density (γ_d), liquid limit (L.L), plastic limit (P.L), plasticity index (P.I), initial void ratio (e_o), compression index (c_c), recompression index (c_r), precompression stress (σ_p), overconsolidation ratio (OCR), effective overburden pressure (σ_v), undrained shear strength by pocket penetrometer ($s_{u\text{-pocket}}$), laboratory vane shear ($s_{u\text{-lab.vane}}$), torvane ($s_{u\text{-torvane}}$), and unconsolidated-undrained triaxial ($s_{u\text{-uu}}$). These soil parameters were determined based on ASTM standard test methods, Table 2.

Table 1 Summary of lithostratigraphic succession at the study area

Age	Unit	Subunit	Average Thickness	Description	Environment
HOLOCENE	Sequence III deposits or Bilqas Formation or Coastal Member	Beach and Dune Sand	10.0 m	Medium dense, poorly graded loose to very loose silty clayey sand, with traces of calcareous materials, yellowish-brown. This unit is locally underlain by dark grey medium stiff to very stiff, sandy silt bed, and it is locally interbedded by dark grey, very soft to medium stiff fat clay beds	Deltaic Coastal Sands Reworked by Wave Erosion.
		Lagoon Mud to Marsh Peat and Mud	6.5 m	Olive grey to dark grey very soft to medium stiff fat clay interbedded by thin laminae of sand with traces of shell fragments and mica, and underlain by medium stiff to very stiff dark grey to black peat layer (2.0 m average thickness).	Marine Pro-Delta Muds and Fluvial Sands
		Fluvial Sand	10.0 m	Grey to yellowish-grey medium dense to very dense silty clayey sand with traces of calcareous materials, it is locally interbedded by medium stiff fat clay and hard sandy silt layers (1.0 average thickness).	
		Lagoon Mud	2.05 – 19.45 m	Dark grey soft to medium stiff fat clay locally interbedded by yellowish-grey medium dense to very dense poorly graded sand and stiff peat layer.	
	Sequence II deposits or Transgressive sands Formation	Nearshore Marine Sand		Yellowish grey to yellowish-brown dense to very dense poorly graded sand with silt intercalations, traces of clay lumps, iron oxides, and mica.	Open Shelf Littoral Zone Shallow Water to Fluvial Origin

Table 2 Descriptive statistics of the geotechnical parameters as well as their correlation matrix for the studied Nile Delta clays

Soil Properties		γ_b	γ_d	W_n	L.L	P.L	P.I	σ_p	OCR	C_c	C_r	e_o	σ_v	S_{u_Pocket}	$S_{u\_Torvane}$	S_{u_uu}	$S_{u\_lab. Vane}$
γ_b	R	1	0.99	-0.96	-0.84	-0.83	-0.82	-0.24	0.12	-0.80	-0.70	-0.96	-0.30	-0.29	-0.22	-0.18	-0.41
	N	521	465	521	360	360	360	129	129	129	129	128	129	466	270	210	277
γ_d	R		1	-0.96	-0.82	-0.81	-0.81	-0.23	0.12	-0.78	-0.68	-0.97	-0.32	-0.25	-0.22	-0.16	-0.38
	N		465	465	333	333	333	112	112	112	112	111	112	418	242	194	274
W_n	R			1	0.84	0.85	0.83	0.24	-0.08	0.78	0.66	0.99	0.26	0.29	0.20	0.21	0.43
	N			551	381	381	381	129	129	129	129	128	129	471	273	211	277
L.L	R				1	0.96	0.99	0.30	-0.19	0.71	0.64	0.82	0.43	0.38	0.36	0.20	0.48
	N				383	383	383	110	110	110	110	109	110	327	184	142	197
P.L	R					1	0.94	0.29	-0.19	0.70	0.61	0.81	0.42	0.36	0.33	0.17	0.46
	N					383	383	110	110	110	110	109	110	327	184	142	197
P.I	R						1	0.30	-0.19	0.70	0.64	0.81	0.43	0.38	0.36	0.21	0.48
	N						383	110	110	110	110	109	110	327	184	142	197
σ_p	R							1	0.17	0.39	0.29	0.23	0.57	0.61	0.45	0.76	0.59
	N							129	129	129	129	128	129	104	66	19	44
OCR	R								1	-0.25	-0.32	-0.09	-0.61	-0.22	-0.36	-0.40	0.12
	N								129	129	129	128	129	104	66	19	44
C_c	R									1	0.92	0.78	0.50	0.75	0.60	0.65	0.70
	N									129	129	128	129	104	66	19	44
C_r	R										1	0.66	0.52	0.69	0.55	0.53	0.56
	N										129	128	129	104	66	19	44
e_o	R											1	0.25	0.44	0.31	0.05	0.52
	N											128	128	103	65	19	44
σ_v	R												1	0.62	0.63	0.85	0.46
	N												129	104	66	19	44
S_{u_Pocket}	R													1	0.81	0.93	0.96
	N													473	256	207	267
$S_{u\_Torvane}$	R														1	0.60	0.78
	N														275	102	133
S_{u_uu}	R															1	0.94
	N															211	123
$S_{u\_lab. Vane}$	R																1
	N																277
Min.		11.77	4.80	23.00	28.00	13.00	7.00	72.00	0.45	0.16	0.02	0.95	26.00	5.00	3.00	4.45	5.00
Max.		19.72	16.03	152.00	272.00	106.00	183.00	510.00	3.97	2.40	0.38	4.08	327.00	135.00	85.00	155.53	117.00
Mean		15.64	9.74	63.84	94.34	36.47	57.97	197.46	1.52	0.64	0.10	1.74	145.66	37.60	33.33	39.44	38.15
Median		15.79	9.99	58.00	78.00	32.00	47.00	180.00	1.36	0.53	0.06	1.61	149.00	35.00	30.00	33.24	34.00
St. Dev.		1.24	1.83	21.02	40.98	11.19	30.28	74.34	0.64	0.37	0.08	0.54	62.99	21.82	17.59	24.18	24.24
ASTM Test Reference		[31]		[32]	[33]			[34]						[35]	[36]	[37]	[38]

R: Absolute value of correlation coefficient

N: Number of correlated samples

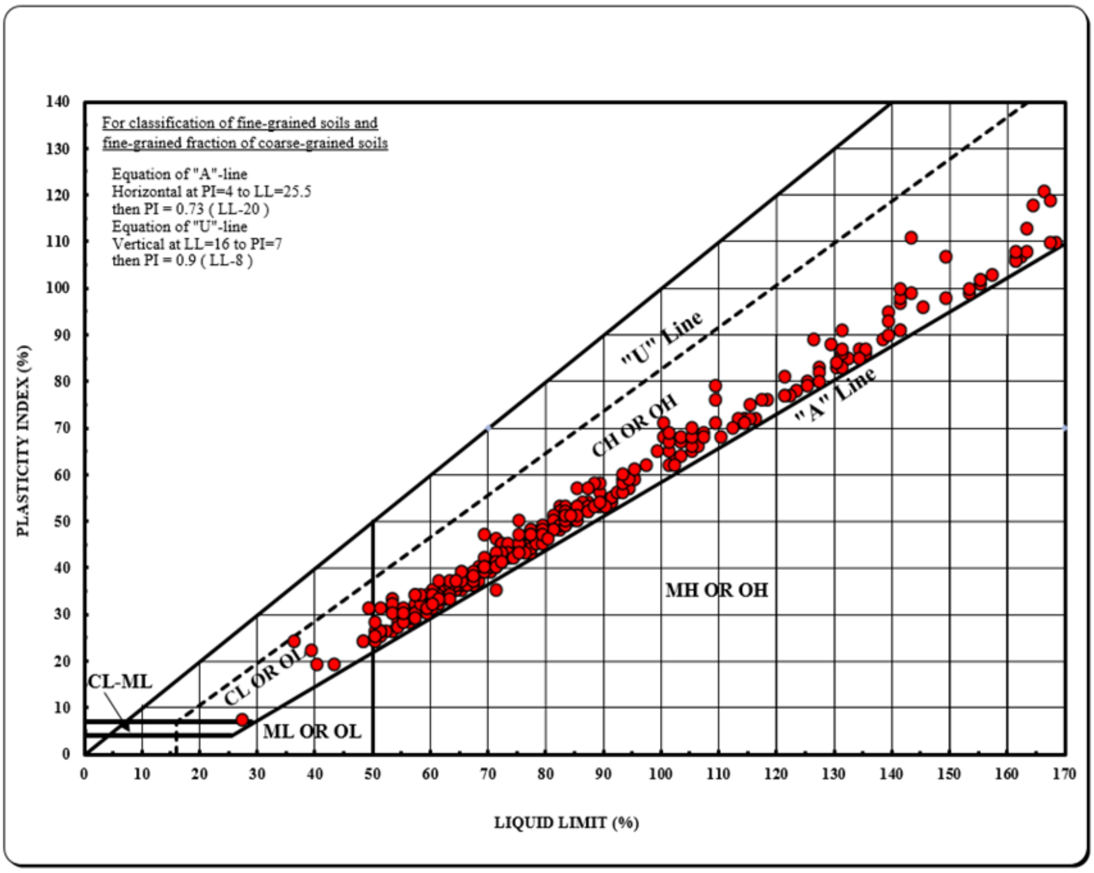


Fig.3 Plasticity chart of the studied Nile Delta clay soils

Adequate and reliable data on soil compressibility and soil strength are often not available either due to time constraints or heterogeneity of soil deposits or non-availability of undisturbed soil samples. So, the main purpose of this study is to determine the most suitable correlations between these parameters and index properties of high plastic clay soils to evaluate the compressibility parameters that are used in settlement analysis and undrained shear strength which is widely used as input parameter for the design and practice of various engineering projects as well as is used in bearing capacity calculation of fine-grained soils.

The first step to frame high predictive models to determine crucial properties of the soil effectively was the calculation of correlation coefficient matrices for the whole database by using simple regression analysis (Pearson's correlation coefficients). In recent years, the simple regression analysis is widely used in geotechnical engineering and engineering geology to develop mathematical expression among significant geotechnical parameters of different soil types, as well as to decide the geotechnical design parameters. The simple regression analysis is a statistical tool for the investigation of relationships between dependent and independent variables, and it has many types of regression models as linear regression, exponential regression, logarithmic regression, polynomial regression, and power regression models. Assessment of regression relationships can be done through estimation of Pearson's correlation coefficient [27]. Whereas, the Pearson's correlation coefficient (R) is used to disclose the degree of dependency of one variable to the other. From matrix plot, strong ($\pm 0.68 \leq R \leq \pm 1.00$), moderately ($\pm 0.36 \leq R \leq \pm 0.67$), and weak ($R \leq \pm 0.35$) correlations between selected variables were found [28].

4. Results and Discussion

4.1 Geotechnical Properties

The geotechnical parameters, Table 2, of the studied clay soils showed the wide ranges of bulk density (11.77-19.72 kN/m^3), water content (23-152%), initial void ratio (0.95-4.08), liquid limit (28-272%), plastic limit (13-106%), plasticity index (7-183%), pre-compression stress (72-510 KPa), overconsolidation ration (0.45-3.97), compression index (0.16-2.4), recompression index (0.02-0.38), and undrained shear strength (from pocket test 5-135 KPa, from torvane test 3-85 KPa, from lab. Vane test 5-117 KPa, and from unconsolidated-undrained triaxial test 4.45-155.53 KPa). The high values of water content and Atterberg limits (liquid and plastic limits, and plasticity index), as well as the low values of dry density for some studied clay samples are mostly due to the presence of considerable amounts of fibrous peat, whereas the organic content in the studied clay samples ranges from 1% to 40% with average of about 9.76%. These wide ranges of results suggest that the studied clay samples have variable clay content, texture, structure, and initial compaction. These variable parameters were controlled by a complex geological/physical setting (depositional environments, groundwater/surface water, and clay sample depth in borehole (vertical overburden)).

4.2 Regression analysis and empirical equations

The absolute correlation coefficients (R) were calculated between the studied soil parameters based on the linear regression model by using SPSS computer statistical software that are shown in Table 2. In order to improve these calculated coefficients, other simple regression models were used (as exponential, logarithmic, polynomial, and power models). It was observed that the value of the absolute correlation coefficient increased approximately 10%-20% by using these regression models. The resulted empirical regression equations can be giving an initial indication of some properties in order to perform geotechnical design calculations.

4.2.1 Relationships between clay's physical properties

The water content shows a direct correlation with a bulk density of the clay soil until the optimum limit of water content (water content at which the soil has a maximum density), after this limit the relation becomes reversible because the water density is lower than the soil particle density [29,30].

In this study, the relation between the natural water content and bulk density is a perfect strong negative relationship with an absolute correlation coefficient of -0.98 as shown in Fig. 4. This relation revealed that the water content of these clay soils is above the optimum limit that is mainly due to the existence of these clay soils under the water table in the study area.

The void spaces in the studied soils are occupied by water because the tested clay soils exist under the water table, so the measuring of water content in these soils is considered as an indirect estimation of soil void ratio. The relation between the natural water content and initial void ratio, Fig. 4, is a perfect strong positive relation (R= +0.99). On the other hand, the initial void ratio has a perfect negative correlation with the bulk density (Fig. 4, R= -0.98). This relation is logical because the soil solids that are the main factor controlling the density of soils, and the soil voids that are occupied by low-density phase, water, are belonged to the same soil system. So, the relationships of bulk density versus both water content and void ratio are almost perfect strong negative relations.

The bulk and dry densities of any soil are mainly controlled by the density of the soil particles and the void ratio within the soil system. The bulk and dry densities of the soil are the ratio of the mass of the soil solid grains to the total volume in natural and dry states of the soil, respectively. Therefore, the correlation between dry density and bulk density provides a perfect strong positive correlation that is confirmed by the relationship between them in this study (R= +0.99, Fig. 4). Based on this relation, the relationships of bulk and dry densities with natural water content and initial void ratio provide perfect strong negative correlations with correlation coefficient of about -0.99 as shown in Fig. 4.

The indirect swelling parameters of clay soils as consistency limits (liquid and plastic limits and plasticity index) depend mainly on the amount of water adsorbed on the basal surfaces of the clay particles [39]. Nelson and Miller [40] stated that the natural water content influences the shrink-swell potential and indicates the activity of clay types in the soil. The natural water content also influences the clay bulk density and consistency of the clay soils [41]. Therefore, the natural water content shows strong positive correlations with the consistency limits, Fig. 5. In the same manner, the initial void ratio has perfect strong positive correlations while the bulk density has perfect strong negative correlations with these consistency limits, Fig. 5.

The relationships between liquid limit, plastic limit, and plasticity index are direct and perfect relations, Table 3. These relations are logical because these parameters depend on the same factors, such as clay content and types [40,42].

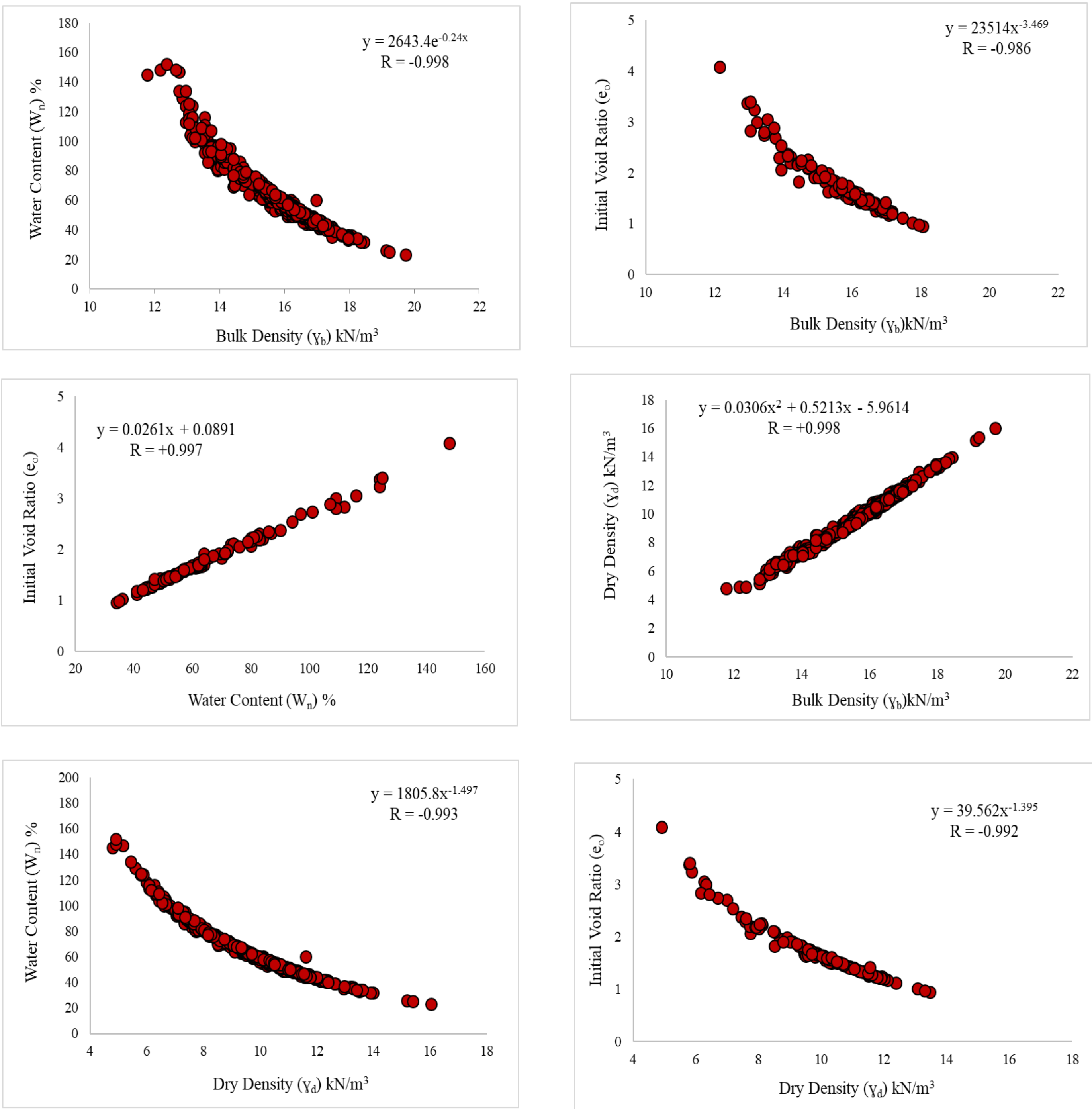


Fig.4 Bivariant plots between water content, bulk density, dry density, and initial void ratio of studied clay soils

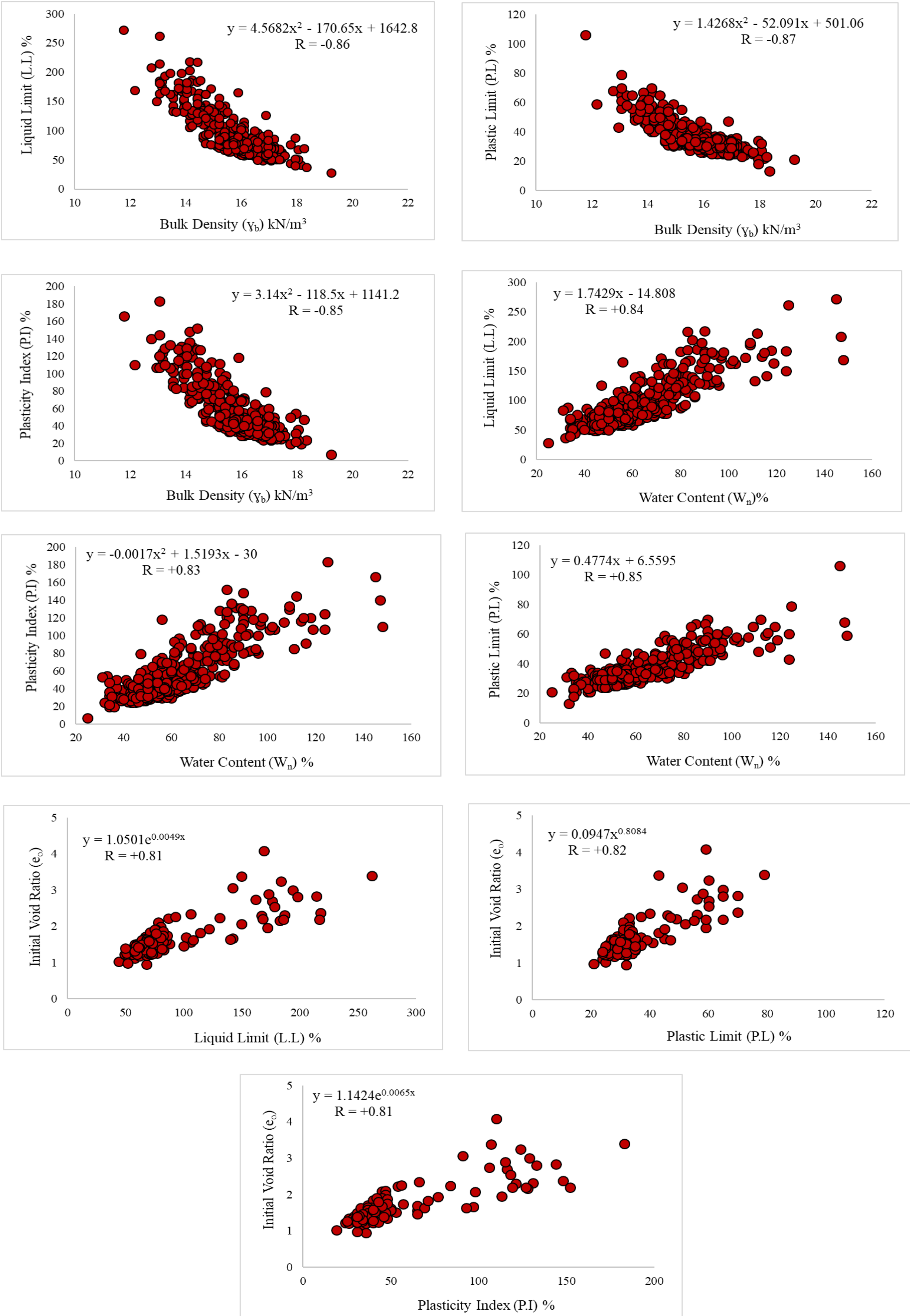


Fig.5 Bivariant plots of water content, bulk density, and initial void ratio with consistency limits of studied clay soils

Table 3 Relationships between consistency limits of the studied Nile Delta high plastic clay samples.

Independent variables (X)	Dependent variables (Y)	Absolute value of correlation coefficient (R)	Relation equation
Liquid limit	Plastic limit	+0.97	Y=0.264X+11.537
Liquid limit	Plasticity index	+0.99	Y=0.735X+11.45
Plastic limit	Plasticity index	+0.94	Y=2.541X+34.704

4.2.2 Relationships between clay's compressibility parameters and their physical properties

The compressibility parameters of cohesive soil are useful in: (a) carrying out long term settlement analysis, (b) providing key parameters for analysis and design of ground improvement, and (c) profiling undrained shear strength parameters with the aid of other laboratory and/or in-situ field investigation tests [2]. The settlement of any engineering structure due to self-weight (permanent load) compression of clay soils as well as temporary loads are practically the major problems in the geotechnical engineering. Therefore, it is necessary to understand the consolidation curve, Fig. 6, in order to calculate soil settlement caused by the engineering structure. The parameters from consolidation curve are determined in terms of compression index (c_c), recompression index (c_r), precompression stress (σ_p), and overconsolidation ratio (OCR). The compression index (c_c) represents the curve slope of the void ratio versus the logarithm of effective stress (effective pressure) beyond the maximum past effective stress. On the other hand, the recompression index (c_r) represents the slope of the initial curve before the maximum past effective stress. The maximum past effective stress or effective precompression stress (σ_p) is the maximum vertical pressure (overburden) experienced by the soil during its geological history or it's the largest overburden at which the soil had been consolidated [43,44].

The precompression stress is estimated graphically from the laboratory test by using Casagrande's method based on the relationship of experimental void ratio and logarithm of effective stress curve as shown in Fig 6.

The ratio of effective precompression stress to effective present overburden pressure or effective vertical geostatic stress (σ_v) is defined as the overconsolidation ratio (OCR) and is a convenient term for describing the stress state [44]. Overconsolidation ratio is used to estimate the settlement in clay soils, correlation of strength parameters, and estimating of at-rest earth pressure coefficient [45 - 47].

The compressibility parameters of the clay soils are affected mainly by physical parameters as initial void ratio, natural water content, and intrinsic parameters, such as liquid and plastic limits and plasticity index as well as they particularly affected by the in-situ state parameters as sedimentation, deposition environments, stress history and natural soil conditions [48]. Intrinsic parameters as Atterberg limits reflect the relative content of clay in the clay soils and their mineralogy. The initial void ratio and effective overburden pressure reflected the existing in-situ stress state and the precompression stress. The natural water content is an indication of water absorption capacity of the clay particles and free water present in the clay soil voids, in addition to the bulk unit weight may be an indicator to the compressibility of soil grains to some degree. Several investigators predict many empirical correlations between compressibility parameters and physical properties of clay soils [47, 49, 50, 51, 52, 53, 54, 55].

During this study, all possible relationships were tried and the relations with low absolute correlation coefficient values (R) were neglected while the relations with correlation coefficient values greater than or equal to ±0.5 were adopted for developing various regression models.

The bivariate relationships of the compressibility parameters (c_c and c_r), OCR, and σ_p with the soil physical properties are shown in Figs. 7 and 8. The other resulting equations of all adopted regression models are shown in Table 4. As we can be observed in these figures and table, there is a significant level of correlation between the consolidation test parameters (c_c, c_r, OCR, and σ_p) and the physical parameters of the present high plastic clay soils. The compression and recompression indices have moderately to strong correlations ($\pm0.53 \leq R \leq \pm0.79$) with bulk density, natural water content, liquid and plastic limits, plasticity index, initial void ratio, and the effective overburden pressure, in addition to the deduced multi-variables relations as shown in Figs. 7 and 8, and Table 4. Figures 7 and 8 show that, the relationships between the compressibility parameters and the Atterberg limits (L.L, P.L, and P.I) are positive strong relations (R >+0.75) and all correlated points have the same pattern up to the critical values, whereas beyond these values some of the correlated points have the reverse pattern. These critical values are 190%, 60%, and 125% for L.L, P.L, and P.I, respectively. Therefore, the reliable correlations can be applied on the clay soils that have Atterberg limits below these critical values as the following equations:

C_c=0.0078(L.L)-0.0718	(R= +0.82)	C_r=0.0017(L.L)-0.0554	(R= +0.79)
C_c=0.0303(P.L)-0.4385	(R= +0.80)	C_r=0.0064(P.L)-0.1293	(R= +0.76)
C_c=0.0102(P.I)+0.0669	(R= +0.81)	C_r=0.0022(P.I)-0.0264	(R= +0.79)

These relationships concluded that the clay soils that have high swelling potentiality, active clay content, high initial void ratio, and found at high effective overburden pressure as well as have low bulk unit weight undergo more compression or undergo large amount of deformations than those have low swelling potentiality, active clay content and initial void ratio, high bulk density and found under low effective overburden pressure.

The relationship between compression index and recompression index is a perfect strong positive relation with R=+0.91. This perfect strong positive relation is logical because these compression parameters are controlled by the same factors (water content, bulk density, L.L, P.L, P.I, void ratio, and overburden pressure) that confirmed from this study as shown in Figs. 7 and 8.

The precompression stress and overconsolidation ratio are depending mainly on the in-situ stress state affecting the clay soil, therefore the effective overburden pressure has moderately correlations with the precompression stress and overconsolidation ratio with absolute correlation coefficient values +0.57 and -0.69, respectively, Fig. 8. The ratiocinated moderately to strong correlations of c_c, c_r, OCR, and σ_p with clay soil physical parameters by using multi-variables regression analysis are listed in the Table 4. These relations revealed that the addition of other independent variables to the effective overburden pressure in the estimation of c_c, c_r, OCR, and σ_p for the deltaic clay soil has a significant contribution in the deducing of these good relationships.

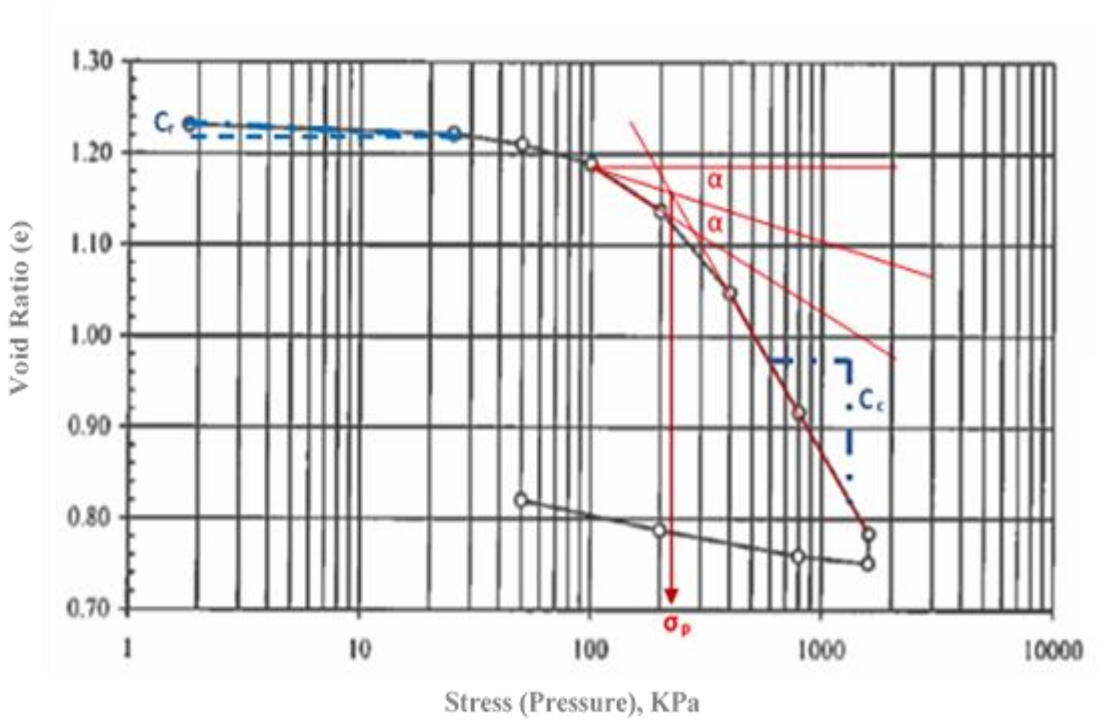


Fig.6 Definition of (c_c) and (c_r) indices and Casagrande's method for the determination of precompression stress (σ_p)

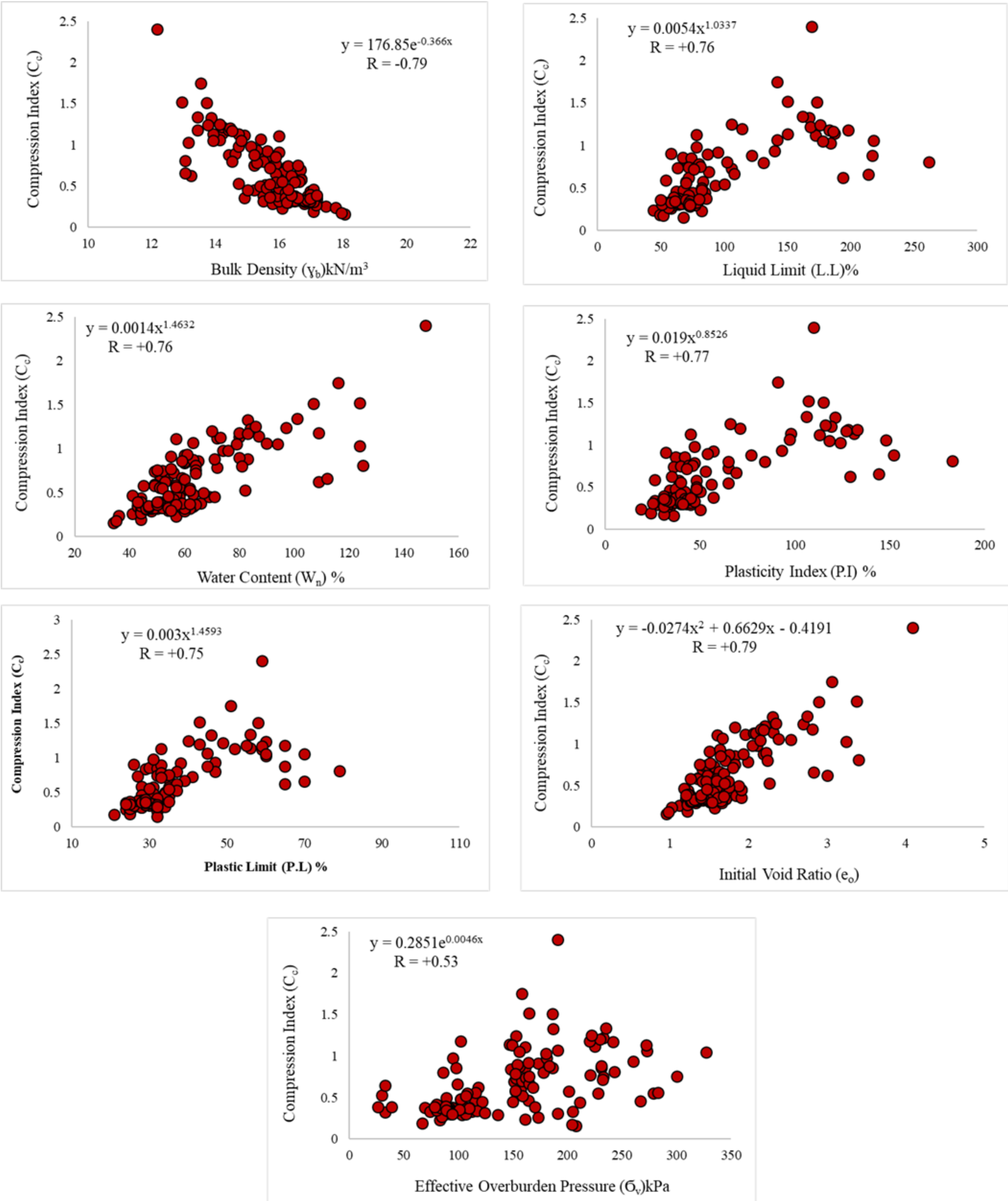


Fig.7 Bivariant plots between compression index and physical properties of studied clay soils

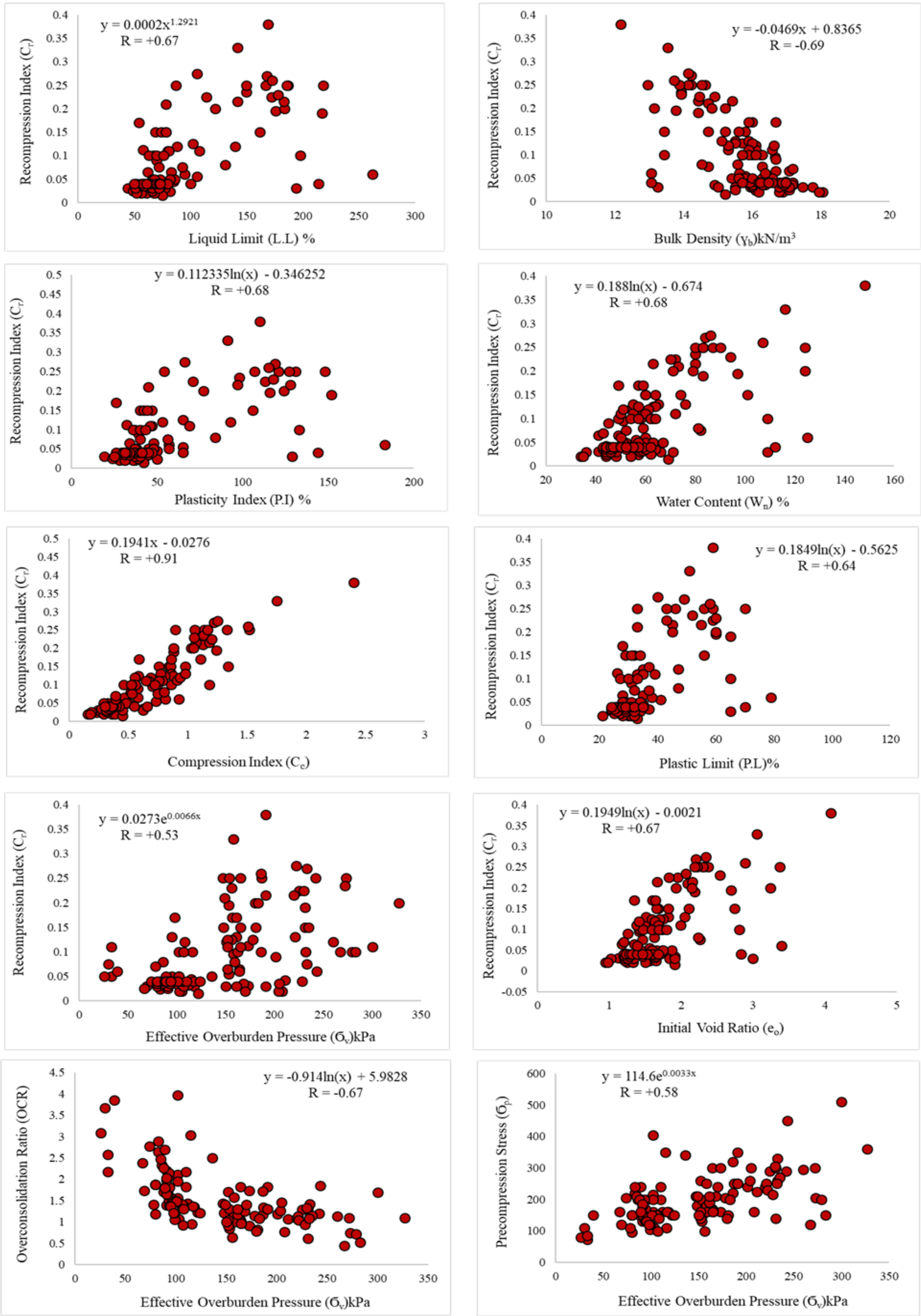


Fig.8 Bivariant plots of recompression index, overconsolidation ratio, and precompression stress with physical properties of studied clay soils

Table 4 Relationships of c_c, c_r, OCR, and σ_p with physical properties of the studied Nile Delta high plastic clay samples by using multi-variables regression analysis

Independent variables (X)	Dependent variables (Y)	Absolute value of correlation coefficient (R)	Relation equation	Number of correlated samples
$[30*(\sigma_v)^{0.5}]/(\sigma_v)$	Compression index (C_c)	-0.54	$Y = 0.1132X^2 - 0.9842X + 2.4177$	128
$\gamma_b/(\sigma_v)$		-0.63	$Y = 10.245X^2 - 7.24X + 1.3654$	129
$[30*(\sigma_v)^{0.5}]/(\sigma_v)$	Recompression index (C_r)	-0.55	$Y = 0.0268X^2 - 0.2264X + 0.4993$	128
$\gamma_b/(\sigma_v)$		-0.62	$Y = 2.21X^2 – 1.53X +0.248$	129
$[30*(\sigma_v)^{0.5}]/(\sigma_v)$	Precompression stress (σ_p)	-0.6	$Y = 436.21X^{-0.889}$	128
$\gamma_b/(\sigma_v)$		-0.6	$Y = 75.667X^{-0.421}$	129
$(\sigma_v)/[0.55(L.L)+88.99\ln(P.L)-80]$		+0.57	$Y = 275.88X^{0.4711}$	110
$[30*(\sigma_v)^{0.5}]/(\sigma_v)$	Overconsolidation ratio (OCR)	+0.70	$Y = -0.0283X^2 + 0.8061X -0.428$	128
$(\sigma_v)/[0.55(L.L)+88.99\ln(P.L)-80]$		-0.67	$Y = 4.005X^2 – 6.3383X +3.5823$	110
$P.L/(\sigma_v)$		+0.58	$Y = 2.144X+0.9194$	110
$L.L/(\sigma_v)$		+0.5	$Y = 0.055X^2 + 0.5474X +1.1156$	110
$\gamma_b/(\sigma_v)$		+0.69	$Y = -6.8924X^2 + 8.4696X +0.5441$	129
$e_o/(\sigma_v)$		+0.63	$Y = 41.929X+0.915$	128
$W_n/(\sigma_v)$		+0.63	$Y = 1.1556X+0.9132$	129

4.2.3 Relationships between clay's undrained shear strength and their physical properties

The undrained shear strengths (S_u) of deltaic clay soils were measured by using different methods as the unconsolidated-undrained triaxial test (UU), pocket penetrometer test, laboratory vane shear test, and torvane test. The undrained shear strength of clay soils is a very important and critical geotechnical property that is used as an input parameter in a final decision for the design and practice of various geoengineering projects. These laboratory tests required a large number of undisturbed clay samples and the use of expensive laboratory instruments. So, the estimation of the clay strength property from the other clay physical geotechnical parameters by empirical equations is economic and very important in the preliminary stage of any civil project [56,57].

The shear resistance of soils is the result of friction, interlocking of soil particles, and possibly cementation or bonding at the contacts of soil particles. The undrained shear strength depends on the mode of shear or failure, soil anisotropy, sample disturbance, strain rate effect, direction of the strain, effective stress, drainage conditions, and density of the soil particles. Thus, the undrained shear strength is affected by the consistency of clay soil materials, overconsolidation ratio, clay and organic contents, effective overburden pressure, soil mineral composition, bulk density, initial void ratio, cementation materials, and microstructures or fissures [56,57].

Ersoy *et al.* [58] estimated the shear strength parameters (cohesion and friction angle) of Tertiary volcanic regolith northeast Turkey from the plasticity properties by using multiple regression analysis. They founded that the friction angle has a strong negative polynomial relation with (P.I/L.L), while cohesion has a strong positive exponential relation with (P.I/L.L) with a regression coefficient of 0.8.

The simple and multiple regression analyses that carried out in this study revealed that the undrained shear strengths of the studied clay soils that measured by the pocket penetrometer, laboratory vane shear, torvane, and unconsolidated-undrained triaxial compression tests have almost weak relationships with the physical properties, as reported in the Table 2. The obtained moderate relationships between the undrained shear strength results from some shear strength tests and the physical properties are shown in Fig. 9. This figure shows that the undrained shear strength can be estimated from the nonlinear relationships with the effective overburden pressure that reflect the stress state at depth which the studied clay soils located. The results of the present study disagree with the study of **Ersoy *et al.*** [58].

Multi-variables analyses by using liquid and plastic limits and effective overburden pressure with undrained shear strength give moderate to strong correlation coefficient as shown in Fig. 10. Due to the undistinctive and moderately relationships exist between undrained shear strength and physical properties of Nile Delta clays, the most available relationships of undrained shear strength from various tests with c_c, c_r, OCR, and σ_p were studied.

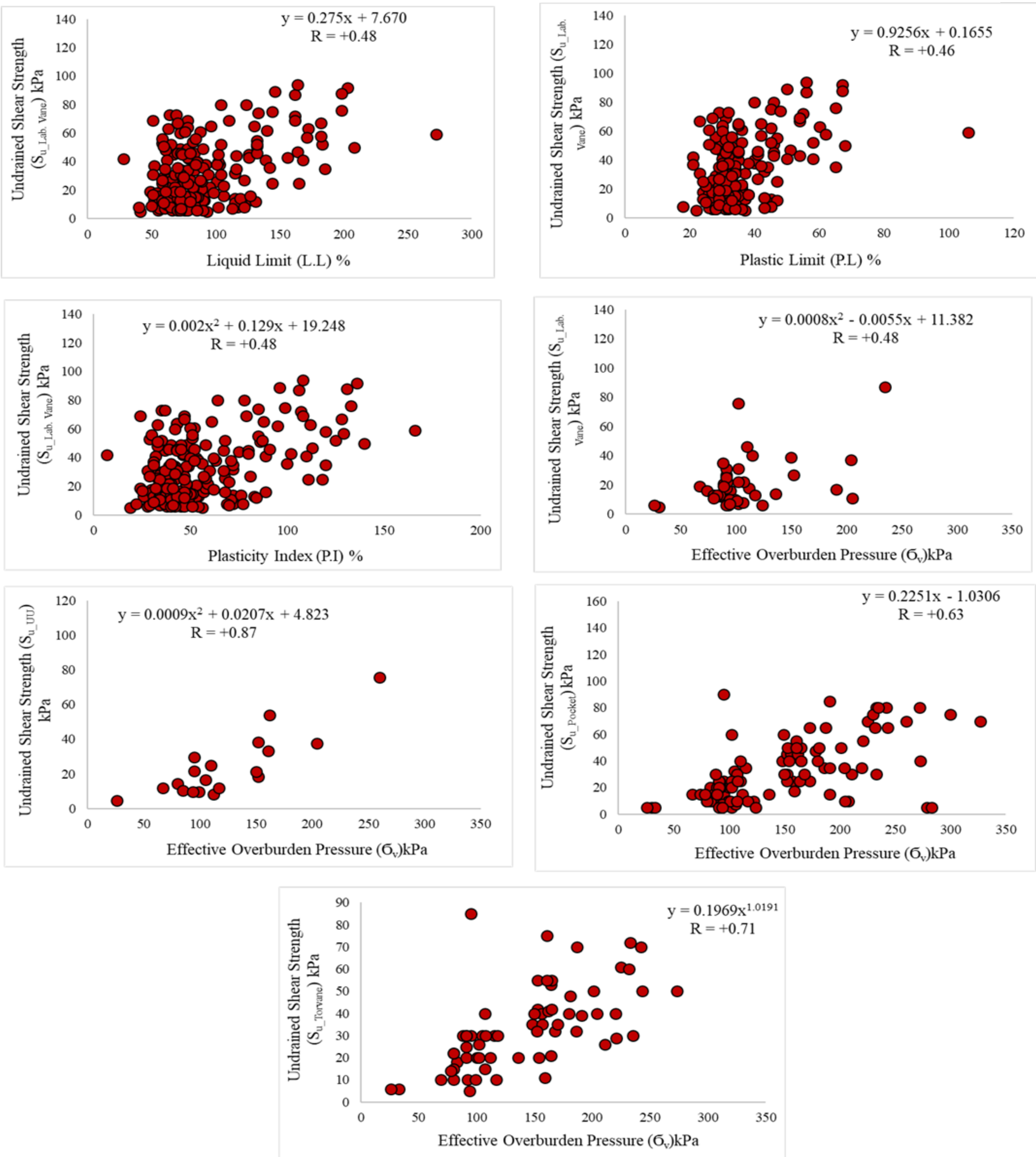


Fig.9 Bivariant plots between undrained shear strength and some physical properties of studied clay soils

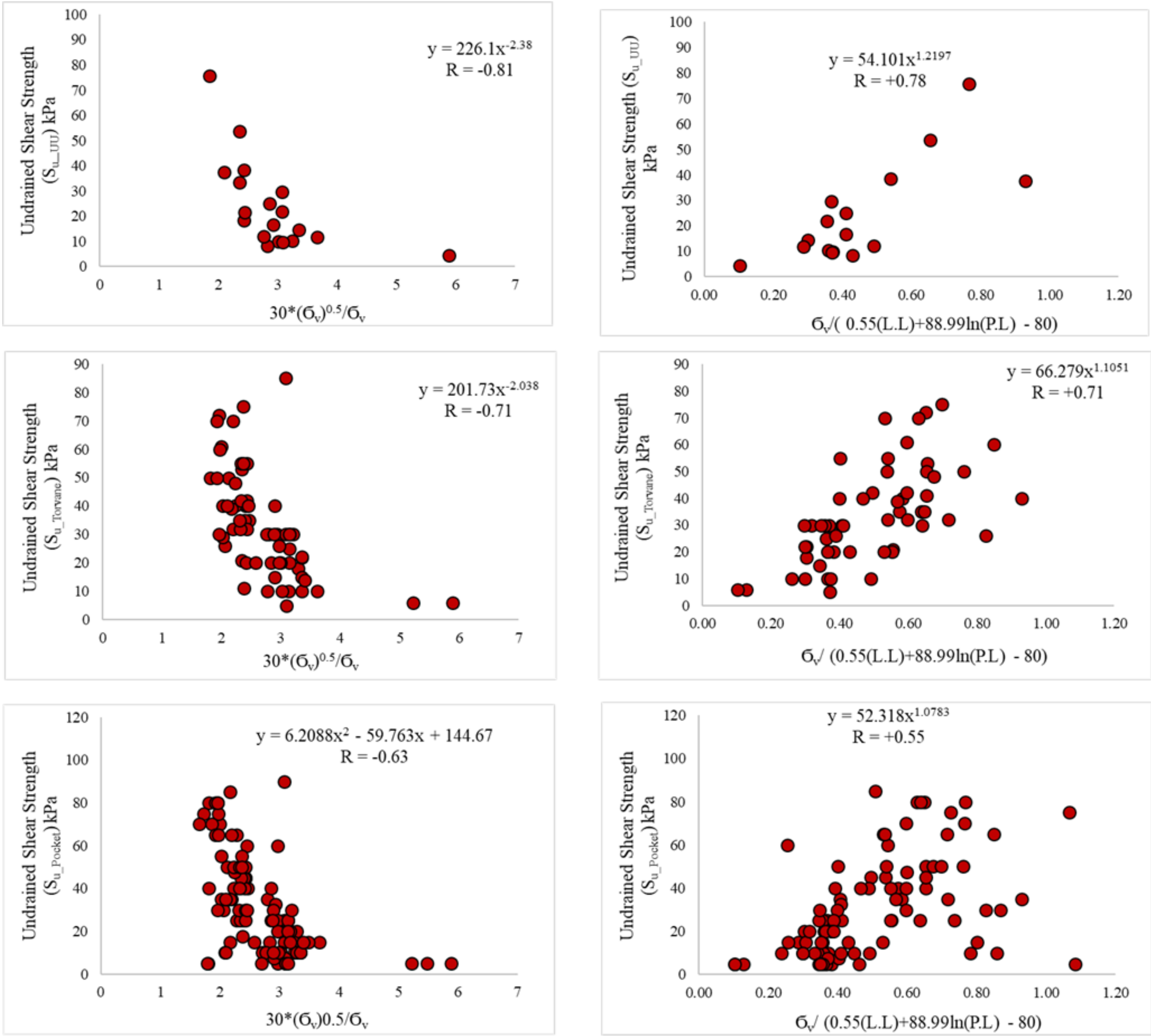


Fig.10 Bivariant plots of undrained shear strength from pocket penetrometer, torvane, and unconsolidated-undrained triaxial compression with some physical properties of studied clay soil

4.2.4 Relationships of c_c, c_r, OCR, and σ_p with undrained shear strength of Nile Delta clay soils

Figures 11 and 12 and Table 2 disclosed that the c_c, c_r, OCR, and σ_p can be estimated clearly from the strength measurements of Nile Delta clay soils. The relationships between these parameters are considered moderate to strong relations with absolute correlation coefficients ranging between 0.53 and 0.84. These moderate and strong relations are logical because the c_c, c_r, OCR, σ_p and strength parameters of clay soils depend mainly on the same factors, such as in-situ effective stress, stress during geological history, cementation and diagenesis process, mineralogical, and microstructure, and textures. Also, the undrained shear strength can be estimated from the compressibility parameters, OCR, and σ_p as shown in Figs. 13 and 14. By using the multi-variables regression analysis, the combination between some strengths obtained from different tests, physical, compressibility parameters, OCR, and σ_p, some strong relationships provided as listed in Tables 5 and 6.

The strong relationships between different undrained shear strengths concluded that, the shear strength parameters can be predicted from each other because they depend on the same geological factors that control the clay soil condition, Fig. 15. So, the undrained shear strength from more complicated and expensive laboratory tests can be estimated from other simple and cheap laboratory tests.

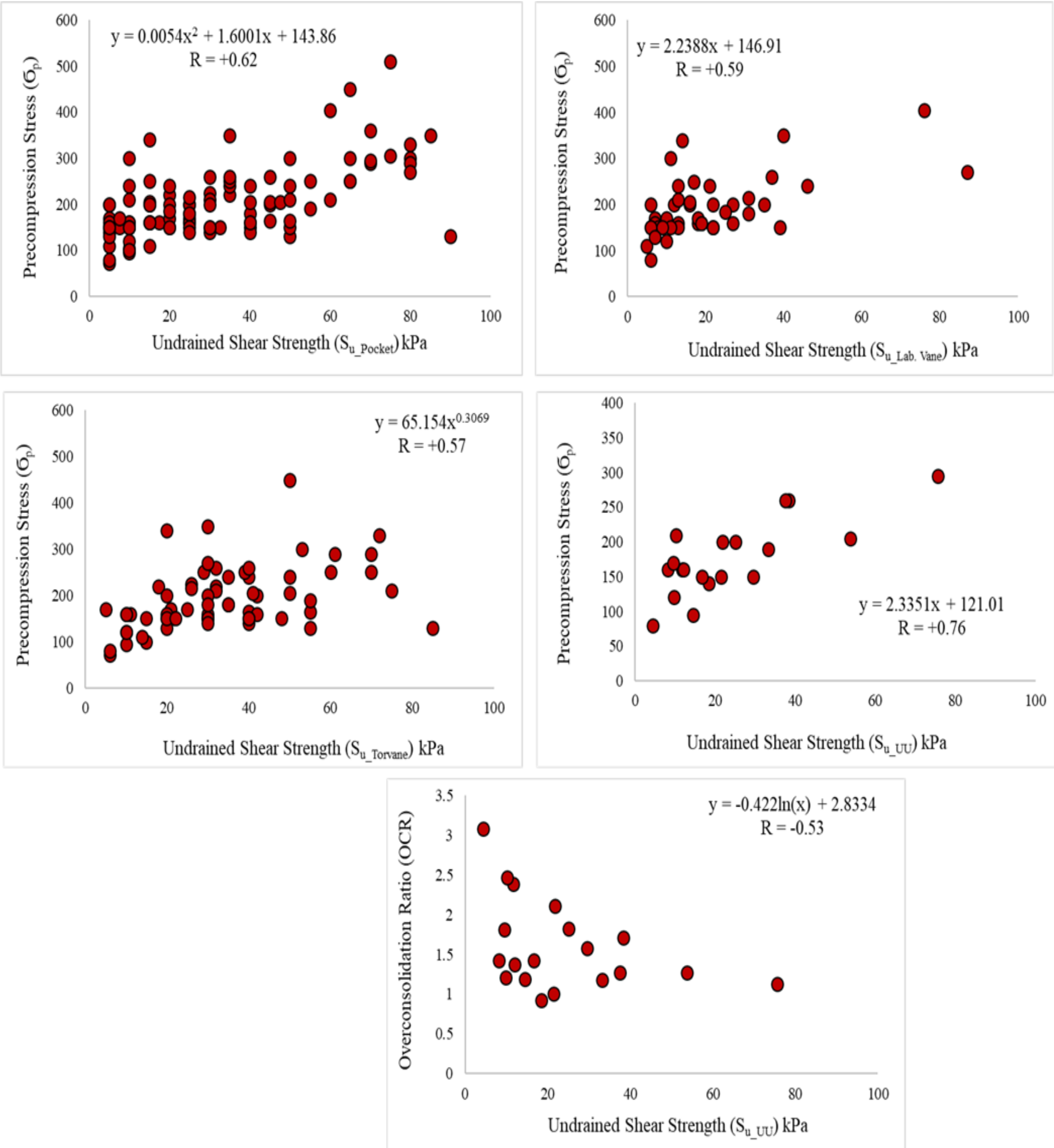


Fig.11 Bivariant plots of precompression stress and overconsolidation ratio with undrained shear strengths of studied clay soils

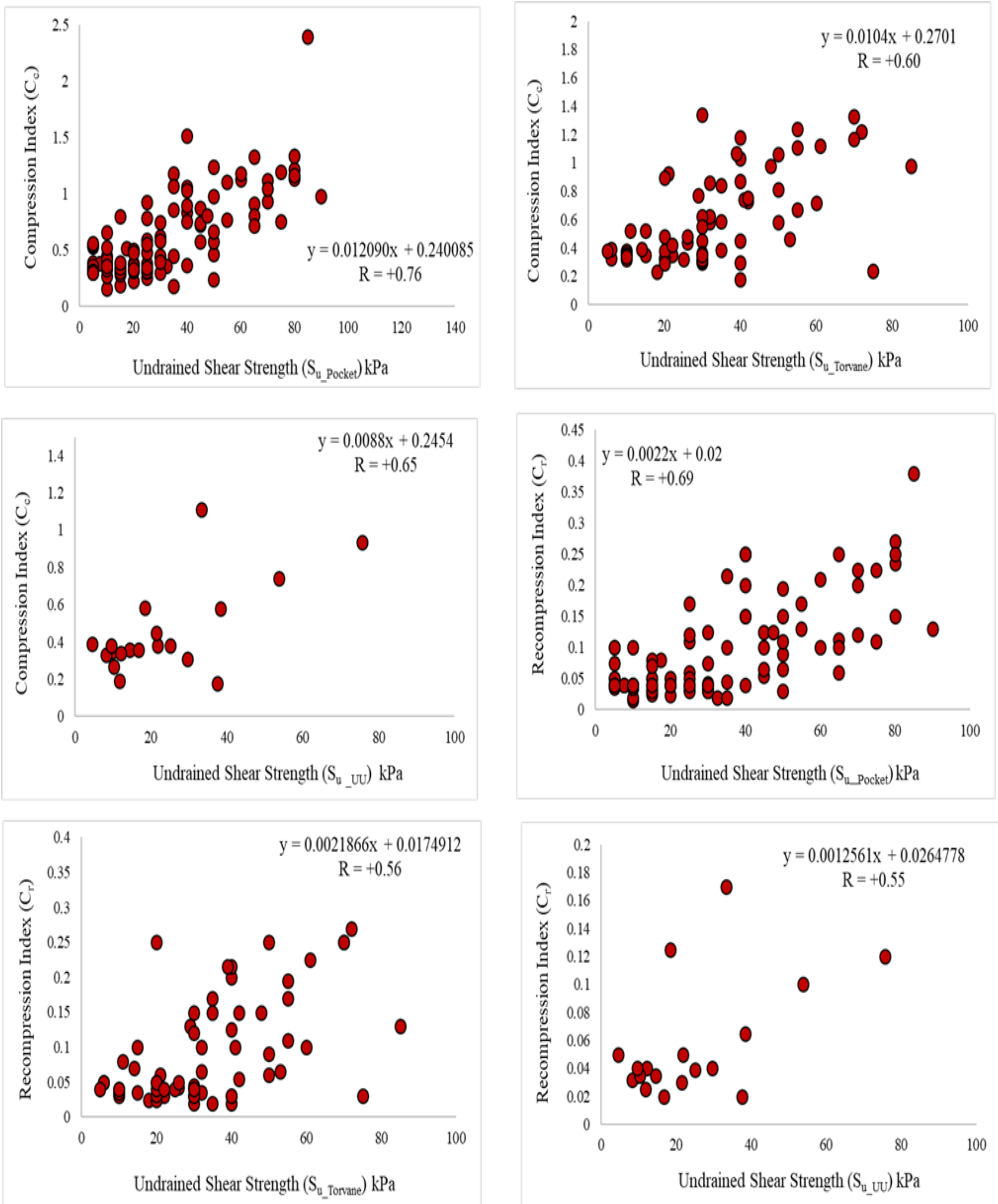


Fig.12 Bivariant plots of compression and recompression indices with undrained shear strengths of studied clay soils

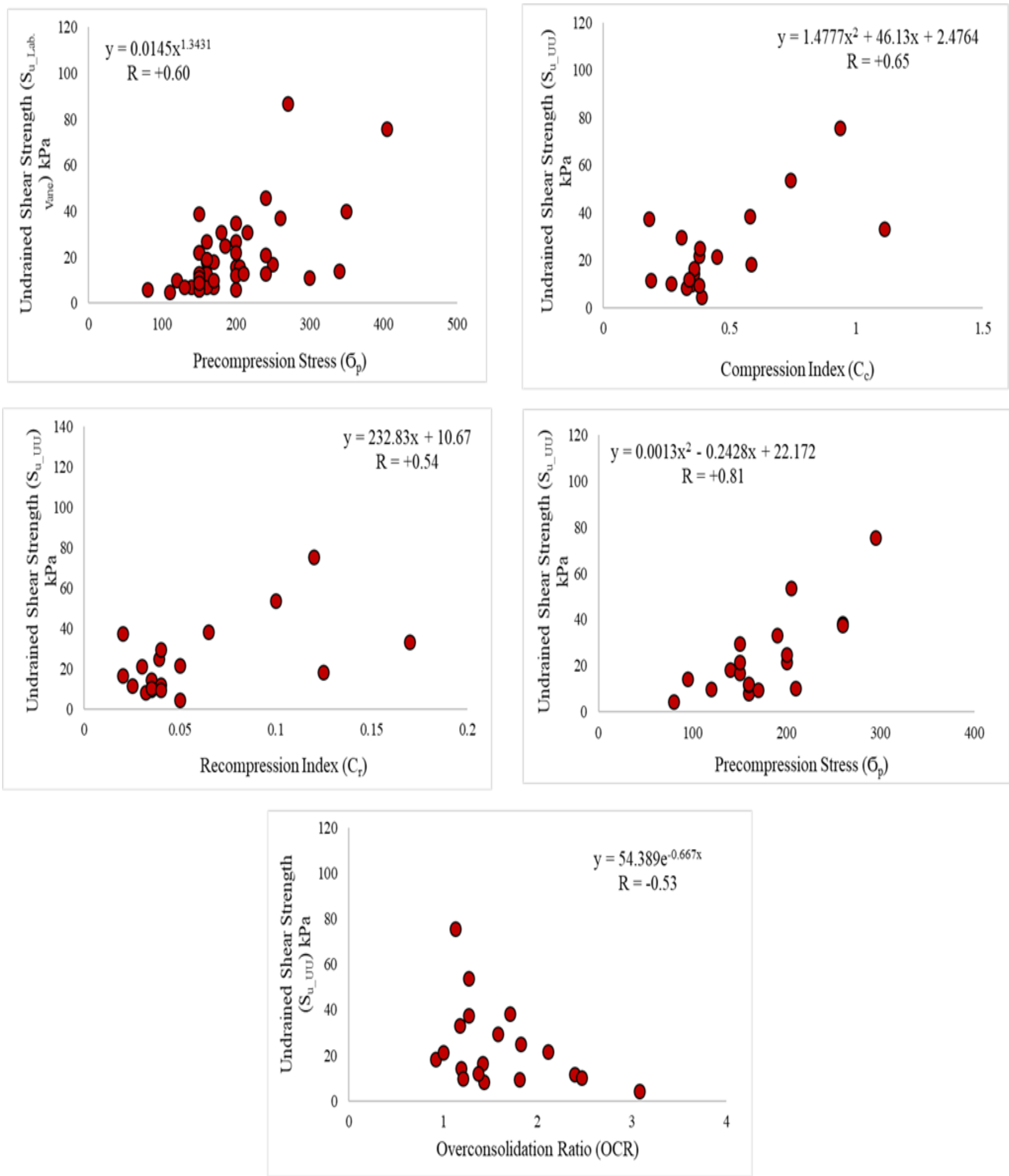


Fig.13 Bivariant plots of undrained shear strength from laboratory vane shear and unconsolidated-undrained triaxial compression with compressibility parameters of studied clay soils

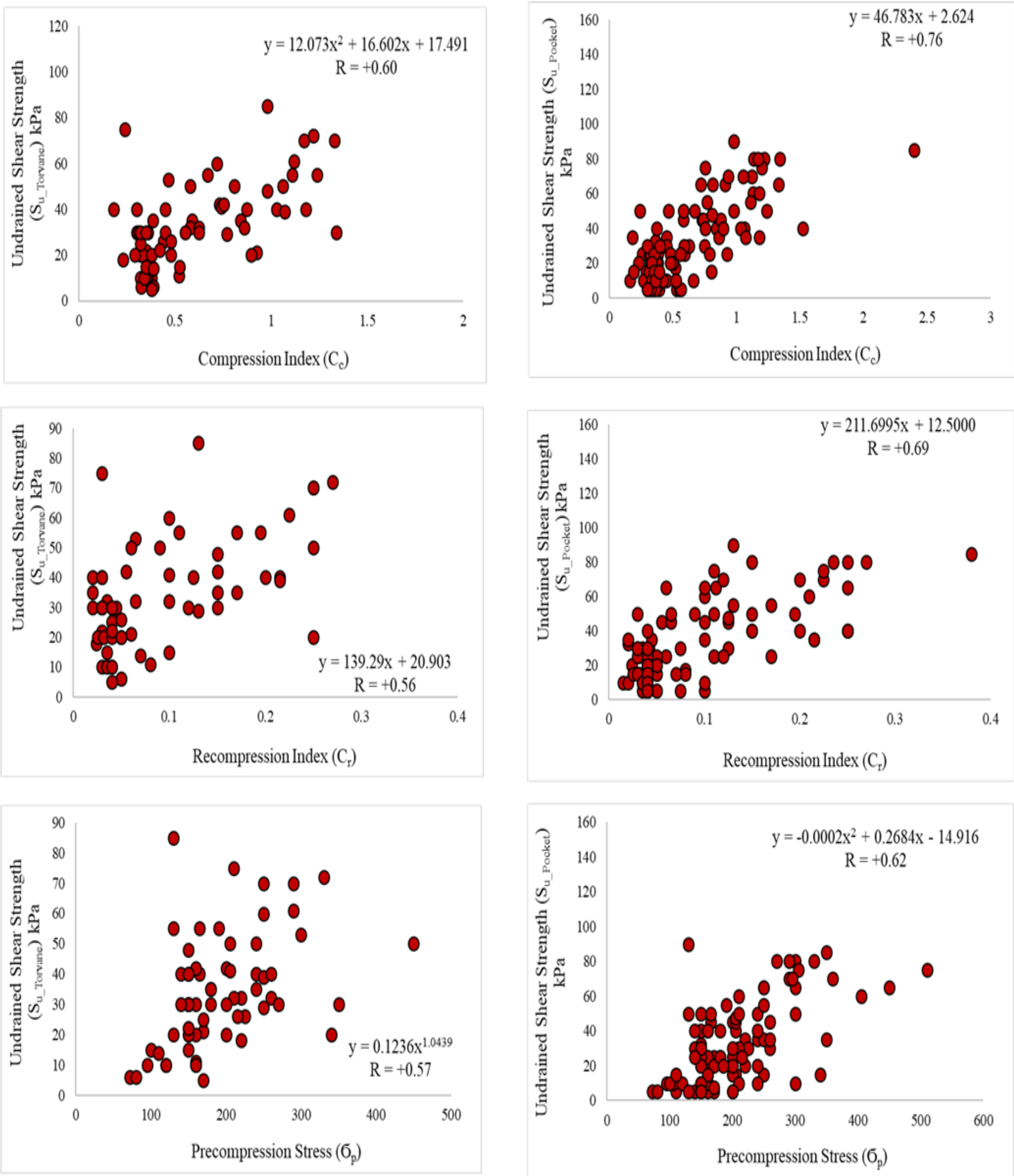


Fig.14 Bivariant plots of undrained shear strength from a pocket penetrometer and torvane with compressibility parameters of studied clay soils

Table 5 Relationships between compressibility parameters and some strengths obtained from different tests and physical properties of the studied Nile Delta high plastic clay samples; using multivariable regression analysis

Independent variables (X)	Dependent variables (Y)	Absolute value of correlation coefficient (R)	Relation equation	Number of correlated samples
$(S_{u\_Pocket}*\sigma_v*P.L)/1000Wn$	Compression index (C_c)	+0.69	$Y= -0.0072X^2 + 0.1557X + 0.2789$	92
$(S_{u\_Pocket}*\sigma_v)/1000e_O$		+0.52	$Y= 0.3989e^{0.0926X}$	103
$(S_{u\_Pocket}*\sigma_v)/1000$		+0.75	$Y= -0.0025X^2 + 0.0931X + 0.2624$	104
$(65.154*(S_{u\_Torvane})^{0.3069})/\sigma_v$		-0.51	$Y= 0.6989X^{-0.765}$	66
$(S_{u\_Pocket}*\sigma_v*P.L)/1000Wn$	Recompression index (C_r)	+0.66	$Y= -0.0012X^2 + 0.0277X + 0.0254$	92
$(S_{u\_Pocket}*\sigma_v)/1000e_O$		+0.66	$Y= -0.0014X^2 + 0.0275X + 0.0317$	103
$(S_{u\_Pocket}*\sigma_v)/1000$		+0.71	$Y= -0.0004X^2 + 0.0165X + 0.0243$	104
$(S_{u\_Pocket}*\sigma_v*P.L)/1000Wn$	Precompression stress (σ_p)	+0.68	$Y= 0.1433X^3 - 3.0577X + 29.467X + 148.17$	92
$(S_{u\_Pocket}*\sigma_v)/1000e_O$		+0.66	$Y= 16.657X + 150.85$	103
$(S_{u\_Pocket}*\sigma_v)/1000$		+0.69	$Y= 9.1998X + 152.14$	104
$(65.154*(S_{u\_Torvane})^{0.3069})/\sigma_v$		-0.63	$Y= 224.87X^{-0.648}$	66
$(2.5*S_{u\_UU} + 125)/\sigma_v$		-0.61	$Y= 233.8e^{-0.202X}$	18
$(2.5*(S_{u\_Pocket}) + 140)/\sigma_v$	Overconsolidation ratio (OCR)	+0.72	$Y= -0.0765X^2 + 0.9521X + 0.2148$	129
$(2.5\ (S_{u\_Lab.\ Vane}) + 150)/\sigma_v$		+0.76	$Y= -0.1179X^2 + 1.3078X - 0.1839$	43
$(65.15*(S_{u\_Torvane})^{0.30})/\sigma_v$		+0.62	$Y= 0.5173X + 0.6973$	66
$(2.5*S_{u\_UU} + 125)/\sigma_v$		+0.81	$Y= 1.2953\ln(X) + 0.9751$	18

Table 6 Relationships between strengths from different tests and compressibility properties of the studied Nile Delta high plastic clay samples by using multivariable regression analysis

Independent variable (X)	Dependent variables (Y)	Absolute value of correlation coefficient (R)	Relation equation	Number of correlated samples
$\sigma_p/(OCR)^2$	Undrained shear strength (S_{u-UU})	+0.77	$Y= 0.001X^2 + 0.009X + 11.684$	19
$\sigma_v/(OCR)^2$		+0.67	$Y= 3.2727X^{0.4498}$	19
σ_v *OCR		+0.81	$Y= 0.0013X^2 – 0.2511X + 22.739$	19
σ_p *OCR		+0.89	$Y= 0.0009X + 2.0233$	19
$\sigma_p/(OCR)^2$	Undrained shear strength ($S_{u-Torvane}$)	+0.64	$Y= 1.8742X^{0.597}$	66
$\sigma_v/(OCR)^2$		+0.58	$Y= 5.6013X^{0.3838}$	66
σ_v *OCR		+0.57	$Y= 0.124X^{1.0432}$	66
σ_p *OCR		+0.70	$Y= 0.0638X^{0.6047}$	66
$\sigma_p/(OCR)^2$	Undrained shear strength ($S_{u-Lab.\ Vane}$)	+0.60	$Y= 0.0038X^2 + 0.594X + 36.41$	44
$\sigma_v/(OCR)^2$		+0.67	$Y= 0.0052X^2 - 0.6673X + 30.945$	44
σ_v *OCR		+0.60	$Y= 0.0145X^{1.3436}$	44
σ_p *OCR		+0.58	$Y= 0.0007X + 5.0674$	44
$\sigma_p/(OCR)^2$	Undrained shear strength ($S_{u-Pocket}$)	+0.62	$Y= 0.2209X + 8.7176$	104
$\sigma_v/(OCR)^2$		+0.54	$Y= 4.1553X^{0.4332}$	104
σ_v *OCR		+0.61	$Y= 0.1852X – 5.7478$	104
σ_p *OCR		+0.67	$Y= 20.888\ln X – 179.86$	104

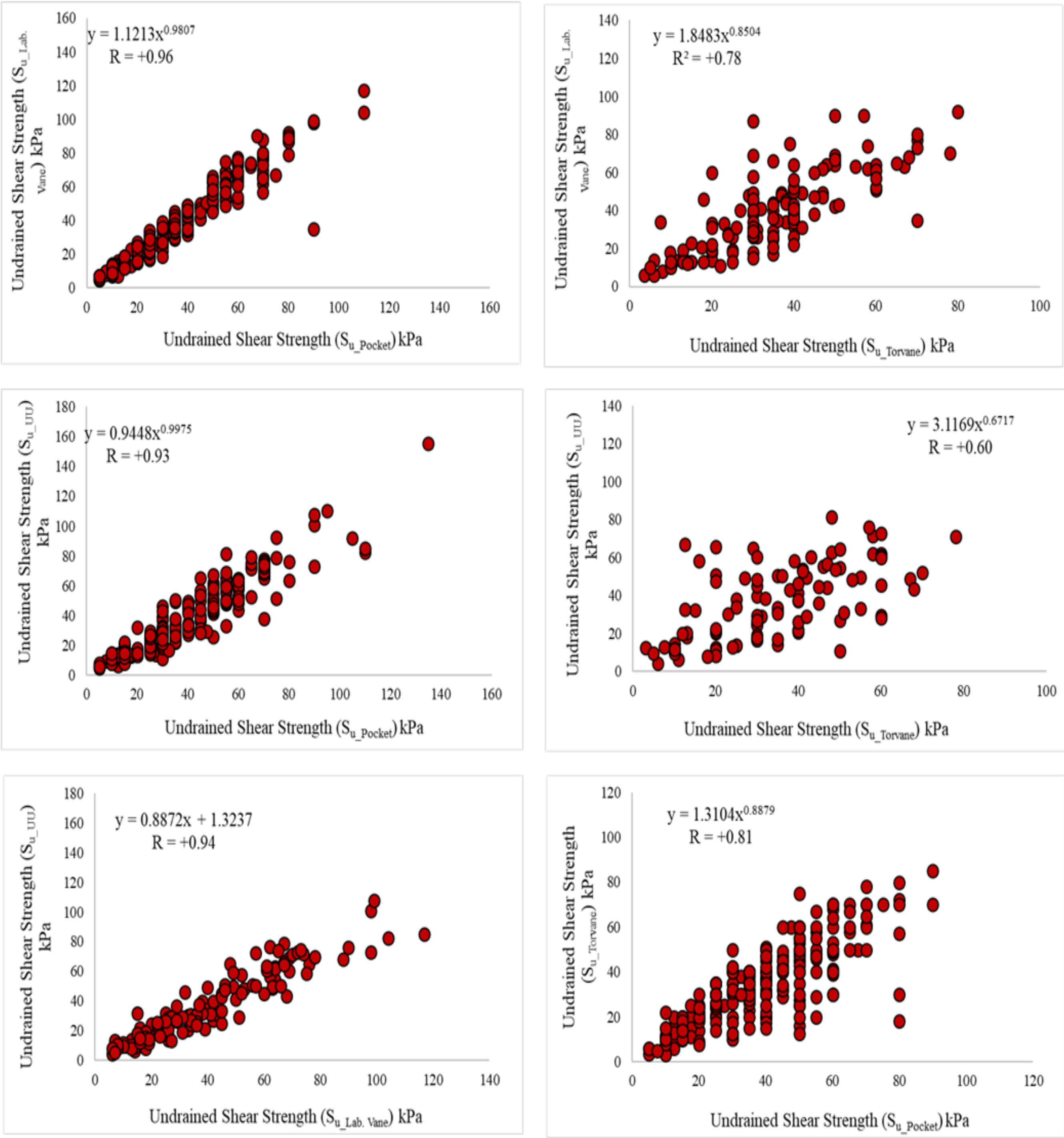


Fig.15 Bivariant plots between undrained shear strength parameters from different test methods of studied clay soils

5. Conclusions

The construction of any engineering structure on a compressible and/or weak clay layer leads to settlement and/or failure through this clay layer. The amount of settlement is related mainly to the obtained consolidation test parameters (compressibility parameters, overconsolidation ratio, and precompression stress), while the failure is related to the undrained shear strength of this clay layer.

The obtained consolidation test parameters are used in settlement analysis and the undrained shear strength is widely used as an input parameter for the design and practice of various engineering projects. Due to the expensive, cumbersome and, time consuming of these evaluation tests; several attempts have been made to estimate these critical geotechnical parameters by using simple, cheap, and time-saving index properties of the soil.

In this study, the performance of applying empirical equations for the estimation of the settlement and strength parameters for the Nile Delta high plastic clays was assessed by using the database consisting of 551 undisturbed clay soil samples. This study includes 129 consolidation tests, 521 bulk density and 465 dry density tests, 551 natural water content and 383 Atterberg limits tests, 473 pocket penetrometer and 275 torvane tests, and 211 unconsolidated-undrained triaxial compression tests and 277 laboratory vane shear tests. This database was used to determine valuable correlations for estimating settlement and strength parameters of the studied clay soils. For this purpose, various linear and multi-variables regression models were adopted in order to obtain the most valuable and practically applicable relationships.

The regression analysis results depict statistically moderate to strong correlations of the compression and recompression indices with the bulk density, natural water content, liquid and plastic limits, plasticity index, initial void ratio, and the effective overburden pressure with absolute correlation coefficient ranging between 0.53 and 0.79. On the other hand, the precompression stress and overconsolidation ratio have no remarkable correlations with these physical properties, except with the effective overburden pressure they show moderate correlations with absolute correlation coefficients of 0.59 and 0.69, respectively, because they depend mainly on the in-situ stress state.

Most physical properties have no remarkable role in the undrained shear strength of clay soils, except the effective overburden pressure that reflects the stress state of the clay soils.

The compressibility and undrained shear strength parameters depend on the same factors, such as in-situ effective stress, stress during geological history, diagenesis and cementation process, mineralogy, microstructure, and texture of clay soils. Therefore, there are meaningful relationships between these main geotechnical design parameters.

Finally, the mathematical equations derived from various linear and multi-variables regression models are mostly reliable and capable to predict the main geotechnical design parameters with an acceptable degree of confidence for the initial stage of any project investigation in the Nile Delta region.

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