Site Characterization of Al-Burrulus Clay Formations

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Abstract. An extensive subsurface investigation program was executed to characterize the formations in the city of Al-Burrulus site in the north coast of Egypt. The site is situated on the Mediterranean Sea coast with shallow ground water at the area. According to the subsurface ground investigations, thick layers of sands with relative densities varying from very loose to very dense sand underlain by very soft to hard clay and intermixed soils are characteristic of this area. A plethora of high quality laboratory and insitu tests were performed to identify the soil properties. The field tests include the Standard Penetration Test (SPT), Piezocone (CPTu), Seismic Piezocone (SCPT) and Downhole Test (DHT). Additionally, "undisturbed" specimens are extracted from the cohesive soils using Shelby tube samplers, while disturbed samples are obtained from cohesionless soil layers. Several laboratory tests were performed on the extracted specimens for classification purposes (e.g. grain size distribution and Atterberg limits). Tests on "undisturbed" samples are conducted to determine the strength properties (e.g. consolidated undrained triaxial test, unconsolidated undrained triaxial test, and direct shear tests). Site specific correlations are developed between the clay strength obtained from tests performed on high quality Shelby tube specimens and insitu tests. These correlations are beneficial to estimate clay strength in future projects in Al-Burrulus area based on field tests.

1 Introduction

Soil is characterized by a significant degree of variability/uncertainty in its properties. Proper selection of soil parameters is important for the analysis and design of any civil engineering project. Traditionally, boreholes are executed to extract soil samples at regular intervals with depth. The soil specimens are transported to the laboratory for classification and further characterization. Index laboratory tests are performed be to confirm visual soil classification. Soil strength parameters were determined using triaxial and direct shear tests. Typically, laboratory tests are time consuming and expensive. Noting the fast construction projects nowadays, other more economic subsurface investigation techniques are needed to provide reliable results in a shorter timeframe. On the other hand, insitu tests provide a faster and more economic means to characterize the subsurface. At Al-Burrulus site, several insitu tests, including the Standard Penetration Test (SPT), Piezocone (CPTu), Seismic Piezocone (SCPT) and Downhole Test (DHT), were executed to characterize ground conditions. These tests

L. Mohammad and R. Abd El-Hakim (Eds.): GeoMEast 2019, SUCI, pp. 72–91, 2020.
https://doi.org/10.1007/978-3-030-34187-9_6

are used for soil classification and to quantify some soil parameters by the use of correlations. This paper focuses on quantifying the short term shear strength of clay at Al-Burrulus area in Egypt.

2 Project Site Location/Geology

Al-Burrulus site is located in the Western Nile Delta about 55 km North East of Alexandria, on the Eastern side of the Rosetta Nile branch. The site is situated on the Mediterranean Sea coast, as shown on Fig. 1. The ground consists of low sand dunes, surface salt crusts and shallow ground water. A geological map of the area is shown in Fig. 2.

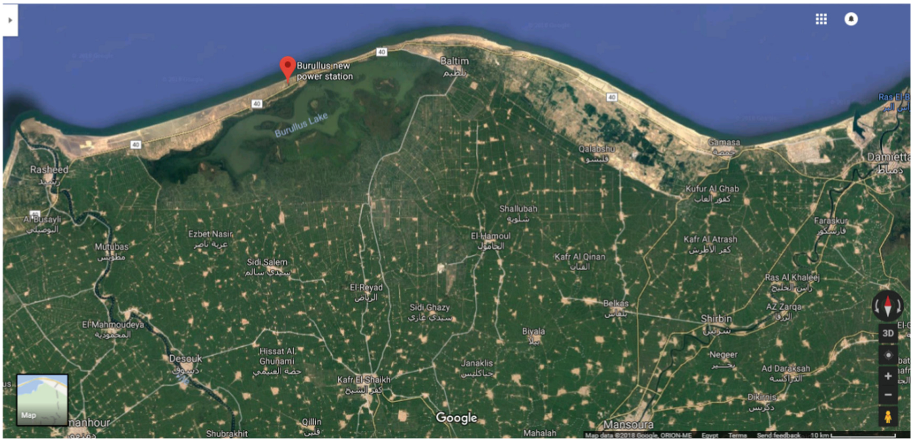

Fig. 1. The project location map (source: Google Map) Link: www.google.com/map. Access date: 3 May 2018

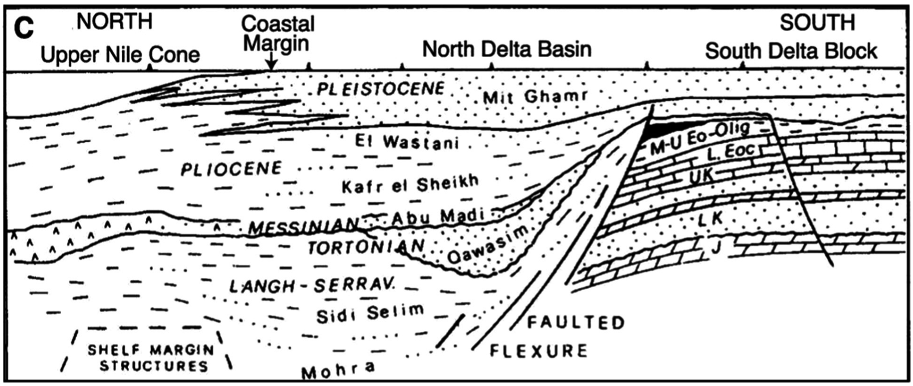

Fig. 2. Geological map of north delta basin (source: Google Images) Link: www.google.com/search/images. Access date: 13 May 2018

The ancient Nile delta ground surface now is being about 50–60 m below sea level. The sediments of the delta are marine sediments until Pleistocene time. The lower clay deposit in the northern shores of the Nile delta is extending to depth about 50 m is marine. Sand was deposited due to deposit became coarser grained, as the delta advanced. Recent alluvial and deltaic deposits are thought to be about 60–160 m thick so thick deposits of silts, clays and sands existed due to the area was infilled with marine and Nile sediments. Figure 2 shows a geological map of north delta basin.

3 Subsurface Ground Profile

An extensive subsurface investigations campaign was performed in the area of Burrulus site in the north coast of Egypt for the design of a major project. A total of 75 boreholes, 124 CPTu piezometers, etc... were performed. Figure 3 shows a representative a borehole log of study project zone.

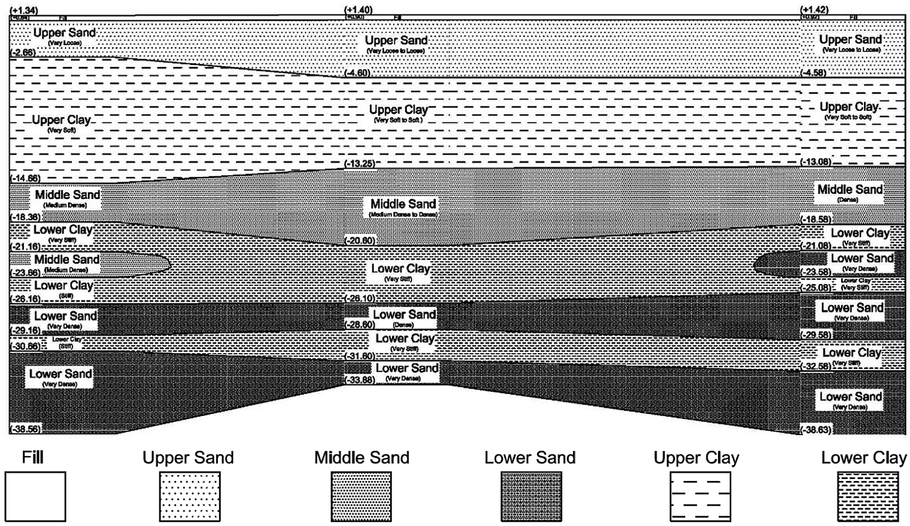

Fig. 3. Representative boreholes of study zone

According to soil investigation results in study zone, the upper 14 m soil crust is composed of very loose to loose sand extends to depth 0.6–7 m underlain by very soft to medium stiff clay with depth 0.5–8 m. While below 14 m, layers are medium dense sand extends to depth 0.6–7 m, followed by dense to very dense sand with depths 1–13 m below stiff to hard clay with depths 0.5–8 m.

In situ tests included penetration tests (SPT and CPTu) for getting soil shear strength and geophysical tests (DHT and SCPT) for obtaining soil shear modulus at small strain (G_{max}). Advantages of in situ tests are obtaining soil parameters at its natural environment (Stress state and chemical conditions) and applying different loading schemes to get soil response at various loading conditions. CPT and SCPT data were obtained within 20 m below ground level, while SPT and DH data within 40 m as shown in figures of soil subsurface investigation.

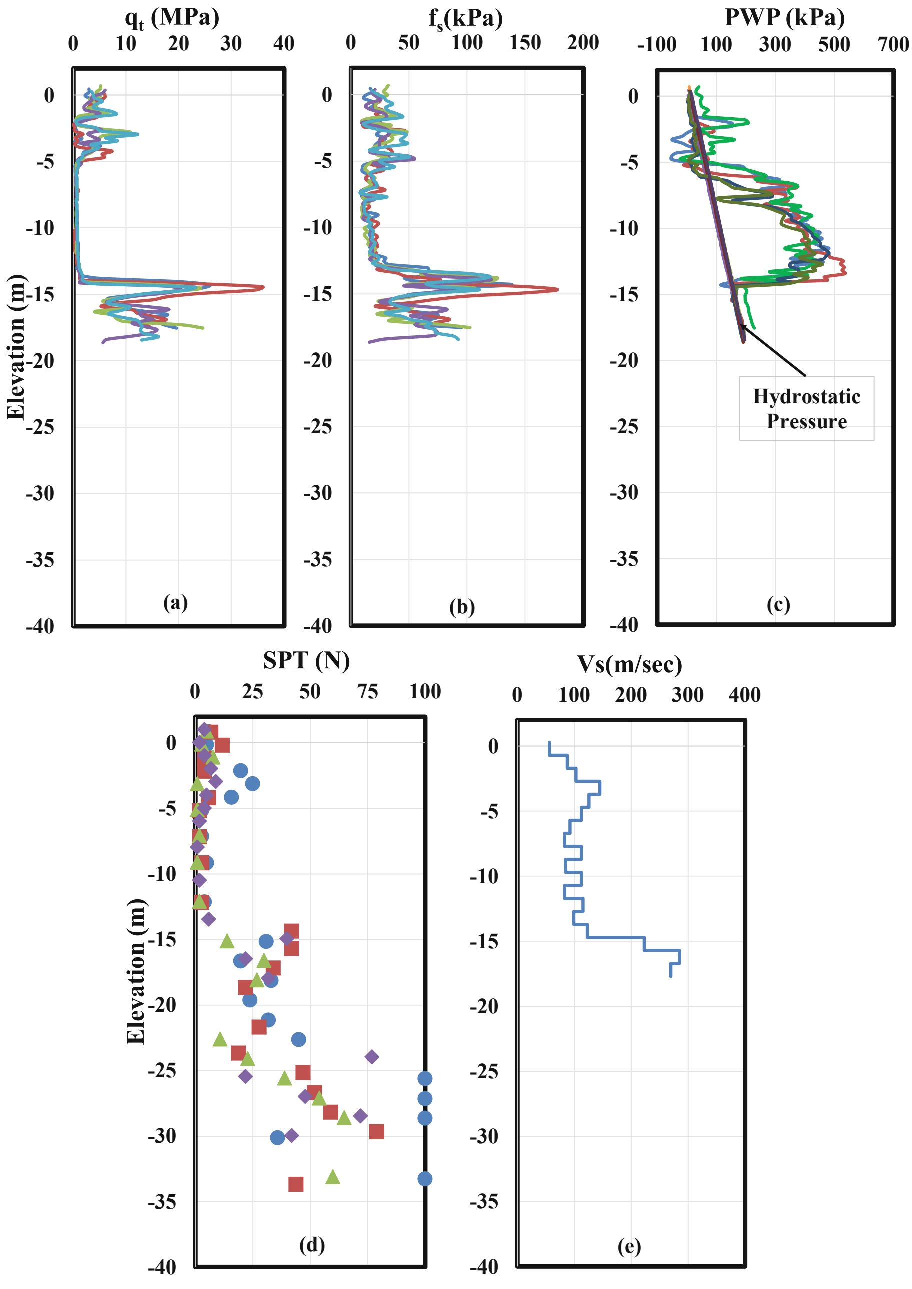

Fig. 4. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Seismic Piezocone data versus elevation in Module (1) Zone (A)

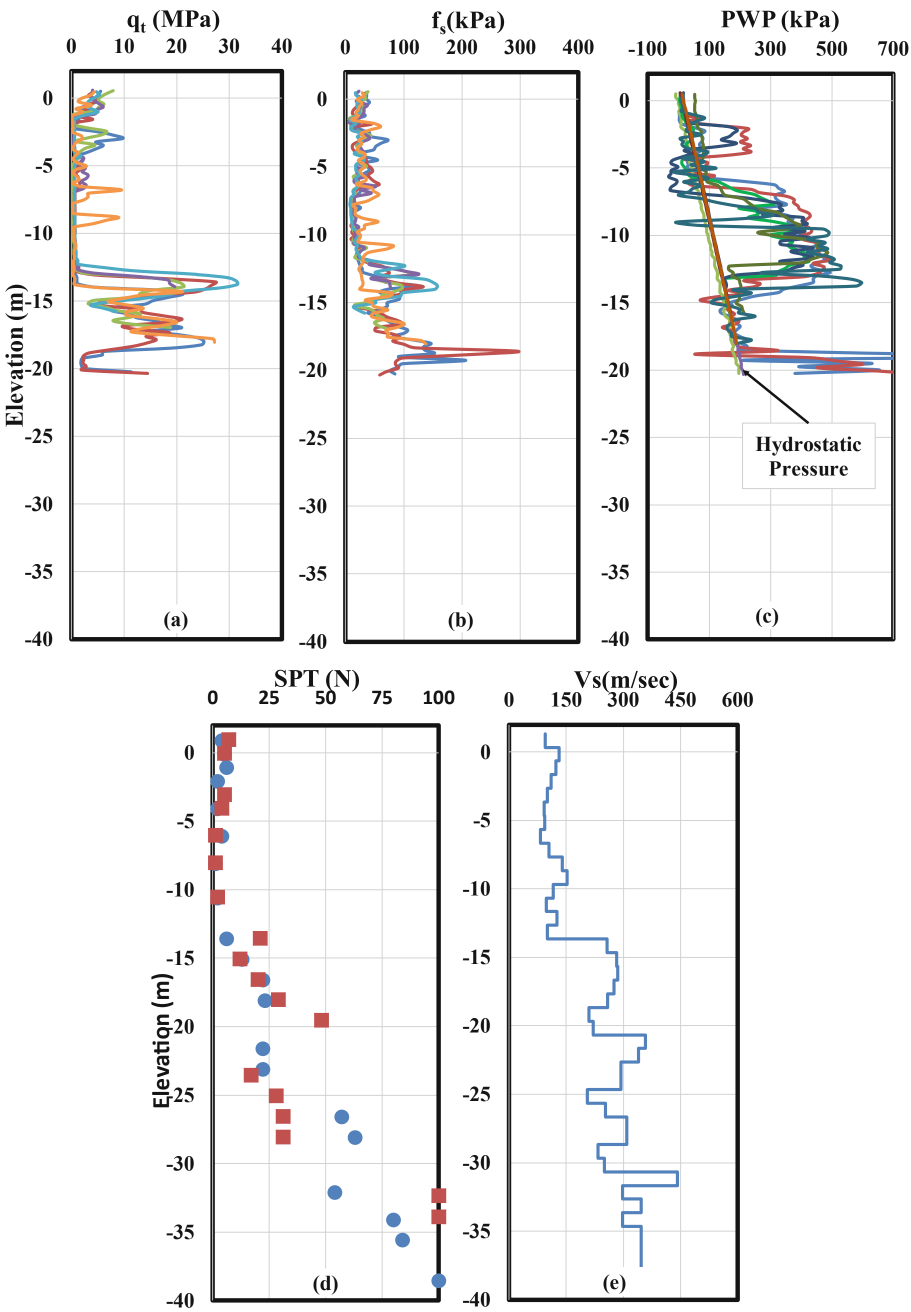

Fig. 5. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Downhole data versus elevation in Module (1) Zone (B)

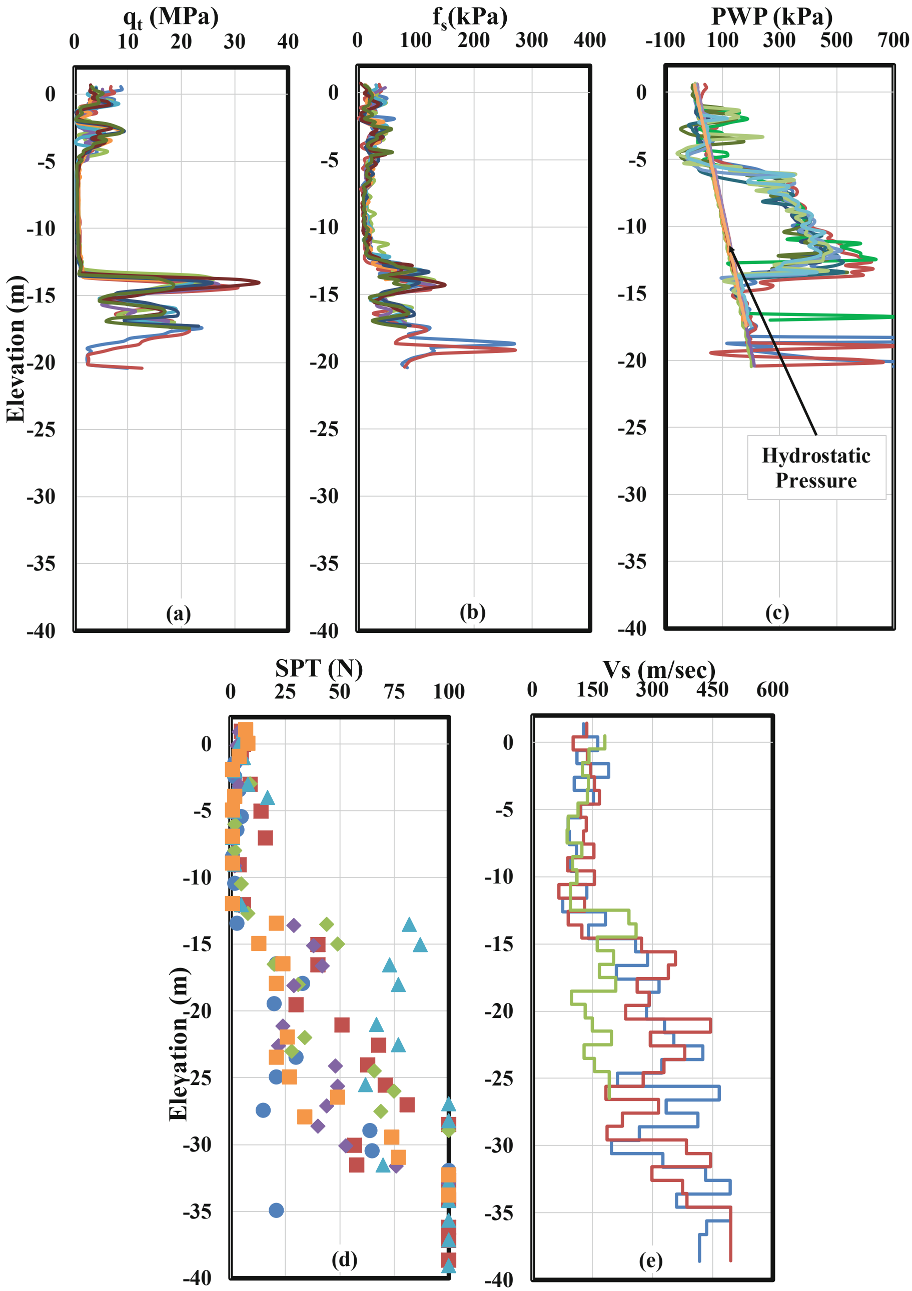

Fig. 6. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Downhole and SCPTu data versus elevation in Module (1) Zone (C)

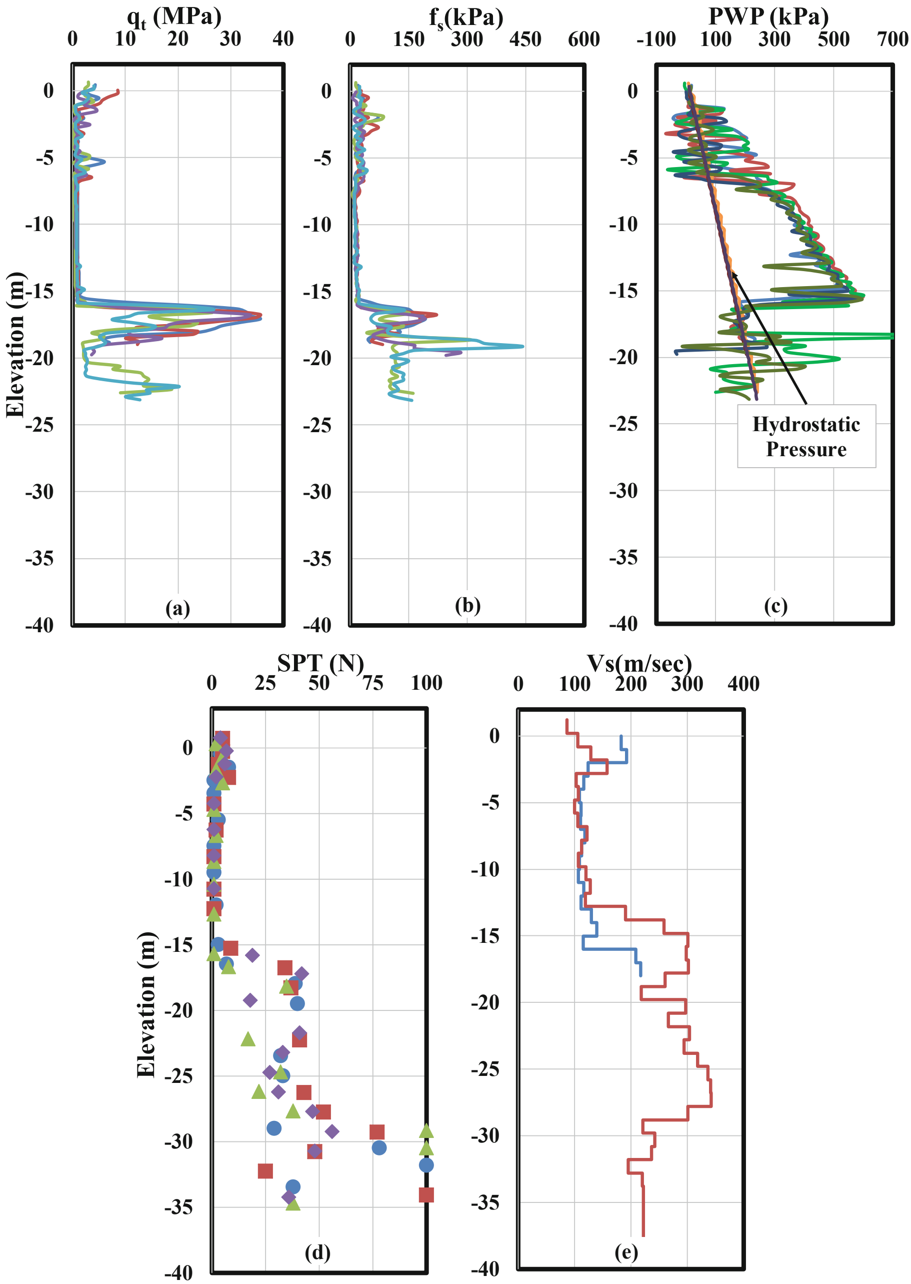

Fig. 7. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Downhole and SCPTu data versus elevation in Module (4) Zone (A)

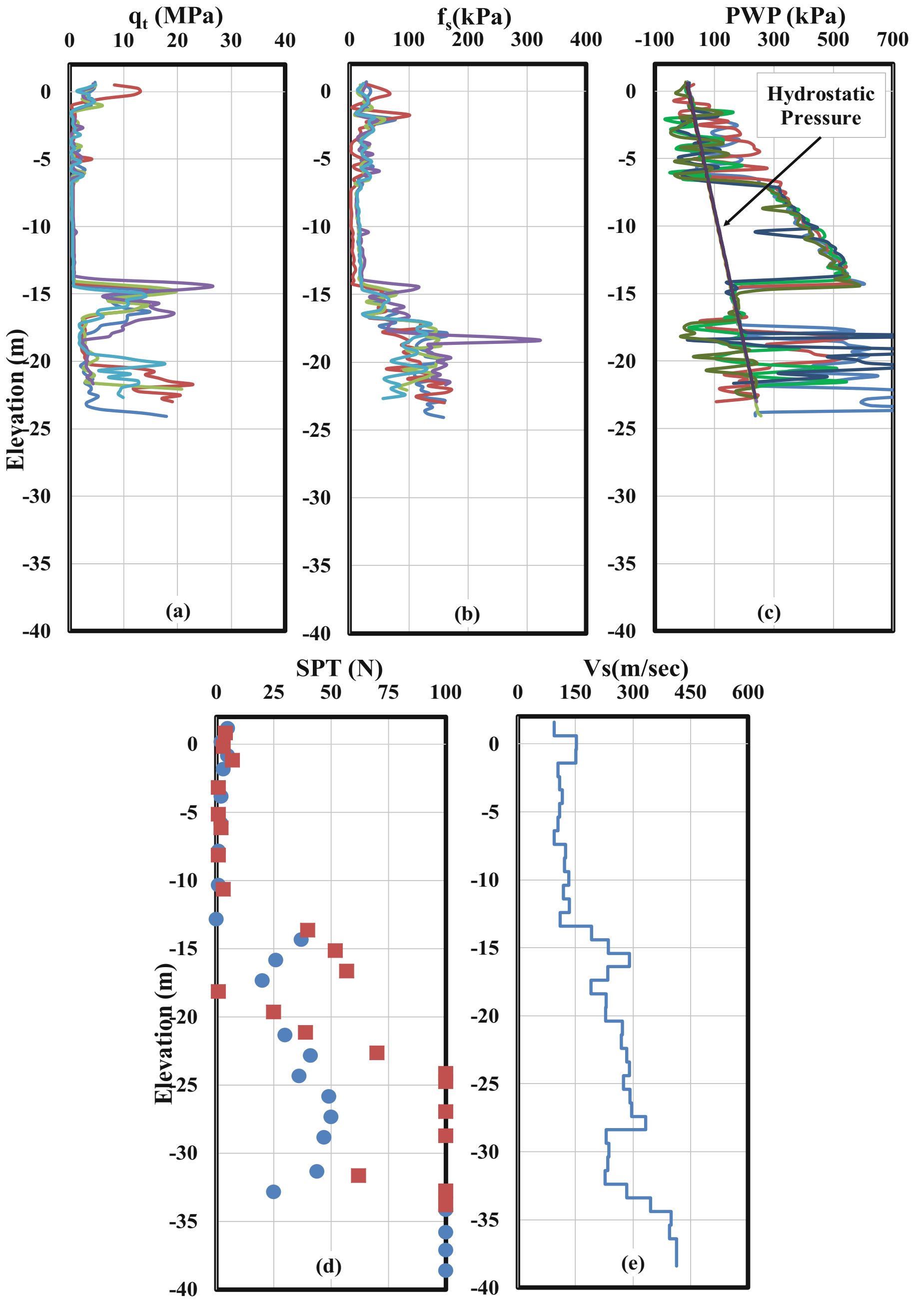

Fig. 8. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Downhole data versus elevation in Module (4) Zone (B)

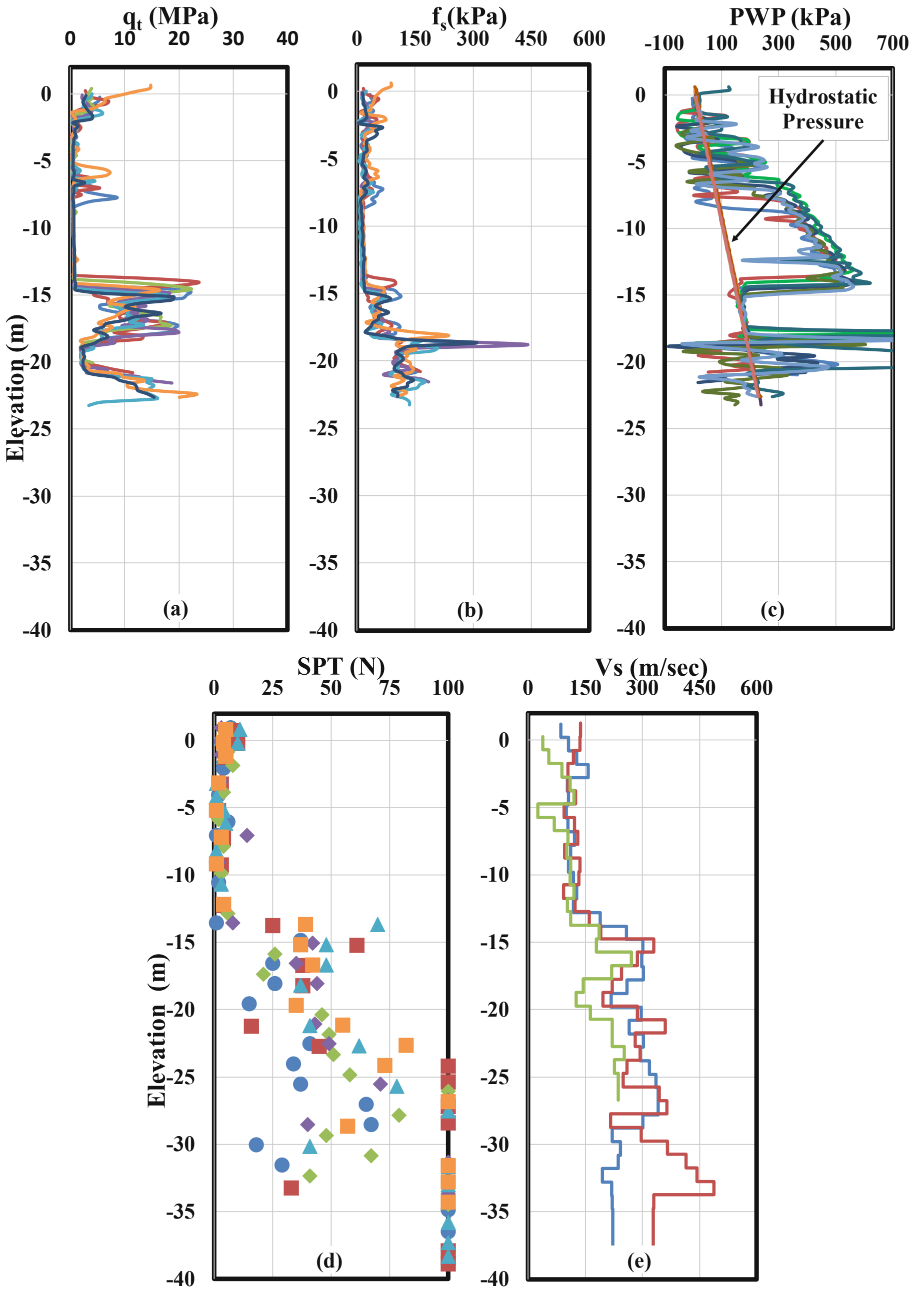

Fig. 9. (a), (b), (c) Piezocone data versus elevation (d) Standard Penetration test results versus elevation (e) Downhole and SCPTU data versus elevation in Module (4) Zone (C)

The site consists of four large modules (1, 2, 3 & 4). Each module was broken down into three zones (A, B & C) to reduce soil stratification variability. Figures 4, 5, 6, 7, 8 and 9 show data reduction of module 1 & 4 that we applied relationships of predict soil parameters.

This paper presents a comparison between the undrained shear strength parameter predicted from in situ tests and the measured parameter from laboratory tests.

4 Laboratory Tests on Clay Specimens

A plethora of laboratory tests were performed on clay specimens to determine strength parameters, as summarized below. These tests included index properties such as the liquid limit, plastic limit, shrinkage limit and water contents. The results of these tests are presented in Fig. 10. Based on the index properties, the clay is classified as CH. The consistency index varies between 0.25 and 1.65, which is indicative of very soft clay to very stiff clay as per the Egyptian Code of Practice for Soil Mechanics and Foundations (2001).

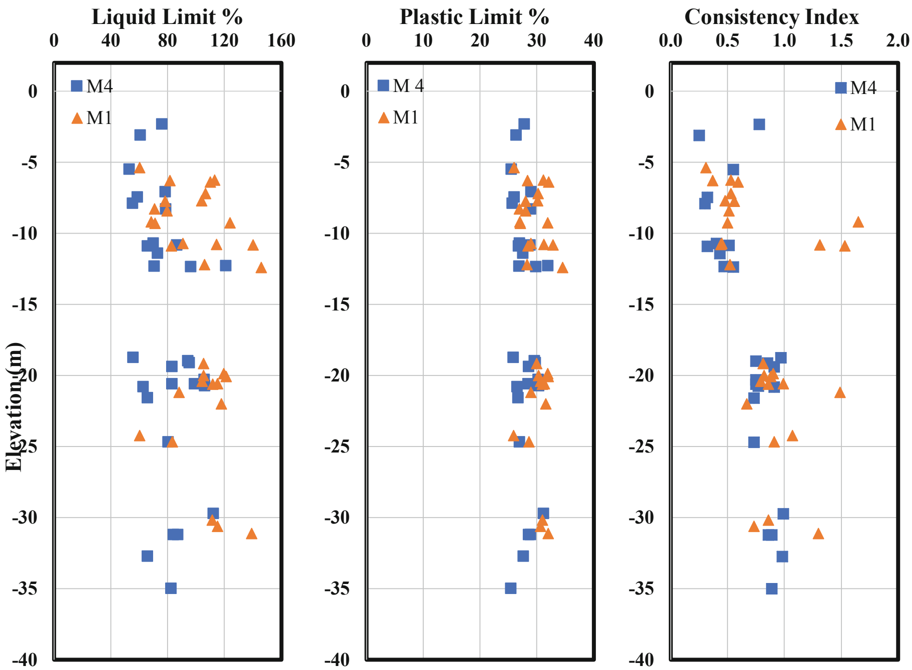

Fig. 10. Index properties with elevation of Module 1 & 4

Additionally, the stress history parameters (pre-consolidation pressure p_c and over consolidation ratio OCR) are measured from the one dimensional consolidation test performed on undisturbed samples. Alternatively, the pre-consolidation pressure ($p_c^{'}$) is estimated using the piezcone results as proposed by Mayne et al. (2009) and presented in Eq. (1)

$$p_c^{'} = 0.33(q_t - \sigma_{vo})^{m'}(\frac{P_{atm}}{100})^{1-m'} \quad (1)$$

Where exponent (m′) is calculated the CPT soil index I_c according to Eq. (2).

$$\mathrm{m}^{'} = 1 - \frac{0.28}{1 + \left(\frac{\mathrm{I}_c}{2.65}\right)^{25}} \quad (2)$$

Where the CPT soil index I_c is computed as per Eq. (3) (Robertson 2009)

$$I_c = \sqrt{\left[(3.47 - \log Q_{tn})^2 + (1.22 + \log F_r)^2\right]} \quad (3)$$

Where Q_{tn} = stress normalized cone tip resistance and F_r = normalized sleeve friction as outlined in Robertson (2009).

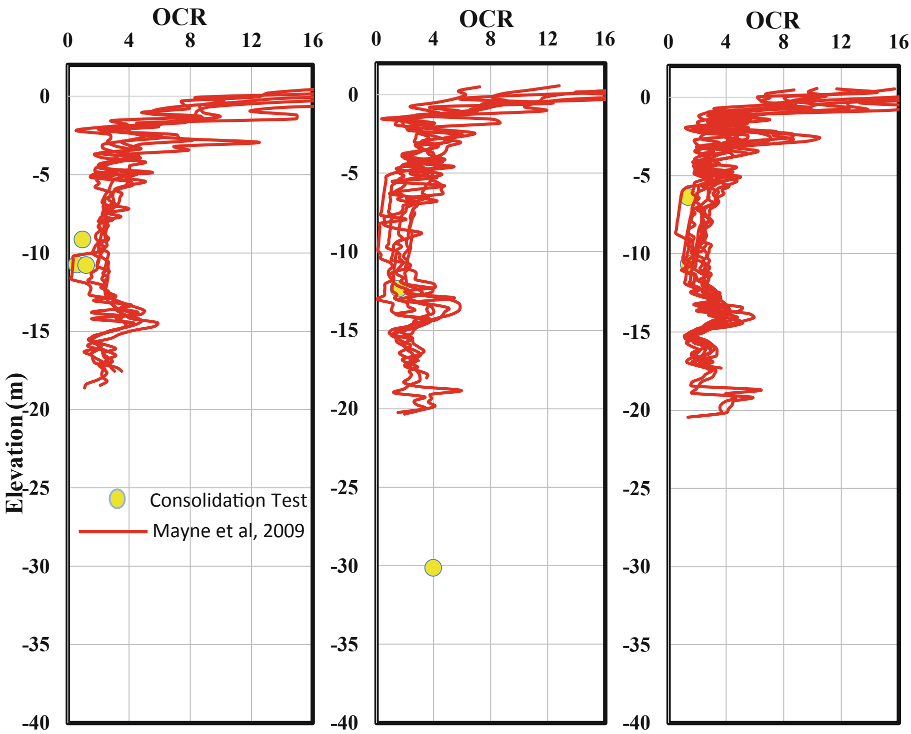

Fig. 11. Predicted versus measured OCR with elevation of Module 1

The measured and predicted values of OCR are presented in Figs. 11 and 12 for modules 1 and 4, respectively. Relatively good agreement is found between laboratory measured and piezocone evaluated values for both areas.

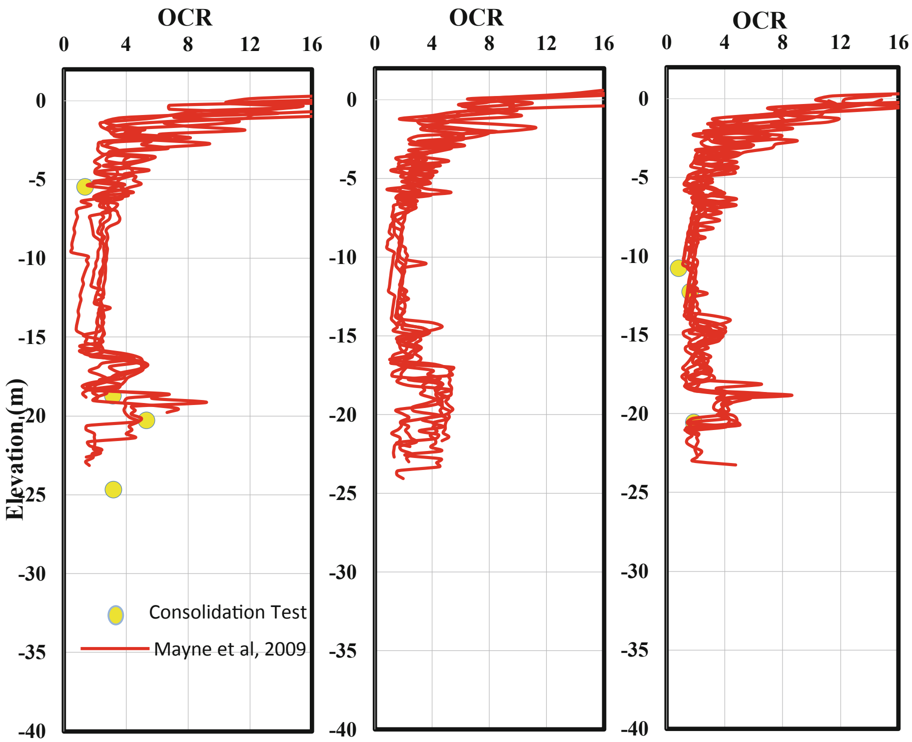

Fig. 12. Predicted versus measured OCR with elevation of Module 4

In addition, the undrained shear strength was measured by testing "undisturbed" specimens extracted using Shelby tubes. Soil strength is not a unique property but is affected many factors which include the boundary conditions, mode of loading, rate of loading, and drainage conditions. In the current study, the following tests were performed on the clay specimens to measure its undrained shear strength.

- The Unconsolidated Undrained Compression Test (UU) where drainage is not allowed during both the confining pressure and shearing stages. As no drainage is permitted, there are no changes in either the total volume or the void ratio. Although this test is not representative of the actual insitu conditions, it provides a quick and economic evaluation of strength.
- The Consolidated Undrained Compression Test (CU) where drainage is allowed during the application of confining pressure and drainage is prevented during the shearing stage. The pore water pressure may be monitored during the shearing stage. The shear strength parameter can be presented as total and effective stresses. The test may be used to measure both the undrained and drained soil strength.

– The Unconfined Compression Test (UC) is performed on cohesive soils to provide rapid approximate values of the undrained shear strength. The test is conducted on axially loaded cylindrical samples without any lateral confinement. The load applied at a high rate to prevent drainage. Usually, the measured undrained shear strength is underestimated relative to the in-situ values because of the zero confinement stresses.

The unconsolidated undrained tests are conducted at three confining stresses 100 kPa, 200 kPa, and 300 kPa that are applied to the specimen with no drainage allowed. Then the samples are loaded up to failure. Similarly, the consolidated undrained tests are performed on specimens subjected to three different confinement stresses of 100 kPa, 200 kPa and 300 kPa. The specimens are permitted to consolidate under the applied stress then loaded to failure with no drainage allowed. Pore water measurements are measured during the loading stage.

Figures 13 and 14 present the undrained shear strength values versus depth for zones 1 and 4, respectively. The laboratory test results are shown as dots while the values estimated from the field data using the correlations listed in Table 1 are presented as lines. The upper clay layer, which is approximately 14 m thick, exhibit

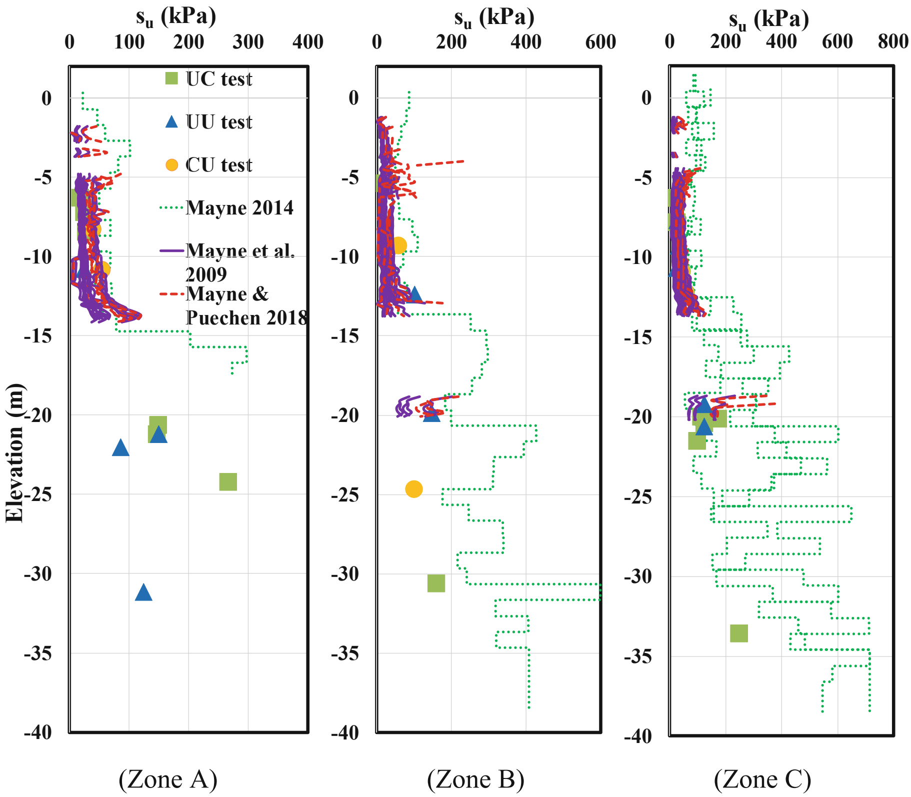

Fig. 13. Predicted versus measured undrained shear strength with Depth of Module 1

undrained shear strength that vary between 7.5 kPa and 101 kPa. The recorded undrained shear strengths are 7.5 kPa to 46 kPa, 22 kPa to 101 kPa and 38 kPa to 57 kPa for UC, UU and CU tests, respectively. The clay is described as soft to medium stiff clay according to Egyptian code of practice (2001). The predicted undrained shear strength from UC tests are estimated using Mayne et al. (2009) from the cone penetration test results and found to range between 14.5 kPa to 20.5 kPa. Similarly, the undrained shear strengths are evaluated to be 22.5 kPa to 37.38 kPa and 36 kPa to 61 kPa for UU and CU tests, respectively. The undrained shear strength from the consolidated undrained compression test is also calculated from the CPT results using the correlation proposed by Mayne and Puechen (2018). The values range between 30 kPa and 56 kPa. Finally, the undrained shear strengths are calculated using the shear wave velocity according to Mayne (2014) with values varying between 29 kPa and 109 kPa.

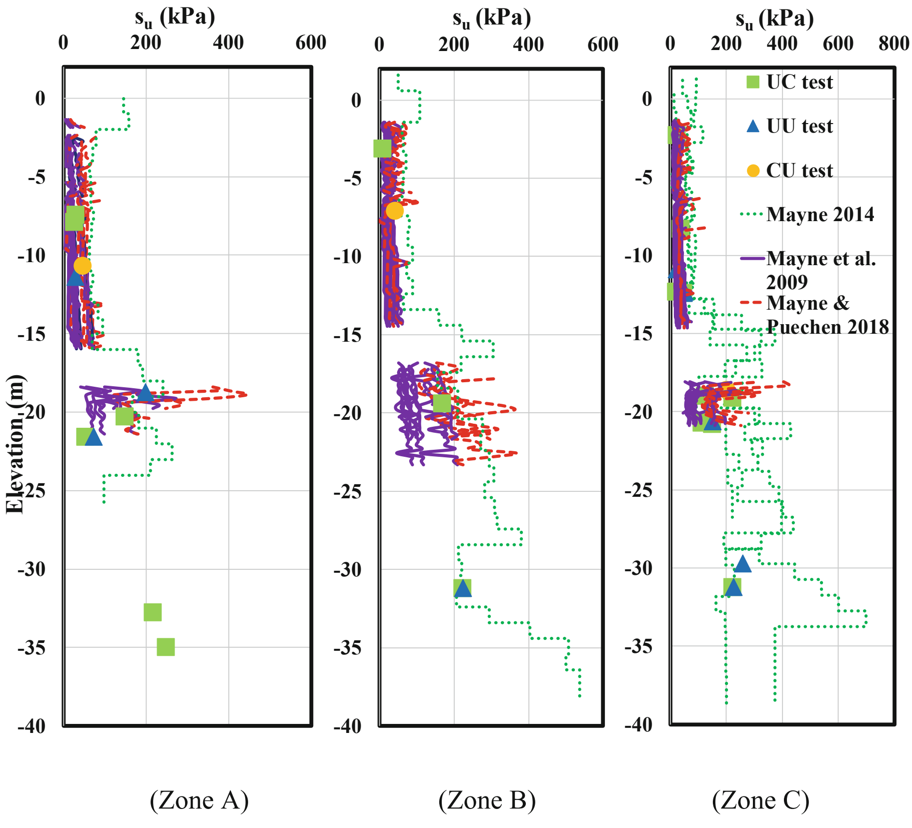

Fig. 14. Predicted versus measured undrained shear strength with Depth of Module 4

Table 1. Selected correlations for calculating undrained shear strength

Equation	Reference
$\left(\frac{S_u}{\sigma'_{vo}}\right)_{UC} = 0.14\ OCR^{0.8}$ $\left(\frac{S_u}{\sigma'_{vo}}\right)_{UU} = 0.185\ OCR^{0.8}$ $\left(\frac{S_u}{\sigma'_{vo}}\right)_{CU} = 0.33\ OCR^{0.8}$	Mayne et al. (2009)
$s_u = \frac{q_t - \sigma_{vo}}{N_{KT}}$ N_{KT} = 13.3 - consolidated undrained triaxial Where $q_{net} = q_t - \sigma_{vo}$	Mayne and Puechen (2018)
$s_u(kPa) = \left(\frac{V_s}{7.93}\right)^{1.59}$	Mayne (2014)

Higher shear strength values are recorded for the lower clay layer (deeper than 14 m). The undrained shear strength measured from the unconfined compression, unconsolidated undrained and consolidated undrained are 53 kPa to 221 kPa, 73 kPa to 199 kPa and 200 kPa, respectively. As per the Egyptian Code of Practice (2001), the clay is described as stiff to hard. Using Mayne et al. (2009), the predicted undrained shear are 63 kPa to 75 kPa corresponding to unconfined compression test, 86 kPa to 109 kPa corresponding to unconsolidated undrained triaxial tests and 187 kPa for the consolidated undrained tests. While the undrained shear strengths representative of consolidated undrained triaxial loading are computed according to Mayne and Puechen (2018) with value 219 kPa. The highest estimated shear strengths are based on the shear velocity using the correlation proposed by Mayne (2014) with values of 86 kPa to 482 kPa.

All the measured and predicted strength values are presented in Fig. 15. As shown, there is a high degree of scatter in the data. The ratios of the predicted to measured undrained shear strengths are computed and presented in Table 2. The maximum average ratio is 1.8 which is highest for the shear wave based relationship proposed by Mayne (2014). For the other cases, the ratio of the predicted to measured undrained strength varies between 0.72 and 0.96. Figure 15 shows comparisons between measured and predicted undrained shear strengths for the different modes of loading. The results are bound by 2:1 line (over prediction) and 0.5:1 line (under prediction).

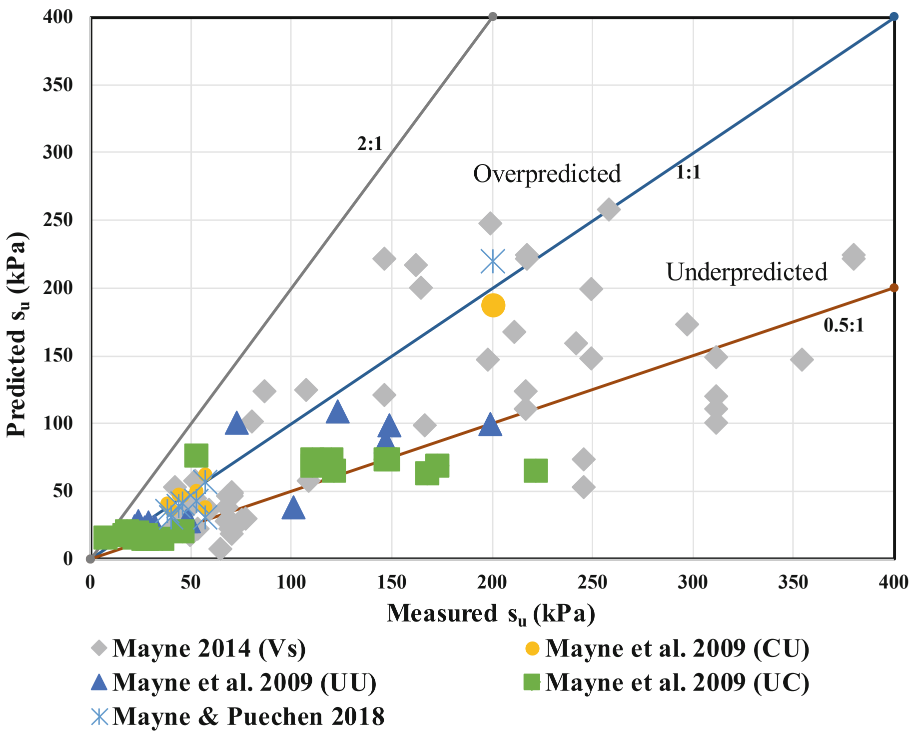

Fig. 15. Predicted versus measured undrained shear strength values

Table 2. Ratios of predicted to measured value of the undrained shear strength

	Mayne et al. (2009)			Mayne and Puechen (2018)	Mayne (2014)
	UC	UU	CU	CU	–
Minimum ratio	0.29	0.37	0.66	0.53	0.66
Maximum ratio	2.1	1.37	1.08	1.1	4.63
Mean ratio	0.72	0.81	0.96	0.86	1.8
Standard deviation	0.4	0.29	0.14	0.17	0.84

5 Site Specific Correlations

As discussed above, the soil strengths estimated using field tests show a large degree of variation compared with laboratory tests. Although some of the differences between the measured and predicted parameters may be attributed to natural soil variability, the development of site specific correlations is beneficial to improve on existing correlations. Accordingly, revised correlations are deduced to evaluate the undrained shear strength from the piezocone and seismic shear wave velocity for Al-Burrulus formations.

Consequently, the undrained shear strength obtained from the different laboratory shear tests on high quality "undisturbed" clay specimens. Figure 16 shows the correlation between the undrained shear strengths values and shear wave velocity. Correlations are developed to evaluate the undrained shear strengths for consolidated undrained triaxial, unconsolidated undrained triaxial and unconfined compression tests, as presented in Eqs. 4, 5 and 6, respectively.

$$(s_u)_{CU} = \left(\frac{V_s}{2.79}\right)^{1.12}, R^2 = 0.4 \tag{4}$$

$$(s_u)_{UU} = \left(\frac{V_s}{3.57}\right)^{1.13}, R^2 = 0.68 \tag{5}$$

$$(s_u)_{UC} = \left(\frac{V_s}{5.52}\right)^{1.27}, R^2 = 0.66 \tag{6}$$

Where undrained shear strength s_u in kPa and shear wave velocity V_s in m/s.

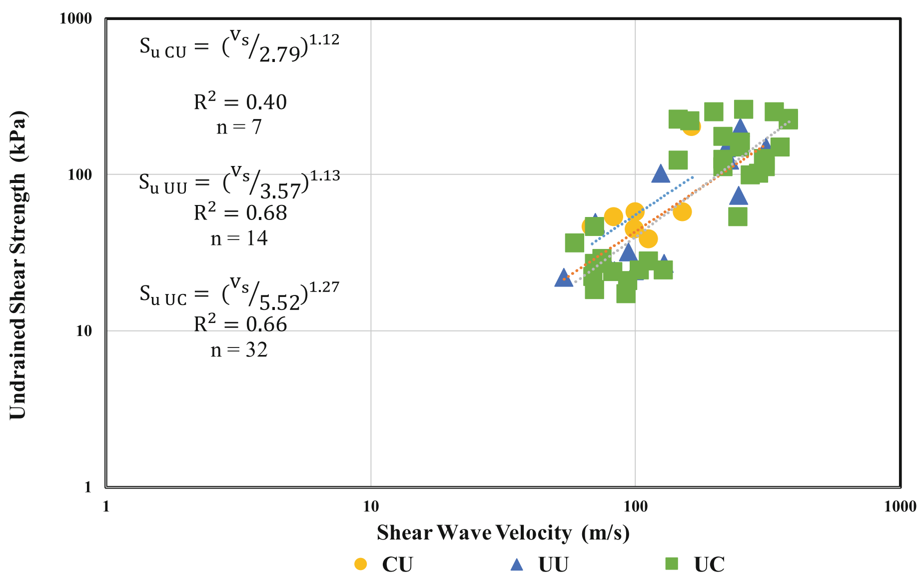

Fig. 16. Correlation between undrained shear strength and shear wave velocity

Similarly, the undrained shear strengths values are plotted versus the over consolidation ratios for the consolidated undrained triaxial, unconsolidated undrained triaxial and unconfined compression tests as shown in Fig. 17. The best fit correlations are listed in Eqs. 7 through 9 for the three loading types.

$$(s_u/\sigma'_{vo})_{CU} = 0.34(OCR)^{0.8}, R^2 = 0.9 \tag{7}$$

$$(s_u/\sigma'_{vo})_{UU} = 0.29(OCR)^{0.8}, R^2 = 0.66 \tag{8}$$

$$(s_u/\sigma'_{vo})_{UC} = 0.26(OCR)^{0.8}, R^2 = 0.46 \tag{9}$$

Finally, the undrained shear strengths are plotted versus the net cone resistance as shown in Fig. 18. Equations 10, 11 and 12 show the best fit correlations for the consolidated undrained triaxial, unconsolidated undrained triaxial and unconfined compression tests, respectively.

$$(s_u)_{CU} = \frac{q_{net}}{13.75}, R^2 = 0.93 \tag{10}$$

$$(s_u)_{UU} = \frac{q_{net}}{22.32}, R^2 = 0.67 \tag{11}$$

$$(s_u)_{UC} = \frac{q_{net}}{18.62}, R^2 = 0.75 \tag{12}$$

Where $q_{net} = q_t - \sigma_{vo}$.

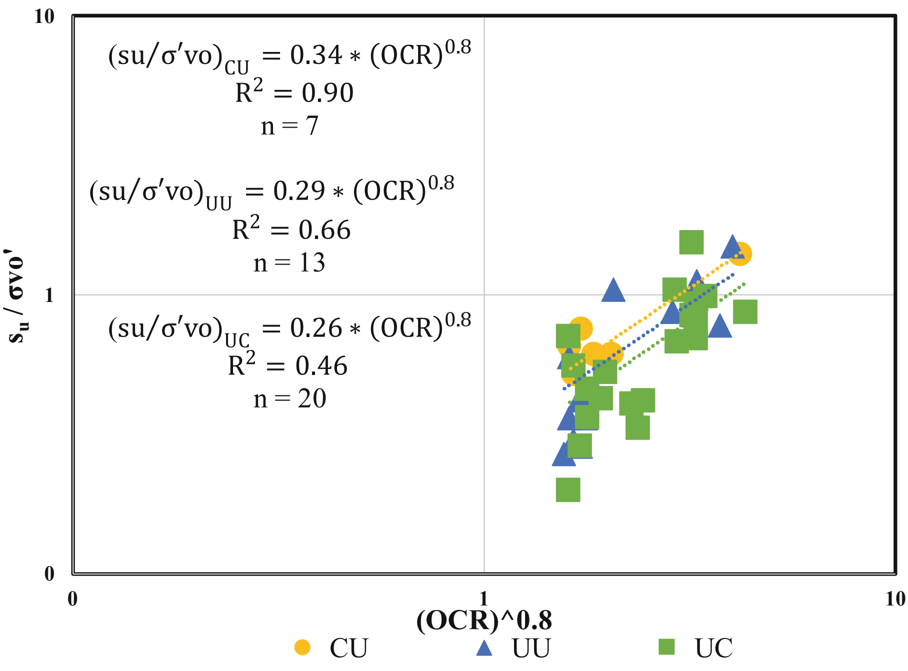

Fig. 17. Correlation between undrained shear strength and over consolidation ratio

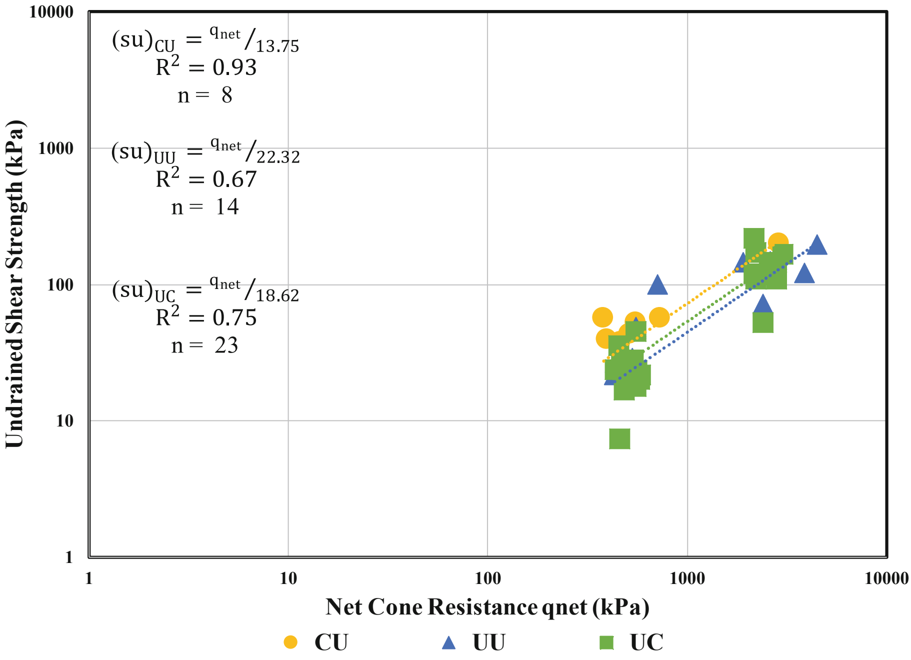

Fig. 18. Correlation between undrained shear strength and net cone resistance

6 Conclusions

This paper presents the results of an extensive subsurface investigations campaign in Al-Burrulus area in Northern Egypt. The site is situated on the Mediterranean Sea coast with shallow ground water at the area. The ground is formed of thick layers of very loose to very dense sands underlain by very soft to hard clay and intermixed soils are characteristic of this area. High quality “undisturbed” clay samples are extracted at different depths. The piezocone and shear wave velocity results are used to evaluate the undrained shear strengths for different loading types (consolidated undrained triaxial, unconsolidated undrained triaxial and unconfined compression tests) are evaluated using a number of correlations. Site specific correlations are developed to quantify clay strengths from field tests. These correlations can be used to estimate shear strengths from insitu test at Al-Burrulus area which is valuable because extracting high quality “undisturbed” soil specimens is expensive and time consuming. Thus, the use of these correlations would save cost and time on future subsurface investigation campaigns.

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