Acta Geodyn. Geomater., Vol. 16, No. 1 (193), 71–83, 2019
DOI: 10.13168/AGG.2019.0006

journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

CHARACTERIZATION AND FINITE ELEMENT ANALYSIS OF LIME AND POLYMER TREATED ULTRA-SOFT CLAY SOILS USING THE ELECTRICAL RESISTIVITY AND MINIATURE PENETROMETER METHODS

Aram M. RAHEEM [1)] * and Cumaraswamy VIPULANANDAN [2)]

[1)] *Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq*
[2)] *Civil and Environmental Engineering Department, University of Houston, TX,*

**Corresponding author's e-mail:* engaram@yahoo.com

ARTICLE INFO

Article history:
Received 12 May 2018
Accepted 22 January 2019
Available online 1 February 2019

Keywords:
Shear strength
Ultra-soft soil
Electrical resistivity CIGMAT miniature penetrometer
Polymer
Lime
pH
FEM
Mohr-Coulomb model

ABSTRACT

The characterization of ultra-soft soil behavior is one of the most difficult challenges since the water content in such soils is very high. Hence, nondestructive or special measurement is required. Therefore, the behavior of untreated and treated ultra-soft soil was characterized using both miniature penetrometer and electrical methods. The ultra-soft soil was prepared with 2 % to 10 % bentonite. The soil with 10 % bentonite was treated with 2 % to 10 % lime and with 1 % to 10 % polymer separately. The pH, CIGMAT miniature penetrometer, and electrical resistivity combined with the measured shear strength from the modified vane shear device were used to characterize the ultra-soft soils. The CIGMAT miniature penetrometer penetration varied linearly with the shear strength of the untreated and treated soft soils with 10 % bentonite. Relative electrical resistivity decreased by 246 % when the bentonite content was increased from 2 % to 10 % in the ultra-soft soil. The addition of 10 % of the lime to the ultra-soft soil with 10 % of bentonite content decreased the relative electrical resistivity by 171 %. The addition of 10 % of the polymer to the ultra-soft soil with 10 % of bentonite content reduced the relative electrical resistivity by 545 %. Power law, linear and hyperbolic models were used to predict the shear strength-electrical resistivity relationship for the untreated, lime-treated and polymer-treated ultra-soft soils respectively. The CIGMAT miniature penetrometer was modeled using 3-D axisymmetric finite element method, which predicted the penetration of CIGMAT penetrometer that agreed well with the experimental results of the ultra-soft soils.

1. INTRODUCTION

Due to a lack of land in the coastal cities, ground improvement has to be done to increase the availability of land for various applications (Bo et al., 2010; Anggraini et al., 2015). Also, because of the difficulty in obtaining undisturbed soil samples of ultra-soft soils in the coastal areas or deep seawater, in situ testing are becoming more popular (Lunne, 2001; Hasan and Samadhiya, 2016). In the deep water, seabed testings have to be done to characterize the soft soil within penetration about 3 m to 5 m as required (Hawkins and Markus, 1998). Several methods such as Vane Shear Test (VST), Cone Penetration Test (CPT) and T-Bar method are being used for the downhole testing. The vane shear test has been used widely in offshore site investigations, especially in the Gulf of Mexico (Johnson et al., 1988; Young et al., 1988) while T-bar can be considered as a modified cone penetration device and both have been used for soft soil characterization (Teh and Houlsby, 1991).

The potential of determining the soil profile near the top level of the seabed has given light penetrometer uniqueness over other typical methods of field-testing such as standard penetration method (cone penetration) and vane shear testing (Nader et al., 2015). To better quantify the soil properties, penetrometers with different sizes and shapes have been used. Generally, cone, ball, and T-bar penetrometers are widely used. The cone penetration method has been used extensively to correlate cone penetration tests (CPTs) with different soil properties such as shear strength, sensitivity, grain size distribution, and consolidation history (Rad and Lunne, 1986; Low et al., 2010). However, the minimum measured undrained shear strength was 230 kPa with the CPT used at different locations all around the world (De Jong et al., 2011). Ball penetration and T-bar penetrometers were primarily used for centrifugal tests (Stewart and Randolph, 2001). Recently, the use of full-flow penetrometers to quantify the undrained shear strength and sensitivity of the clays has become more popular (De Jong et al., 2011). Moreover, it was indicated that the full-flow penetrometers have higher projected areas of the tip and less influenced by overburden pressure in comparison to cone penetrometers, therefore; they have been used in very soft soils (Stewart and Randolph, 2001). However, the minimum measured

Cite this article as: Raheem AM, Vipulanandan C: Characterization and finite element analysis of lime and polymer treated ultra-soft clay soils using the electrical resistivity and miniature penetrometer methods. Acta Geodyn. Geomater., 15, No. 1 (193), 71–83, 2019**.** DOI: 10.13168/AGG.2019.0006

undrained shear strength were 8 kPa and 11 kPa with T-bar and ball penetrometers used respectively (Stewart and Randolph, 2001) while in the ultra-soft soil the undrained shear strength may have much lower value and it could reach to 0.01 kPa (Vipulanandan and Raheem, 2015). Hence, a new penetrometer with more accuracy is required to quantify the undrained shear strength of ultra-soft soil.

As early as 1939, Casagrande proposed an average shear strength of soil at the liquid limit as 2.65 kPa taking into considering a large spread of values depending on the apparatus used for determining the liquid limit (Casagrande, 1958). Norman (1958) stated that the shear strength at the liquid limit controlled by using an apparatus in compliance with the British standard ranged from 0.8 kPa to 1.6 kPa whereas using an apparatus of ASTM standards, the strength varied from 1.1 kPa to 2.3 kPa (Norman, 1958). Skempton and Northey (1952) described the value of shear strength at the liquid limit of four soils with very different values of plasticity index as 0.7 kPa to 1.75 kPa (Skempton and Northey, 1952). Youssef et al. (1965) found that the values of shear strength of clay at the liquid limit of a large number of soils (liquid limit varied from 32 % to 190 %) ranged from 2.4 kPa to 1.3 kPa with a mean value of 1.7 kPa (Youseff et al., 1965). Other studies (Wroth and Wood, 1978; Nagaraj et al., 2012) have indicated that the shearing strength of all fined grained soils at the liquid limit falls within a limited range of about 1.7 kPa to 2.0 kPa. Dredged nearshore materials exhibit properties such as high water contents and low shear strengths where the shear strength of most clayey soils is less than 0.01 kPa (Bartos, 1977; De Meyer and Mahlerbe, 1987).

Soft clay deposits are located in many coastal areas and they exhibit poor strength and compressibility (Pourakbar et al., 2016). Various soil improvement methods have been used for improving the shear strength of soft clays. These methods are based on using lime, cement and fly ash stabilization for treating ultra-soft clay soils (Ali et al., 1992; Muntohar, 2004). Since the gravimetric water content was low in such untreated and treated soils, these studies have mainly tested the soils for compaction, unconfined compression strength, and Atterberg limits. However, the gravimetric water content in ultra-soft soil is more than 90 %. Therefore, these studies cannot be used to represent the behavior of ultra-soft soil. Further information has been reported in order to improve the soft ground by using soil cement column method (Hebib and Farrell, 2003). Very few studies have used polymer to improve soft soil properties (Raheem et al., 2017). Hence, studying the effect of polymer treatment on the ultra-soft soil shear strength is crucial. The variations of undrained shear strength and water content (percentage of water) with bentonite, lime and polymer contents for untreated and treated the ultra-soft soil were studied by Raheem et al., 2017. It was shown that the shear strength was increased from 0.01 kPa to 0.17 kPa when the water content decreased from 98 % to 90 % as the bentonite content was increased from 2 % to 10 % respectively. However, the shear strength and water content were decreased from 0.17 kPa to 0.15 kPa and from 88 % to 80 % as the lime content was increased from 2 % to 10 % respectively with an optimum shear strength of 0.27 kPa. In addition, the shear strength was increased from 0.17 kPa to 6.8 kPa and the water content decreased from 90 % to 80 % as the polymer content was increased from 0 % to 10 % respectively.

Electrical resistivity investigation methods test soil properties by measuring the current and voltage between electrodes. Electrical resistivity methods, which were developed in the 1900s, have been used for the investigation of geological structures, underground spaces such as cavities, underground water contamination, and salinity distribution of aquifer water (Kaya and Fang, 1997). The electrical resistivity survey was first applied to the oil/gas exploration and prospecting of conductive or bodies, later it found applications in various engineering fields such as mining, agriculture, environment, archeology, hydrogeology and geotechnics (Siddiqui and Osman, 2012). The idea of electrical resistivity measurement has been applied in the subsurface rock investigation (Stadelhofen, 1991) where petroleum companies used this technique for oil inspection. In addition, the electrical resistivity survey was used in compacted clay to obtain the hydraulic conductivity in compacted clay (Abu-Hassanein et al., 1996). Moreover, an archaeological study has used an electrical resistivity method to obtain an equipotential map at the Williamsburg in USA (Bevan, 2000). Attempts have tried to use direct current electrical resistivity to observe the water content variations in the soil (Robain et al., 2003). It was shown that the soil adopted transitional electrical characteristics based on the both chemical and physical properties such as salinity, texture and moisture content (Samouëlian et al., 2005).

The equivalent electrical circuit of the ultra-soft soil behavior had been used as shown in Figure 1 (Vipulanandan and Prashanth, 2013; Raheem et al., 2017). The bulk capacitance of the material (C_b) was neglected and the total impedance of the equivalent circuit was represented as follows:

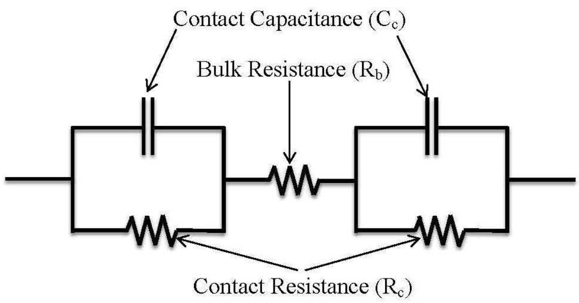


Fig. 1 The correspondace electrical circuit simulating the ultra-soft soil condition.

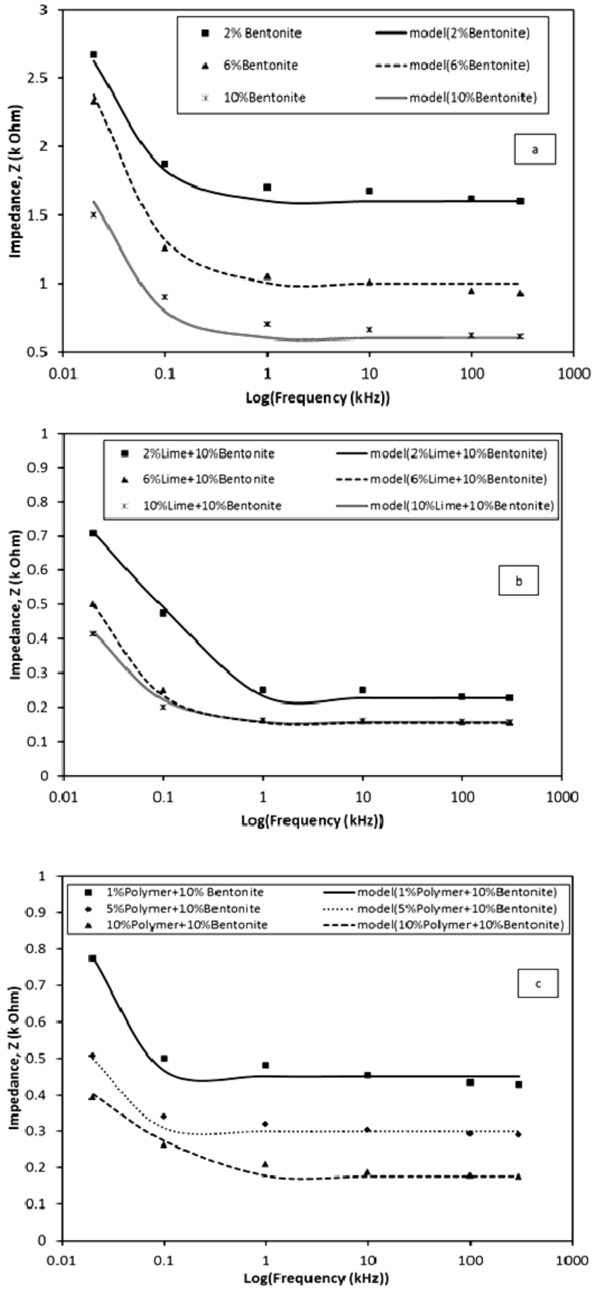


Fig. 2 Predicted and measured impedance frequency relationship (a) untreated ultra-soft soil, (b) 10 % bentonite ultra-soft soil treated with lime and (c) 10 % bentonite ultra-soft soil treated with polymer (Raheem et al., 2017).

$$Z = R_b + \frac{2R_c}{1+\omega^2 R_c^2 C_c^2} - j\frac{2\omega R_c^2 C_c}{1+\omega^2 R_c^2 C_c^2} \quad (1)$$

where Z is the impedance, R_b is ultra-soft soil (bulk) resistance, R_c is the contact resistance, ω is the angular frequency of the alternative current (AC) signal used for the measurements and C_c is the contact capacitance.

The variations of impedance spectroscopy versus frequency for the untreated, lime and polymer treated ultra-soft soil were studied as shown in Figure 2 (Raheem et al., 2017). The electrical impedance for 2 % bentonite ultra soft soil reduced from 2.67 k.Ohm to 1.71 k.Ohm when the current frequency was increased from 0.02 kHz to 300 kHz. The electrical impedance for 10 % bentonite ultra soft soil treated with lime reduced from 0.707 k.Ohm to 0.414 k.Ohm when the current frequency was increased from 0.02 kHz to 300 kHz. The electrical impedance for 10 % bentonite ultra soft soil treated with polymer reduced from 0.773 k.Ohm to 0.394 k.Ohm when the current frequency was increased from 0.02 kHz to 300 kHz. The model (Eq. 1) predictions were agreed with the experimental data for untreated and treated ultra-soft soil as identified in Figure 2a-c. The used bulk ultra-soft soil resistance and the contact capacitance are summarized in Table 1.

Limited attempts have been made by researchers to explore the phenomenon of electrical resistivity in soils and its relationship with other soil properties; such as thermal resistivity, salinity, ground water distributions using four probe methods (Abu-Hassanein et al., 1996). There is no correlation in the literature relating the electrical resistivity with ultra-soft soil shear strength.

2. OBJECTIVES

The overall objective of the study was to investigate methods to characterize ultra-soft soils so the methods can be adopted in the field. The specific objectives are as follows:

1. Investigate the correlation between shear strength, water content and electrical resistivity (2 probe method) of untreated and treated ultra-soft soil.
2. Study the shear strength versus penetration relationship for untreated and treated ultra-soft soils using the miniature CIGMAT penetrometer.
3. Model the observed behavior using the finite element method (FEM).

3. MATERIALS AND METHODS

In this study, the ultra-soft soil was prepared from a low percentage of bentonite and it was treated with the lime and polymer individually. All the soil samples were prepared on weight basis. Extensive physical, pH and electrical tests have been performed on untreated and treated soft soil to evaluate the behavior of the ultra-soft soil with and without treatment.

3.1. SOIL

Ultra-soft soil samples were prepared in laboratory by mixing different percentage of commercially Wyoming available bentonite (2 % to 10 %) with water (90 % to 98 %) at the room temperature for almost 15 minutes until a homo-genous mixture was obtained. The required mixing time is comparatively low since the soil samples are relatively small. The soil slurry mixture was placed in

Table 1 Impedance model parameters for untreated and treated ultra-soft soil.

Ultra-soft soil	R_b (k.Ohm)	R_c (k.Ohm)	C_c (F)	R^2	*RMSE* (k.Ohm)
Untreated					
2 % bentonite	1.6	0.6	5.5	0.98	0.057
6 % bentonite	1	0.8	4	0.99	0.052
10 % bentonite	0.6	0.6	6	0.99	0.075
Lime treatment (10 % bentonite)					
2 % lime	0.23	0.25	6	0.99	0.014
6 % lime	0.15	0.20	16	0.99	0.007
10 % lime	0.16	0.15	20	0.99	0.009
Polymer treatment (10 % bentonite)					
1 % polymer	0.45	1	18	0.99	0.022
5 % polymer	0.30	1	24	0.99	0.016
10 % polymer	0.20	0.1	15	0.99	0.015

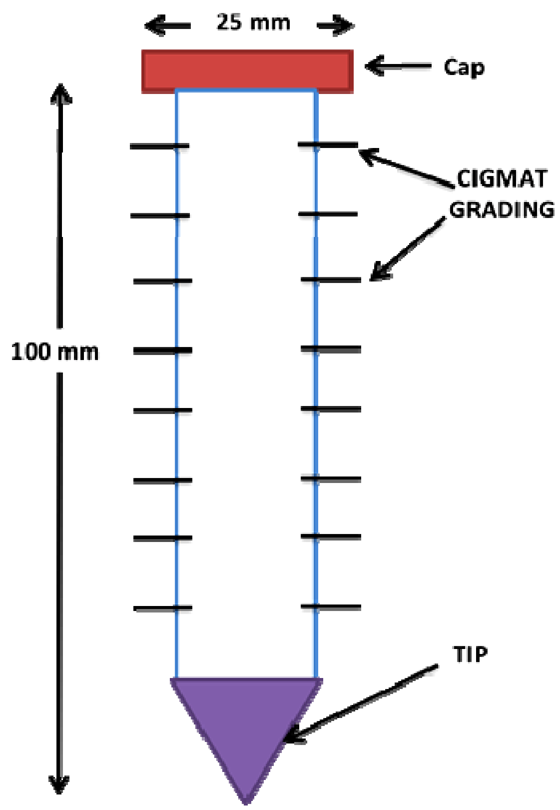


Fig. 3 Schematic of the miniature CIGMAT penetrometer.

50 mm (dia.) x 100 mm (height) cylindrical plastic mold and wires were embedded in the mold for electrical properties measurement. The prepared 10 % bentonite ultra-soft soil has acceptable shear strength, therefore; it was selected to be treated individually with lime and polymer.

3.2. LIME

In this study, hydrated lime was used to treat the soil. When quicklime reacts with water, it transforms into hydrated lime as follows:

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \quad (2)$$

In this study, individual samples were prepared by adding lime ranges from 2 % to 10 % to pre-prepared ultra-soft soil with 10 % bentonite content to study the short-term effectiveness of the lime on bentonite ultra-soft soil.

3.3. POLYMER

Polymer solution was prepared by mixing 15 % of water soluble acrylamide polymer with 0.5 % of catalyst, 0.5 % of activator and 84 % of water. Hence, the polymer solution had 15 % polymer dissolved in it. The pH of the polymer solution was 10. Hence, if 10 % of polymer solution content was used to treat the soil (based on dry weight of soil) actual amount of polymer used was 1.5 %. In this study, different samples were prepared by adding polymer solution ranges from 1 % to 10 % to pre-prepared ultra-soft soil with 10 % bentonite content to study the influence of the polymer on the behavior of ultra-soft soil.

3.4. PHYSICAL METHODS

(i) Vane shear

The untreated and treated bentonite ultra-soft soil with lime and polymer were tested using the modified vane shear device to measure the mud shear strength. Low shear strength measurement is one of the major challenges in the laboratory and field, however; the modified vane shear device (the blade height and diameter were increased by four times the original dimensions) measured the extreme low shear strength of the untreated and treated bentonite ultra-soft soil.

(ii) Miniature CIGMAT penetrometer

Based on the size and weight of the miniature CIGMAT penetrometer, it can be used to measure the shear strength of ultra-soft soils. A schematic sketch of the miniature CIGMAT penetrometer is shown in Figure 3. The penetrometer made out of plastic with a diameter and height of 25 mm and 100 mm respectively. The penetrometer is graduated with parts of millimeter to read the penetration accurately. The tip has a triangular shape to facilitate the penetration process.

3.5. pH METHOD

In this study, pH for both untreated and treated bentonite ultra-soft soil was measured. pH probe was immersed in the untreated and treated ultra-soft soil and reading was taken after 5 minutes and all the tests were performed at room temperature. The pH can be used as an indication for chemical changes as different materials are added to the ultra-soft soil. It is necessary to perform pH measurement before and after the treatment process since the pH method can be used as a non-destructive chemical monitoring technique.

3.6. ELECTRICAL RESISTIVITY

The untreated and treated ultra-soft soils were prepared in a 50 mm (dia.) x 100 mm (height) cylindrical plastic molds with two embedded wires in each mold to measure the electrical resistance using the AC measurement at the highest frequency of 300 kHz for the ultra-soft soil with different bentonite contents. Figure 4 shows the plastic mold configuration with the two embedded wires for the electrical property measurement.

The resistivity of the ultra-soft soil was measured using the conductivity meter and with the measured bulk resistance (R_b) at high frequency, a calibration factor was quantified, which could be used for measuring the changes in the electrical resistivity for the ultra-soft soil.

The following relationship was used to determine the calibration factor:

$$R_b = k * \rho \tag{3}$$

where: R_b is the bulk resistance which was measured using the LCR device, r is the electrical resistivity which measured using the conductivity meter, k is the calibration factor.

Hence, the change in the relative resistivity ($\Delta\rho/\rho$) can be related to the change in the resistance as follows:

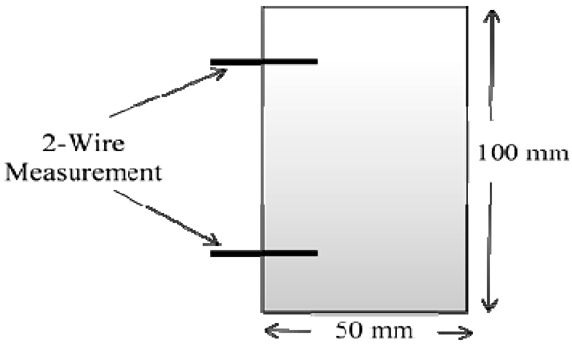


Fig. 4 Plastic mold configuration.

$$\frac{\Delta\rho}{\rho} = \frac{\Delta R}{R} \tag{4}$$

3.7. FINITE ELEMENT MODELING

An elasto-plastic Mohr-Coulomb model was selected to represent the non-linear behavior of ultra-soft soils in this study. Limiting states of stress are described by means of the undrained shear strength of the ultra-soft soil. The initial stresses in the case of ultra-soft soil were generated using Jaky's formula which gives the at rest earth pressure coefficient $K_o = 1 - \sin\phi$ where ϕ is the friction angle in terms of effective stress.

4. COMPARISON OF CORRELATIONS PREDICATION

In order to determine the accuracy of the correlations developed in this study, both coefficient of determination (R^2) and the root mean square error (RMSE) were used and defined in Eqs. (5) and (6) as follows:

$$R^2 = \left(\frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} \sqrt{\sum_i (y_i - \bar{y})^2}} \right)^2 \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - x_i)^2}{N}} \tag{6}$$

where y_i is the actual value; x_i is the calculated value from the model; $\bar{y}$ is the mean of actual values; $\bar{x}$ is the mean of the predicted values and N is the number of data points.

5. RESULTS AND DISCUSSION

5.1. MINIATURE CIGMAT PENETROMETER

Shear strength versus penetration

(i) Untreated ultra-soft soil

As shown in Figure 5a, the penetration depth linearly decreased with shear strength of the ultra-soft soil. With the 7 gm penetrometer, the penetration of 80 mm for 2 % bentonite with a shear strength of 0.02 kPa reduced to 20 mm for 10 % bentonite with a shear strength of 0.17 kPa. With the 28 gm penetrometer, the penetration of 130 mm for 2 % bentonite with a shear strength of 0.02 kPa reduced to 35 mm for 10 % bentonite with a shear strength of 0.17 kPa. Increasing the weight of the penetrometer from 7 gm to 28 gm increased the penetration from 80 mm to 130 mm, a 63 % increase in penetration depth for ultra-soft soil of 0.02 kPa in shear strength (2 % bentonite content). Increasing the weight from 7 gm to 28 gm increased the penetration from 20 mm to 35 mm, a 75 % increase in penetration depth for ultra soft soil of 0.17 kPa in shear strength (10 % bentonite content).

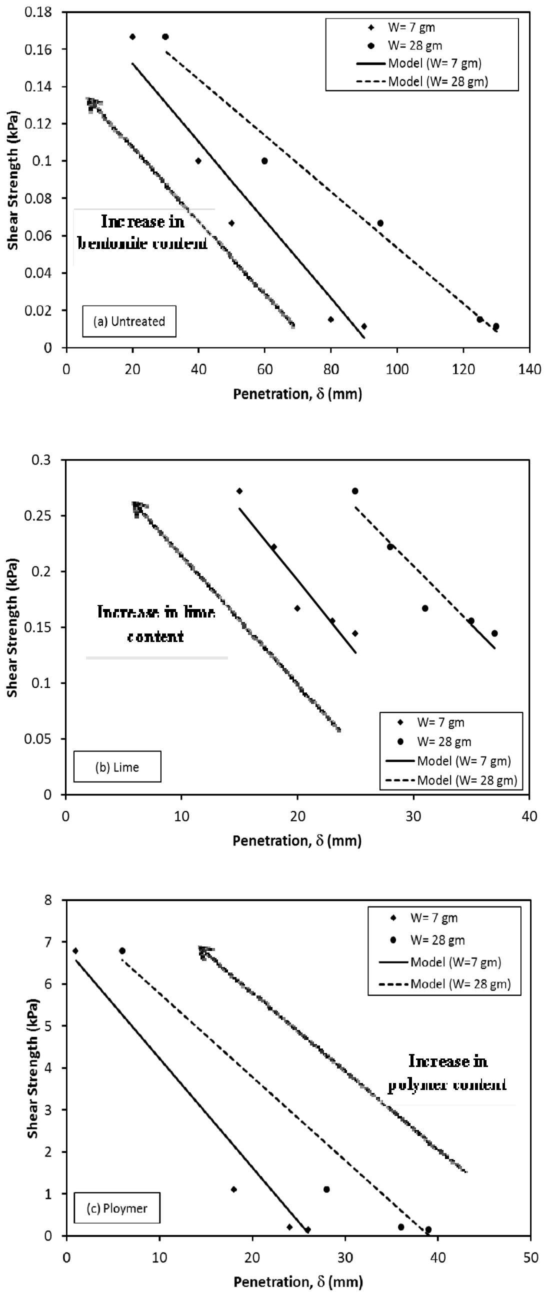


Fig. 5 Relationship between shear strength and CIGMAT penetrometer penetration (a) untreated ultra-soft soil, (b) 10 % bentonite ultra-soft soil treated with lime and (c) 10 % bentonite ultra-soft soil treated with polymer.

(ii) Lime treatment

As shown in Figure 5b, the penetration depth linearly decreased with shear strength of the ultra-soft soil. With the 7 gm penetrometer, the penetration of 25 mm for 10 % lime treatment with a shear strength of 0.14 kPa reduced to 15 mm for 2 % lime treatment with a shear strength of 0.27 kPa. With the 28 gm penetrometer, the penetration of 37 mm for 10 % lime treatment with a shear strength of 0.14 kPa reduced to 25 mm for 2 % lime treatment with a shear strength of 0.27 kPa. Increasing the weight of the penetrometer from 7 gm to 28 gm increased the penetration from 25 mm to 37 mm, a 48 % increase in penetration depth for ultra-soft soil of 0.14 kPa in shear strength (10 % lime treatment). Increasing the weight from 7 gm to 28 gm increased the penetration from 15 mm to 25 mm, a 67 % increase in penetration depth for ultra soft soil of 0.27 kPa in shear strength (2 % lime treatment).

(iii) Polymer treatment

As shown in Figure 5 c, the penetration depth linearly decreased with shear strength of the ultra-soft soil. With the 7 gm penetrometer, the penetration of 26 mm for 1 % polymer treatment with a shear strength of 0.15 kPa reduced to 1 mm for 10 % polymer treatment with a shear strength of 6.8 kPa. With the 28 gm penetrometer, the penetration of 39 mm for 1 % polymer treatment with a shear strength of 0.15 kPa reduced to 6 mm for 10 % polymer treatment with a shear strength of 6.8 kPa. Increasing the weight of the penetrometer from 7 gm to 28 gm increased the penetration from 26 mm to 39 mm, a 50 % increase in penetration depth for ultra-soft soil of 0.15 kPa in shear strength (1 % polymer treatment). Increasing the weight from 7 gm to 28 gm increased the penetration from 1 mm to 6 mm, a 500 % increase in penetration depth for ultra soft soil of 6.8 kPa in shear strength (10 % polymer treatment).

(iv) Model penetrometer

The linear correlation between the shear strength (τ) and CIGMAT penetrometer penetration can be represented as follows:

$$\tau = D + E * \delta \tag{7}$$

where τ (kPa) is the shear strength, δ (mm) is the CIGMAT penetration depth, D (kPa) and E (kPa/mm) are the two model parameters.

The model parameters (Eq. 7) for both untreated and treated ultra-soft soil parameters are summarized in Table 2.

5.2. pH

(i) Untreated ultra-soft soil

The relationship between the measured pH and bentonite content for the ultra-soft soils is shown in Figure 6. Initially, the tap water without bentonite had a pH of 7.5 and with the addition of 2 % bentonite to the tap water then the pH increased to 7.7 and remained constant with the addition of 10 % bentonite.

(ii) Lime treatment

The relationship between the pH and treating 10 % bentonite ultra soft soil with varying lime content is shown in Figure 6. The lime addition increased the pH of the treated ultra-soft soil. As the lime content was increased from 0 % to 10 %, the pH changed from 7.7 to 9.4 with a 22 % increase.

Table 2 Correlation of shear strength parameters for untreated and treated ultra-soft soil.

CIGMAT penetrometer weight (gm)	*D* (kPa)	*E* (kPa/mm)	R^2	*RMSE* (kPa)
Untreated ultra-soft soil				
7	0.19	-0.0021	0.94	0.014
28	0.20	-0.0015	0.98	0.0075
Lime treated ultra-soft soil (10 % bentonite)				
7	0.45	-0.0129	0.90	0.0154
28	0.52	-0.0105	0.89	0.0153
Polymer treated ultra-soft soil (10 % bentonite)				
7	6.83	-0.26	0.96	0.512
28	7.77	-0.20	0.95	0.536

Table 3 Resistivity-solid content model parameters for untreated and treated ultra-soft soil.

Ultra-soft soil	*m*	*n*	R^2	*RMSE* (Ohm.m)
untreated	10.5	-0.65	0.97	0.25
lime treated	0.94	-0.40	0.99	0.035
polymer treated	7.91	-1.20	0.99	0.074

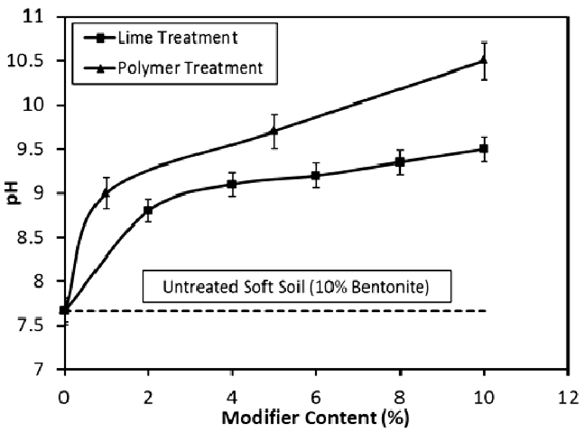


Fig. 6 Variation of pH with modifier content (lime and polymer) for 10 % bentonite ultra-soft soil (bars represent the standard deviation).

(iii) Polymer treatment

The relationship between the pH and treating 10 % bentonite ultra soft soil with varying polymer content is shown in Figure 6. The polymer addition increased the pH of the treated ultra-soft soil. As the polymer content was increased from 0 % to 10 %, the pH changed from 7.7 to 10.4 with a 3 5% increase.

5.3. ELECTRICAL RESISTIVITY

Electrical resistivity versus solid content

(i) Untreated ultra-soft soil

The variation of the electrical resistivity with bentonite content for the untreated ultra-soft soil is shown in Figure 7a. In the untreated ultra-soft soil, the electrical impedance decreased when the frequency was increased. Thus, all the bulk resistance was measured at high frequency (300 kHz). As the bentonite content was increased, the electrical resistivity decreased due to the increase in the conductivity of the medium. As the bentonite content was increased from 2 % to 10 %, the relative electrical resistivity ($\Delta\rho/\rho$) decreased by 246 %.

(ii) Lime treatment

The variation of the electrical resistivity with lime content for the lime treated ultra-soft soil is shown in Figure 7b. As the lime content was increased, the electrical resistivity decreased due to the increase in the conductivity of the medium. As the lime content was increased from 2 % to 10 %, the relative electrical resistivity ($\Delta\rho/\rho$) decreased by 171 %. In the lime treated ultra-soft soil, increasing the lime content had decreased the impedance of the treated ultra-soft soil since the lime had the tendency to increase the conductivity of the media content.

(iii) Polymer treatment

The variation of the electrical resistivity with polymer content for the polymer treated ultra-soft soil is shown in Figure 7c. As the polymer content was increased, the electrical resistivity decreased due to the increase in the conductivity of the medium. As the polymer content was increased from 1 % to 10 %, the relative electrical resistivity ($\Delta\rho/\rho$) decreased by 545 %. In the polymer treated ultra-soft soil, increasing the polymer content had decreased the impedance of the treated ultra-soft soil due to the increase in the conductivi ty of the medium with higher polymer content.

(iv) Modeling

Based on the experimental results, a power law model was developed to predict the relationship between the electrical resistivity and solid content for untreated and treated ultra-soft soil as follows:

$$\rho = m * (\beta)^n \tag{8}$$

where ρ (Ohm.m) is the electrical resistivity, $\beta(\%)$ represent the bentonite content in the ultra-soft soil and modifier content for the treated 10 % bentonite soft soils, m & n are model parameters.

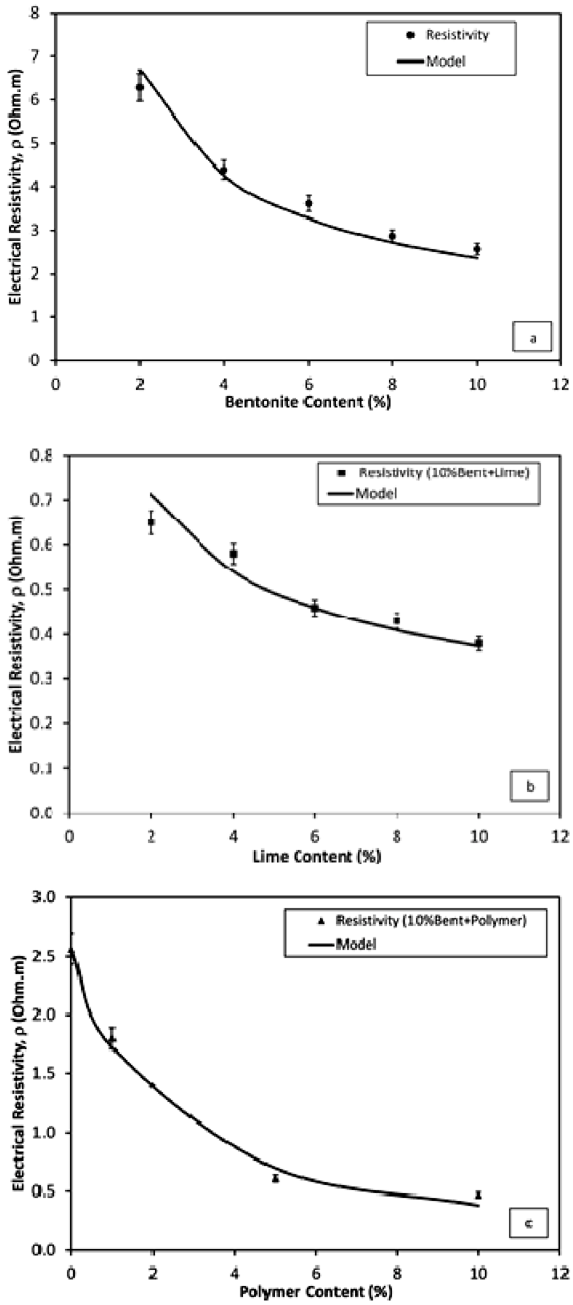


Fig. 7 Variation of electrical resistivity with bentonite and modifier contents (a) untreated ultra-soft soil, (b) 10 % bentonite ultra-soft soil treated with lime and (c) 10 % bentonite ultra-soft soil treated with polymer(bars represent the standard deviation).

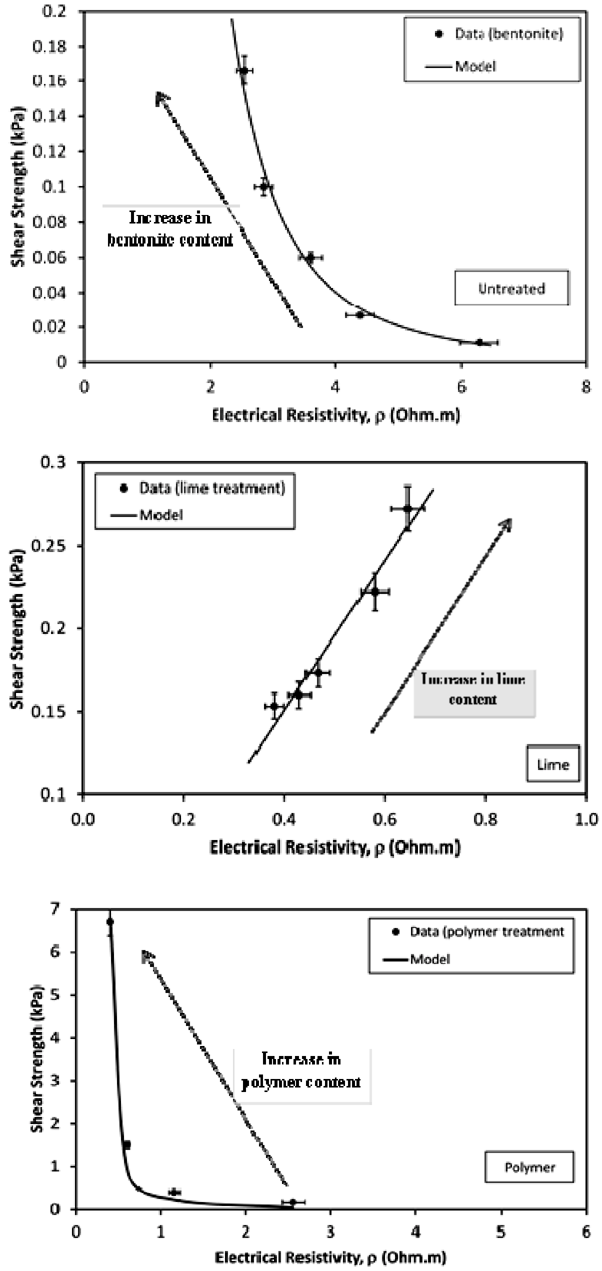


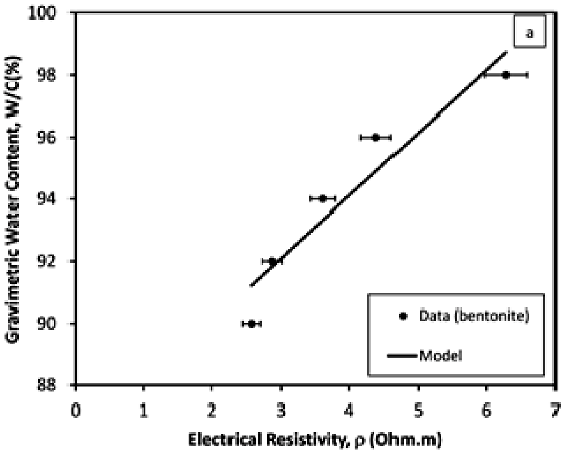
Fig. 8 Variation of the shear strength with electrical resistivity (a) untreated ultra-soft soil, (b) treated 10% bentonite ultra-soft soil with lime and (c) treated 10% bentonite ultra-soft soil with polymer(bars represent the standard deviation).

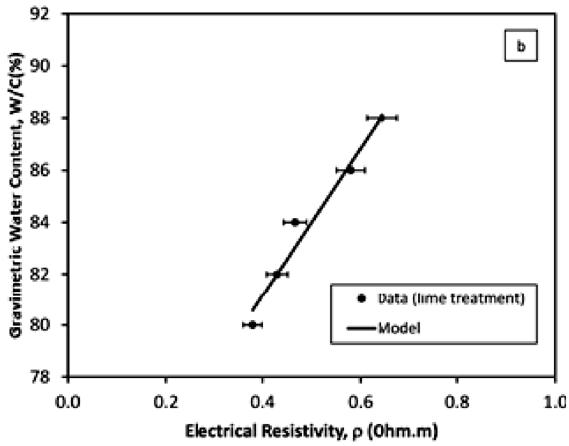
The proposed model predicted the experimental data very well (Figure 7a-c). The model parameters (Eq. 8) for the untreated and treated ultra-soft soils are summarized in Table 3. This correlation can be used as a nondestructive measurement to obtain the solid content in the ultra-soft soil where the solid or modifier content depends on the model parameters (m and n).

Shear strength versus electrical resistivity

(i) Untreated ultra-soft soil

The variation of the shear strength with electrical resistivity for untreated ultra-soft soils are shown in Figure 8a. As the electrical resistivity decreased, the shear strength of the untreated ultra-soft soil is increased. As the shear strength for the untreated ultra-soft soil was increased from 0.011 kPa to 0.17 kPa, the relative electrical resistivity ($\Delta\rho/\rho$) decreased by 59 %.





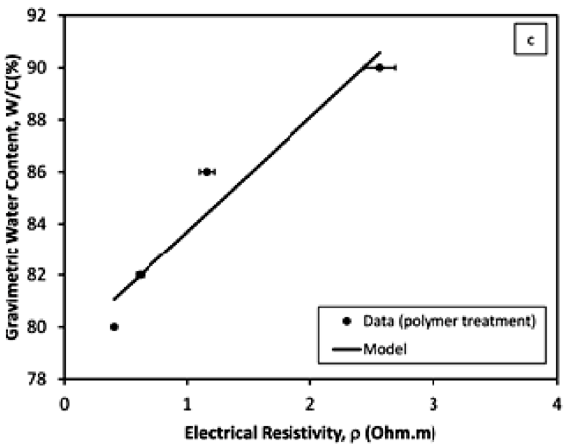


Fig. 9 Variation of gravimetric water content with electrical resistivity (a) untreated ultra-soft soil, (b) 10% bentonite ultra-soft soil treated with lime and (c) 10% bentonite ultra-soft soil treated with polymer(bars represent the standard deviation).

(ii) Lime treatment

The variation of the shear strength with electrical resistivity for the 10 % bentonite ultra-soft soil treated with lime is shown in Figure 8b. As the electrical resistivity increased, the shear strength for the lime treated soft soil is increased. As the shear strength for lime treated soft soil increased from 0.14 kPa to 0.27 kPa, the relative electrical resistivity ($\Delta\rho/\rho$) increased by 51 %.

(iii) Polymer treatment

The variation of the shear strength with electrical resistivity for the 10 % bentonite ultra-soft soil treated with polymer is shown in Figure 8c. As the shear strength the increased, the electrical resistivity for the polymer treated soft soil decreased. As the shear strength of polymer treated soft soil increased from 0.045 kPa to 6.8 kPa, the relative electrical resistivity ($\Delta\rho/\rho$) decreased by 77 %.

(iv) Modeling

Untreated ultra-soft soil

Based on the experimental results, a power law model is proposed to predict the relationship between the shear strength (τ) and electrical resistivity for the untreated ultra-soft soil as follows:

$$\tau = Q*(\rho)^P \tag{9}$$

where ρ is the electrical resistivity and Q & P are the two model parameters.

The proposed model predicted the experimental data very well. The untreated ultra-soft soil parameters (Eq. 9) are summarized in Table 4.

Lime treatment

Based on the experimental results, a linear model is proposed to predict the relationship between the shear strength and electrical resistivity for the lime treated ultra-soft soil as follows:

$$\tau = G + H*\rho \tag{10}$$

where ρ is the electrical resistivity, G & H are the two model parameters.

The proposed model predicted the experimental data very well. The model parameters (Eq. 10) are summarized in Table 4.

Polymer treatment

Based on the experimental results, a hyperbolic model is proposed to predict the relationship between the shear strength and electrical resistivity for the polymer treated ultra-soft soil as follows:

$$\tau - \tau_0 = \frac{(\rho-\rho_0)}{v + w*(\rho-\rho_0)} \tag{11}$$

where τ_o and ρ_o are initial shear strength and electrical resistivity of ultra-soft soil before treatment, ρ is the electrical resistivity and V & W are the two model parameters.

The proposed model predicted the experimental data very well. The model parameters (Eq. 11) are summarized in Table 5.

Water content versus electrical resistivity

(i) Untreated ultra-soft soil

The variation of the gravimetric water content (percentage of water) with electrical resistivity for the untreated ultra-soft soil is shown in Figure 9a. As the gravimetric water content increased, the electrical resistivity for the untreated ultra-soft soil is increased.

Table 4 Resistivity-shear model parameters for untreated and lime treated ultra-soft soil.

Resistivity	*Q*	*P*	R^2	*RMSE* (kPa)
Untreated ultra-soft soil	3.2	-3.280	0.94	0.0137
Lime treated ultra-soft soil (10 % bentonite)	*G*	*H*	R^2	*RMSE* (kPa)
	-0.044	0.472	0.92	0.0134

Table 5 Resistivity-shear model parameters for polymer treated ultra-soft soil.

Resistivity	r_o (Ohm.m)	V	W	R^2	RMSE (kPa)
Polymer treated ultra-soft soil (10 % bentonite)	0.4	-0.005	-0.146	0.99	0.1133

Table 6 Gravimetric water content-resistivity model parameters for untreated and treated ultra-soft soil.

Resistivity	*X*	*Y*	R^2	*RMSE*
Untreated ultra-soft soil	86.02	2.02	0.91	0.86
Lime treated ultra-soft soil (10 % bentonite)	69.8	28.4	0.97	0.49
Polymer treated ultra-soft soil (10 % bentonite)	79.3	04.4	0.93	0.99

Table 7 Values of soil parameters used in FEM analyses.

Parameter	Untreated ultra-soft soil	Treated ultra-soft soil
Unit weight, g (kN/m^3)	11	11.5
Elastic modulus (kN/m^2)	100	300
Shear strength (kN/m^2)	0.17	6.8
Poisson's ratio m	0.45	0.45
At rest earth pressure coefficient K_o	0.82	0.82

As the gravimetric water content for untreated ultra-soft soil increased from 90 % to 98 %, the relative electrical resistivity ($\Delta\rho/\rho$) increased by 145 %.

(ii) Lime treatment

The variation of the gravimetric water content (percentage of water) with electrical resistivity for the 10 % bentonite ultra-soft soil treated with lime is shown in Figure 9b. As the gravimetric water content for the lime treated soft soil increased, the electrical resistivity also increased. As the gravimetric water content for the lime treated soft soil was increased from 80 % to 88 %, the relative electrical resistivity ($\Delta\rho/\rho$) increased by 71 %.

(iii) Polymer treatment

The variation of the gravimetric water content (percentage of water) with electrical resistivity for the 10 % bentonite ultra-soft soil treated with polymer is shown in Figure 9c. As the gravimetric water content for the polymer treated soft soil increased, the electrical resistivity also increased. As the gravimetric water content for polymer treated soft soil was increased from 80 % to 90 %, the relative electrical resistivity ($\Delta\rho/\rho$) increased by 540 %.

(iv) Modeling

Based on the experimental results, a linear model is proposed to predict the relationship between the gravimetric water content (percentage of water) and the electrical resistivity for untreated and treated ultra-soft soil as follows:

$$W/C = X + Y * \rho \quad (12)$$

where *W/C* (%) is the gravimetric water content, ρ is the electrical resistivity, *X* & *Y* are the two model parameters.

The proposed model predicted the experimental data very well. The model parameters (Eq. 12) for both untreated and treated ultra-soft soil are summarized in Table 6. This correlation can be also used as a nondestructive measurement to obtain the water content in the ultra-soft soil where the water content in the ultra-soft soil depends on the model parameters (*X* and *Y*).

5.4. FINITE ELEMENT MODELING

CIGMAT miniature penetrometer

Values of soil parameters used in this investigation are summarized in Table 7. Finite element modeling (FEM) was executed on the CIGMAT penetrometer using the 3-D axisymmetric analyses. The FEM used 545 elements of 15-noded triangular elements with 975 nodes having an average element size of 0.42 mm to provide sufficient accuracy in stress evaluation. The meshes were chosen to match the corresponding prototype geometries in the experimental model test. Also, there was a full fixed at the base of the geometry and smooth conditions at the vertical sides. Loading was applied in very small increments up to the total load.

Shear strength-penetration relationship.

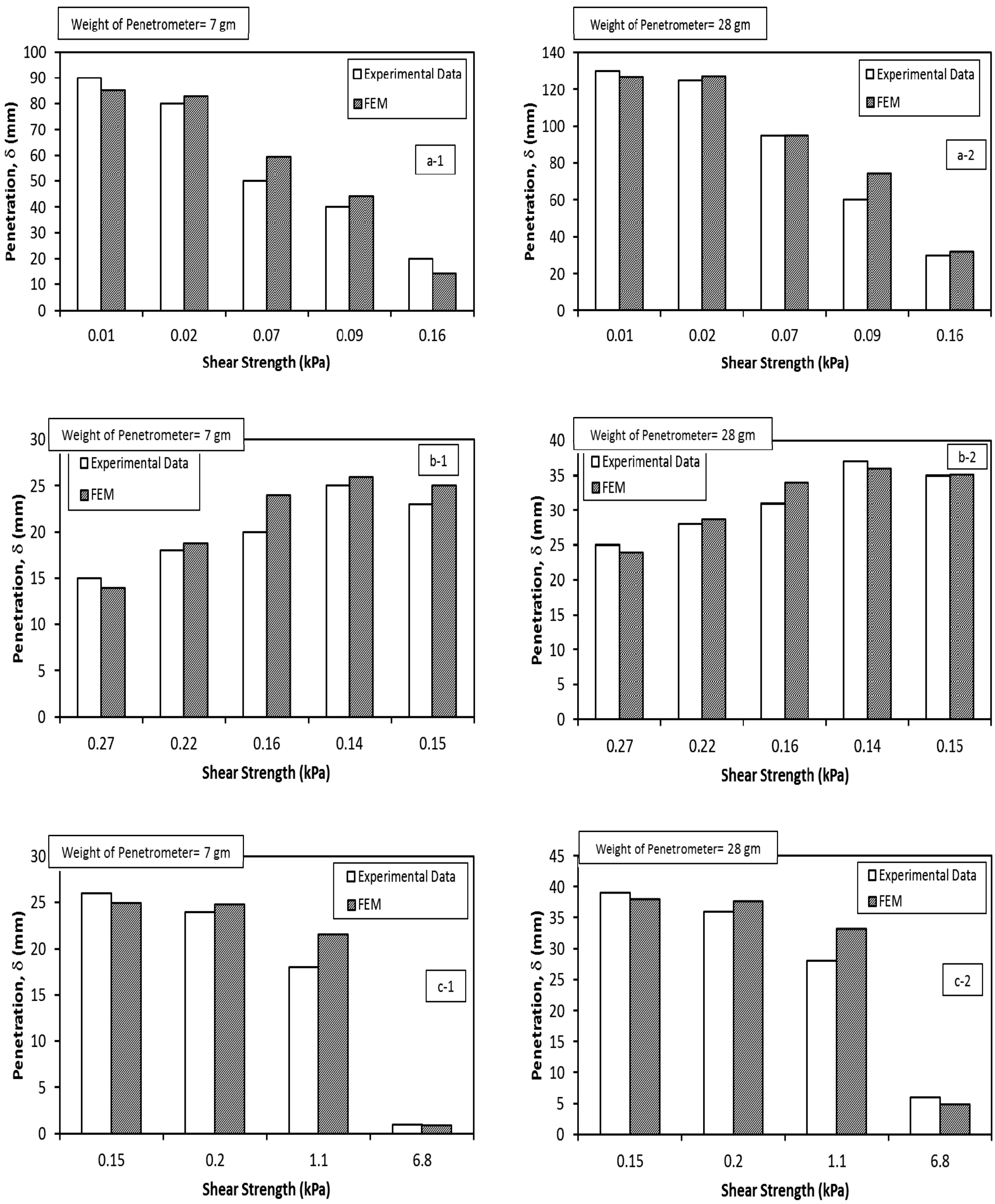


Fig. 10 Comparing the predicted (FEM) and experimental CIGMAT miniature penetrometer penetration (a) untreated ultra-soft soil (b) 10 % bentonite ultra-soft soil treated with lime, and (c) 10 % bentonite ultra-soft soil treated with polymer.

Finite element modeling of shear strength versus CIGMAT penetration for the untreated and treated ultra-soft soils with lime and polymer are shown in Figure 10a-c. The numerical modeling agreed with the experimental data for untreated and treated ultra-soft soils. The R^2 and RMSE for untreated ultra-soft soil were 0.95 and 5.9 mm, 0.97 and 6.7 mm for 7 gm and 28 gm CIGMAT penetrometers respectively. The R^2 and RMSE for the treated ultra-soft soil with lime were 0.63 and 2.1 mm, 0.87 and 1.5 mm for 7 gm and 28 gm CIGMAT penetrometer respectively. The R^2 and RMSE for treating ultra-soft soil with polymer were 0.96 and 1.9 mm, 0.95 and 2.9 mm for 7 gm and 28 gm CIGMAT penetrometer respectively.

6. CONCLUSION

In this study, lime and polymer treated ultra-soft soils were characterized using both electrical resistivity and CIGMAT miniature penetrometer. Based on the experimental and analytical studies, the following conclusions are advanced:

4. Miniature CIGMAT penetrometer can be used as an in-situ instrument to measure the shear strength of the ultra-soft soil since the penetrometer penetration is linearly correlated to the shear strength of the untreated and treated ultra-soft soils.
5. Untreated ultra-soft soil with different bentonite content was independent on pH. However, ultra-soft soil treated with lime or polymer was shown an increase in the pH as the treated agent increased. For the treated ultra-soft soil, the polymer has shown more increase in the pH in comparison with the lime.
6. The electrical resistivity for the untreated and treated ultra-soft soils are nonlinearly function and inversely dependent on the bentonite, lime and polymer content where the electrical resistivity can be used as a nondestructive approach to investigate the material type and content.
7. The electrical resistivity can be used to measure the shear strength of the untreated and treated ultra-soft soils nondestructively. The untreated ultra-soft soil exhibited a nonlinear inverse relationship for the electrical resistivity with the shear strength. However, the lime-treated ultra-soft soil adopted a linear increase of the electrical resistivity with the shear strength. In contrary to the lime treated ultra-soft soil, the polymer-treated ultra-soft soil maintained a nonlinear hyperbolic inverse relationship for the electrical resistivity with the shear strength.
8. The electrical resistivity can be used to evaluate the gravimetric water content of the untreated and treated ultra-soft soils indirectly. A linear inverse relationship for the electrical resistivity with gravimetric water content for both untreated and treated ultra-soft soil is observed.
9. Miniature CIGMAT penetrometer penetrations into untreated and treated ultra-soft soils were modelled using the finite element method (FEM). FEM prediction of penetration in various ultra-soft soils agreed well with the experimental results.

ACKNOWLEDGMENT

This study was supported by the Center for Innovative Grouting Materials and Technology (CIGMAT), University of Houston, Houston, Texas.

REFERENCES

Ali, F.H., Adnan, A. and Choy, C.K.: 1992, Geotechnical properties of a chemically stabilized soil from Malaysia with rice husk ash as an additive. Geotechnical and Geological Engineering, 10, No. 2, 117–134. DOI: 10.1007/BF00881147

Anggraini, V., Asadi, A., Huat, B.B.K. and Nahazanan, H.: 2015, Performance of chemically treated natural fibres and lime in soft soil for the utilisation as pile-supported earth platform. International Journal of Geosynthetics and Ground Engineering, 1, 28. DOI 10.1007/s40891-015-0031-5

Bartos, M.J.: 1977, Classification and engineering properties of dredged material. Technical Report D-77-18, U.S. Army Waterways Experiment Station, Vicksburg, MS.

Bevan, B.W.: 2000, An early geophysical survey at Williamsburg, USA. Archaeological Prospection, 7, No. 1, 51–58. DOI: 10.1002/(SICI)1099-0763(200001/03)7:1<51::AID-ARP128>3.0.CO;2-I

Bo, M.W., Choa, V. and Wong, K.S.: 2010, Constant rate of loading test on ultra-soft soil. Geotechnical Testing Journal, 33, No. 3, 192–200.

Casagrande, A.: 1958, Notes on the design of the liquid limit device. Geotechnique, 8(2), 84–91. DOI: 10.1680/geot.1958.8.2.84

De Meyer, C.P. and Mahlerbe, B.: 1987, Optimisation of maintenance dredging operations in maritime and estuarine areas. Terra et Aqua, 35, 25–39.

De Jong, J., Yafrate, N. and De Groot, D.: 2011, Evaluation of undrained shear strength using full-flow penetrometers. Journal of Geotechnical and Geoenvironmental Engineering, 137, No. 1, 14–26. DOI: 10.1061/(ASCE)GT.1943-5606.0000393

Hasan, M. and Samadhiya, N.K.: 2016, Experimental and numerical analysis of geosynthetic-reinforced floating granular piles in soft clays. International Journal of Geosynthetics and Ground Engineering, 2, No. 3, Article Number 22. DOI 10.1007/s40891-016-0062-6

Hawkins, R.A. and Markus, A.: 1998, New development in offshore geotechnical investigations. Proceeding International Conference Offshore Site Investigations and Foundation Behavior, SUT, London, 259–276.

Hebib, S. and Farrell, E.R.: 2003, Some experiences on the stabilization of Irish peats. Canadian Geotechnical Journal, 40, No. 1, 107–120. DOI: 10.1139/T02-091

Johnson, G.W., Hamilton, T.W., Ebelhar, R.J., Mueller, J.L. and Pelletier, J.H.: 1988, Comparison of in situ vane, cone penetrometer and laboratory test results for Gulf of Mexico deepwater clays. Vane Shear Strength Testing of Soils, Field and Laboratory Studies, ASTM STP 1014, 293–305. DOI: 10.1520/STP10337S

Kaya, A. and Fang, H.Y.: 1997, Identification of contaminated soils by dielectric constant and electrical conductivity. Journal of Environmental Engineering-ASCE, 123, No. 2, 169–177. DOI: 10.1061/(ASCE)0733-9372(1997)123:2(169)

Low, H.E., Lunne, T., Andersen, K.H., Sjursen, M.A., Li, X. and Randolph, M.F.: 2010, Estimation of intact undrained shear strength from penetration tests in soft clays. Geotechnique, 60, No.11, 843–859. DOI: 10.1680/geot.9.P.017

Lunne, T.: 2001, In situ testing in offshore geotechnical investigations. Proceeding International Conference on In Situ Measurement of Soil Properties and Case Histories, Bali, 61–81.

Muntohar, A.S.: 2004, Uses of RHA to enhanced lime-stabilized clay soil. International Conference on Geotechnical Engineering, Sharjah, UAE, 356–357.

Nader, A., Fall, M. and Hache, R.: 2015, Characterization of sensitive marine clays by using cone and ball penetrometers: example of clays in eastern Canada. Geotechnical and Geological Engineering, 33, No. 4, 841–864. DOI: 10.1007/s10706-015-9864-x

Nagaraj Hone, B., Sridharan, A. and Mallikarjuna, H.M.: 2012, Re-examination of undrained strength at Atterberg limits water contents. Geotechnical and Geological Engineering, 30, No. 4, 727–736. DOI:10.1007/s10706-011-9489-7

Norman, L.E.J.: 1958, A comparison of values of liquid limit determined with apparatus having bases of different hardness. Géotechnique, 8(2), 79–83. DOI: 10.1680/geot.1958.8.2.79

Pourakbar, S., Huat, B.B.K., Asadi, A. and Fasihnikoutalab, M.H.: 2016, Model study of alkali-activated waste binder for soil stabilization. International Journal of Geosynthetics and Ground Engineering, 2, No. 4, Article number 35. DOI 10.1007/s40891-016-0075-1

Rad, N. and Lunne, T.: 1986, Correlations between piezocone results and laboratory soil properties. Norwegian Geotechnical Institute, Oslo.

Raheem, A.M., Vipulanandan. C. and Joshaghani, M.S.: 2017, Non-destructive experimental testing and modeling of electrical impedance behavior of untreated and treated ultra-soft clayey soils. Journal of Rock Mechanics and Geotechnical Engineering, 9, No. 3, 543–550. DOI: 10.1016/j.jrmge.2017.02.001

Robain, H., Camerlynck, C., Bellier, C. and Tabbagh, A.: 2003, Laboratory measurements of electrical resistivity versus water content on small soil cores. Geophysical Research Abstracts, 5, 03830.

Samouëlian, A., Cousin, P.I., Tabbagh, P.A., Bruand, P.A. and Richard, P.G.: 2005, Electrical resistivity survey in soil science: a review. Soil & Tillage Research, 83, No. 2, 173–193. DOI: 10.1016/j.still.2004.10.004

Siddiqui, F.I. and Osman, S.: 2012, Integrating geo-electrical and geotechnical data for soil characterization. International Journal of Applied Physics and Mathematics, 2, No. 2, 104–106. DOI: 10.7763/IJAPM.2012.V2.63

Skemption, A.W. and Northey, R.D.: 1952, The sensitivity of clays. Geotechnique, 3, No. 1, 30–53. DOI: 10.1680/geot.1952.3.1.30

Stadelhofen, C.M.D.: 1991, Application of geophysics to water research. Ed. Lavoisier, Paris. 192 pp., (in French).

Stewart, D. and Randolph, M.: 2001, A new site investigation tool for the centrifuge. In Proceedings of the international conference modeling, Balkema Pub, The Netherlands, 531–538.

The, C.I. and Houlsby, G.T.: 1991, An analytical study of the cone penetration test in clay. Geotechnique, 41, No. 1, 17–34. DOI: 10.1680/geot.1991.41.1.17

Vipulanandan, C. and Prashanth, P.: 2013, Impedance spectroscopy characterization of a piezoresistive structural polymer composite bulk sensor. Journal of Testing and Evaluation, 41, No. 6, 898–904. DOI: 10.1520/JTE20120249

Vipulanandan, C., and Raheem, A.M.: 2015, Characterizing ultra-soft soils and anchor-soil interaction for deepwater applications, Proceedings of the Twenty-fifth International Ocean and Polar Engineering Conference Kona, Big Island, Hawaii, USA, June 21-26, 1048–1054.

Wroth, C.P. and Wood, D.M.: 1978, The correlation of index properties with some basic engineering properties of soils. Canadian Geotechnical Journal, 15, No. 2, 137–145. DOI: 10.1139/t78-014

Young, A.G., McClelland, B. and Quiros, G.W.: 1988, In situ vane testing at sea, Vane shear Strength Testing of Soils: Field and Laboratory Studies. ASTM STP 1014, 46–67. DOI: 10.1520/STP10321S

Youseff, M.S, El Ramli, A.H. and El Demery, M.: 1965, Relationships between shear strength, consolidation, liquid limit, and plastic limit for remoulded clays. Proceedings 6th international conference on soil mechanics and foundation engineering, 1. Montreal, 126–129.