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Modeling the Undrained Shear Strength with Soil Index Properties for Niger Delta Soft Clays

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Abstract

The aim of this study was to model the Undrained Shear Strength (USS) of soil found in the coastal region of the Niger Delta in Nigeria with some soil properties. The undrained shear strength (USS) is a key parameter needed for most geotechnical/structural designs. Accurate determination of the USS of soft clays can be challenging to obtain in the laboratory due to the difficulty in remoulding the clay to its *in-situ* conditions before testing and more accurate test such as Cone Penetration test (CPT) can be quite expensive. This study was carried out at Escravos site which is located in Delta state, Nigeria. Three Boreholes were drilled and soil samples were collected at 0.75 m intervals up to a depth of 45 m. Laboratory tests were used to obtain the moisture content, bulk unit weight, liquid and plastic limit, while CPT was used in obtaining the undrained shear strength. Classification of the soil samples was done by adopting the Unified Soil Classification System and various models relating the USS with the soil properties were developed. The result showed that most of the soils at Escravos site were predominately inorganic clay of high plasticity which are problematic due to the expansion and shrinking nature of this type of soil. The model developed showed that the soil properties that gave the best fit with the USS were the moisture content and effective stress of the soil. The coefficient of determination (R^2) and the root mean square error (RMSE) obtained for this model were 0.805 and 6.37 KN/m^2, respectively.

Keywords

Undrained Shear Strength, Inorganic Clay, Escravos, Multiple Regression Modelling

1. Introduction

The Niger Delta region of Nigeria which is located in the southern region of the country has vast oil resources which are primarily found in offshore, near shore and onshore oilfields. Currently, oil and gas companies prefer exploration activities focused near shore, offshore, deep, and ultra-deep offshore as these energy companies seek to find sources of production in low-risk areas and also most of this remote basin may hold the promise of significant deposits of hydrocarbon [1]. For a successful exploration of oil and gas near shore or deep offshore, several oil and gas facilities namely: central tank batteries, produced water injection facilities, natural gathering compression stations etc. need to be built near the well site. Most near shore, offshore or deep offshore sites have soft or marine clay to several depths which are not suitable construction material. Soft or marine clay are usually soil with low shear strength and high compressibility which make geotechnical structural or any structural design on such type of soil often rather challenging [2]. Apart from the low shear strength associated with soft or marine clay, issues such as low bearing capacity and long term excessive settlement are always associated with these types of soils. In order to understand the soil behaviour of soft or marine clay, the undrained shear strength (USS) is a key parameter that needs to be determined in the soil investigation. The short-term undrained shear strength of soft soil is typically smaller than its long-term drained shear strength, and this has a significant impact on geotechnical or structural design [3]. Accurate determination of the undrained shear strength is crucial for the design of oil and gas platform/structures that would be required near oil and gas production sites. One of the most difficult soil parameters to determine accurately both in the field and the laboratory is the undrained shear strength of soft or marine clay [4]. The difficulty in determining the undrained shear strength in the laboratory is usually compounded with the fact that remoulding of the soft or Marine clay to its *in-situ* undisturbed state is usually extremely difficult while the determination of the USS using field test are usually capital intensive.

Several researchers have modelled the USS with other soil properties that are easier to obtain. These models can be used in cases where the USS cannot be directly measured or the measurements are deemed unreliable. [5] developed a model relating the normalized USS obtained from field vane test with the plasticity index for normally consolidated soil. [6] model, related the results of USS obtained from the fall cone test to effective stress which is still considered to represent typical soil behaviour in Scandinavian clays. [4] developed an empirical model that related the USS and the pre-consolidated pressure in Swedish soft clays. [3] adopted machine learning in modeling the USS of sensitive alluvial soft clay. Most of the models developed by researchers relating the USS with other clay properties are typically empirical or semi-empirical models. Empirical or semi-empirical models are usually site-specific which are developed by data fitting through regression analysis. However, such models must be carefully applied and their limitations be recognized, as soil properties, soil behaviour and site geology may differ from the data source from where the models are calibrated. [2] as a direct consequence, predictions from these models may result biased with respect to the actual property USS values. The aim of this study is to model the undrained shear strength of soft clay at Escravos site located in the Niger Delta region with the soil properties of the clay.

2. Methods

2.1. Study Area

The study area for the data collection is Escravos located within the Niger Delta region as shown in **Figure 1**. Escravos site, located in Delta state, is one of the nine oil-producing states within the Niger Delta region. The Niger Delta region is within the southern part of Nigeria. Although it occupies 90% of the Nigerian coastline, and it is specifically between the Mahin river estuary in the west and the Cross river estuary in the east [7]. The geographical area of the Niger Delta region covers a land area of over 70,000 sq·km with a population of over 31 million inhabitants, it is broadly viewed to comprise about 16,000 communities in the nine (9) oil producing states of Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo and Rivers; with over 40 different ethnic groups who speak more than 250 languages and dialects [8]. It is the third largest wetland in the world and considered the 4th largest mangrove area [9]. The delta is described as the home of extraordinary biodiversities, and is also endowed with several mineral deposits. The region has huge oil and gas reservoirs [10], ranking

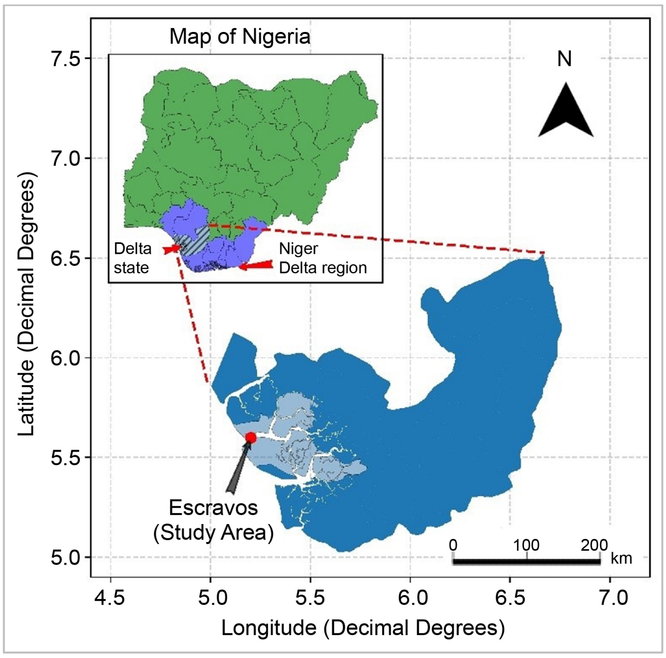

Figure 1. Map of study area.

as the 6th world's largest exporter of crude oil and 3^{rd} world largest producers of palm oil after Malaysia and Indonesia [11]. For many decades, the region has remained the backbone of the Nigerian economy, accounting for over 90% of the country's foreign exchange revenue [12]. The Niger Delta region produces immense oil wealth and has become Nigeria's "economic engine/driver". A total of 57 Multinational and private Nigerian companies have been licensed to explore and produce oil in the region [13] Government and Multinational oil companies earn substantial revenues and profits from oil and gas exports. Today, however, despite the enormous resources that are abound in the region, the region still has majority of its people living and dying in poverty [11].

2.2. Data Sampling and Method of instrumentation

Soil investigations were performed at Escravos site. A trial pit was first dug in other to understand the soil composition, after which drilling of the borehole commenced. Three Boreholes were drilled at the site up to a depth of 45m and soil samples were collected at 0.75 m intervals. After collecting the soil samples, the soils were placed in air-tight containers and taken to the laboratory to conduct the various soil tests. A total of thirteen soil samples were selected before commencing the laboratory test.

The laboratory used in conducting the various experimental procedures was in line with Nigeria regulatory requirements and adopted international best practises. The selected tests (e.g. liquid limit and plastic limit, water content etc.) were chosen and conducted because their soil properties have been indicated by several researchers to significantly affect the undrained shear strength of the soil. The liquid and plastic limits were obtained by adopting ASTM D4318-17e1 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. The water content of the soil was obtained by adopting ASTM D2216-19 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. The unit weight of the soft clay was obtained by adopting ASTM D7263-21 Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens.

Cone penetration test which is a field test was used in obtaining the undrained shear strength of the soil.

2.3. Data Analysis and Procedures

Various analyses were performed on the data obtained after the laboratory experiment. The classification of the soil was done adopting the Unified Soil Classification System (USCS). The relationship between the soil properties and the undrained shear strength (USS) was established using Pearson correlation. Regression modeling of the USS and the soil properties were also done. The regression modelling was done using Microsoft XLSTAT while the plotting of the soil classification chart was done using Seaborn which is a python graphical library package.

3. Results

3.1. Soil Classification at Escravos Site

The result of classification of the soft clay found in Escravos site is presented in **Figure 2**. **Figure 2** showed that all the soil samples tested were either clay of high plasticity, organic clay or silt of high compressibility. Also, **Figure 2** showed that nine of the thirteen soil samples tested were clay of high plasticity which counted for 69.2% of the total soil samples test. The remaining soil samples were either organic clay or silt of high plasticity which accounted for about 30.77% of the total soil sample tests which is presented in **Figure 3**.

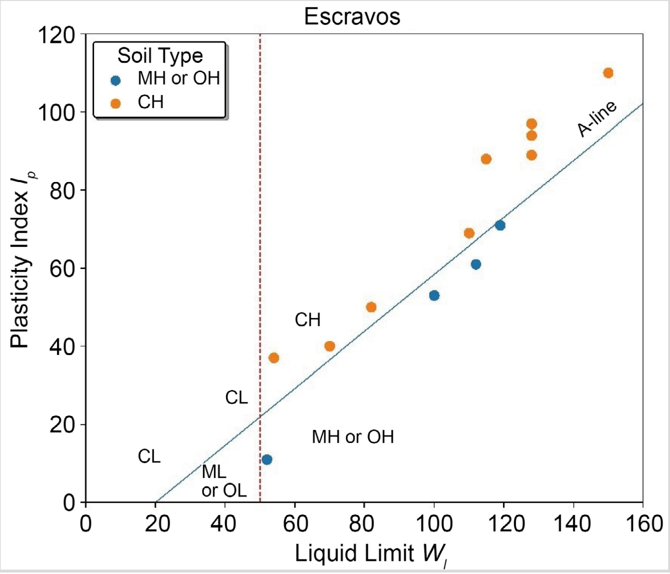

Figure 2. Escravos soil classification based on the Unified Soil Classification System.

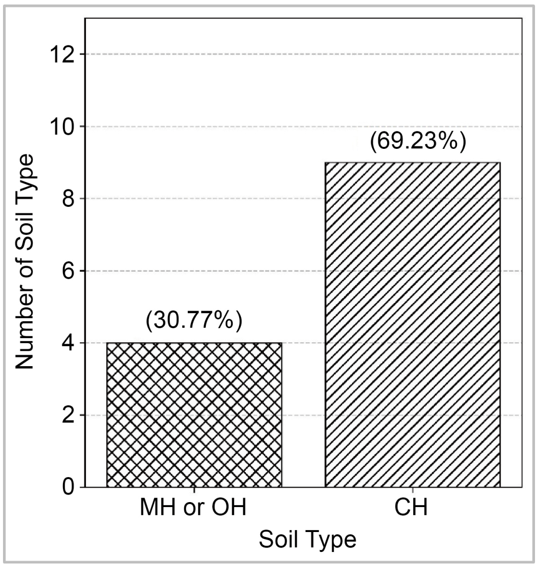

Figure 3. Count Plot showing the number of soil classifications based on the Unified Soil Classification System.

Descriptive statistics results for the soil index properties and USS for the soil samples at Escravos site are presented in **Table 1**. The USS of the soil samples ranged from 4 to 48 KN/m^2, with a mean value of 17.77 KN/m^2 and a standard deviation of 15.09 KN/m^2. The result from **Table 1** showed that all the soil at Escravos site is either soft or very soft clay based on the USS [14]. Murthy stated that clay soil with a USS less than 25 KN/m^3 has a consistency that could be described as very soft while clay soil with USS between 25 to 50 KN/m^3 can be described as a soft clay.

3.2. Pearson Correlation on Clay Properties

The result of Pearson's correlation coefficient of the soil index properties with the USS is presented in **Table 2**. **Table 2** shows that the R-value between the USS and the water content was −0.66 and the result was statistically significant at a level of significance of 5%. The result indicates that an increase in the water content in the soil samples will result to a corresponding decrease in the USS of

Table 1. Descriptive statistic of soil properties at Escravos site.

Variable	Mean	Median	SE Mean	StDev	CoefVar	Min.	Max.	Skewness	Kurtosis
Water content	92.79	93.62	6.52	23.51	25.34	43.00	124.10	−0.77	0.29
Unit wt wet	13.44	13.28	0.35	1.28	9.50	12.40	17.37	2.74	8.55
Unit wt dry	7.00	6.69	0.36	1.30	18.56	5.71	10.16	1.46	1.89
Unit wtsubm	3.63	3.47	0.35	1.28	35.18	2.59	7.56	2.74	8.55
Liquid limit	103.69	112.00	8.45	30.48	29.40	52.00	150.00	−0.56	−0.66
Plastic limit	37.00	39.00	2.57	9.26	25.04	17.00	51.00	−0.47	0.39
Plasticity Index	66.92	69.00	7.89	28.44	42.50	11.00	110.00	−0.35	−0.46
Undrained Shear Strength	17.77	13.00	4.19	15.09	84.95	4.00	48.00	1.15	0.37

Table 2. Pearson Correlation coefficient of the soil index properties with the undrained shear strength (USS) for Escravos site.

Variables	Water content	Unit wt wet	Unit wt dry	Unit wtsubm	LL	PL	PI	Undrained Shear Strength
Water content	**1.00**							
Unit wt wet	**−0.81**	**1.00**						
Unit wt dry	**−0.97**	**0.91**	**1.00**					
Unit wtsubm	**−0.81**	**1.00**	**0.91**	**1.00**				
LL	0.49	**−0.57**	**−0.59**	**−0.57**	**1.00**			
PL	0.48	−0.45	−0.55	−0.45	0.38	**1.00**		
PI	0.37	−0.47	−0.46	−0.47	**0.95**	0.08	**1.00**	
Undrained Shear Strength	**−0.66**	**0.63**	**0.65**	**0.63**	−0.37	−0.17	−0.34	**1.00**

Values in bold are different from 0 with a significance level alpha = 0.05.

the soil samples and *vice versa*. The result also showed that increase in the dry unit weight, wet unit weight, and submerged unit weight will result to a corresponding increase in the USS of the soil. The R-value between the liquid limit and the USS was −0.37, which indicate that increase in liquid limit will result to decrease in the USS of the soil samples but the relationship was not statistically significant.

3.3. Predictive Models for USS

The result of the 9 developed model relating the undrained shear strength and the soil properties is presented in Table 3. The first model developed related the undrained shear strength with the soil index properties using a multiple linear regression model but the result from the goodness of fit showed that the predictive power of the model was low due to the low coefficient of determination (R^2) and high root mean square error (RMSE). In order to improve the predictive power of the model several other model forms were adopted in fitting the USS with the soil properties and the result is presented in Table 3. The result from Table 3 showed that model 4 which related the USS with the water content and effective stress of the soil provided a good fit to the data with R^2 of 0.805, which indicates that 80.5% of the variation in the USS can be explained by the predictor variables (water content and effective stress). The RMSE of the multiple linear regression model was 6.37 KN/m^2, which indicates that on average, the prediction of the USS of the soil will be off by about 6.37 KN/m^2. It is worthy of note that a separate input data set were used for model calibration while a second data set were adopted for model verification. The result showed that other model forms (models 7 and 8) gave higher R^2 and lower RMSE but validating the models with the second input data set showed that the model with higher goodness of fit and lower RMSE performed poorly than model 4. The cross-validation plot of model 4 is presented in Figure 4 while the validation of the developed models with out of sample data (testing data) is presented in Table 4. The result from Figure 4 showed that the observed and predicted USS when plotted on a scatter plot were close to the 45 degree diagonal line which represent a good model fit.

Five models that gave good fit were validated using data obtained from two different site namely: Cawthrone channel and Chanomi, which were site situated within the Niger Delta region. For inorganic soil of high plasticity, model 5 predicted the best as the percentage difference between the actual and predicted USS ranged from −21.23% to 1.76%.

The percentage difference for model 7 which had a higher coefficient of determination (R^2) and lower RMSE ranged from −23.89% to 7.91% while the percentage difference for model 8 ranged from −4.59% to 77.10%. The lower predictive power of models 7 and 8 with 4 independent variables (water content, effective, plastic limit and liquid limit) in comparison with model 4 despite both models having lower R^2 and lower RMSE can be attributed to the influence of the extra two independent variables (liquid & plastic limits). Therefore model 4

Table 3. Model Development Summary.

S/No	Model Type	Model Equation Form	Independent Variables	Model Parameter	Goodness of fit indices	Remark
1	Multiple Linear Regression	$y = a_o + a_1X_1 + a_2X_2$ $+a_3X_3 + a_4X_4$	X_1 = Water Content X_2 = Dry Density X_3 = Liquid Limit X_4 = Plasticity Index	$a_0 = -42.314$ $a_1 = -0.084$ $a_2 = 7.627$ $a_3 = 0.394$ $a_4 = -0.396$	$R^2 = 0.478$ MSE = 178.62 RMSE = 13.37	Model unacceptable
2	Simple Linear Regression	$y = a_o + a_1X_1$	X_1 = Water Content	$a_0 = 57.040$ $a_1 = -0.423$	$R^2 = 0.478$ MSE = 178.62 RMSE = 13.37	Model unacceptable
3	Multiple Linear Regression	$y = a_o + a_1X_1 + a_2X_2$	X_1 = Water Content X_2 = Effective stress	$a_0 = 35.628$ $a_1 = -0.238$ $a_2 = 0.036$	$R^2 = 0.510$ MSE = 133.91 RMSE = 11.57	Model unacceptable
4	Multiple Linear Regression (Outlier removed)	$y = a_o + a_1X_1 + a_2X_2$	X_1 = Water Content X_2 = Effective stress	$a_0 = 29.23$ $a_1 = -0.205$ $a_2 = 0.043$	$R^2 = 0.805$ MSE = 40.612 RMSE = 6.37	Model acceptable
5	Multiple Quadratic Regression (Outlier removed)	$y = a_o + a_1X_1 + a_2X_2$ $+a_3X_3^2 + a_4X_4^2$	X_1 = Water Content X_2 = Effective stress X_3 = Water Content X_4 = Effective stress	$a_0 = 66.497$ $a_1 = -1.098$ $a_2 = 0.0696$ $a_3 = 0.0049$ $a_4 = -7E-5$	$R^2 = 0.828$ MSE = 46.03 RMSE = 6.785	Model acceptable
6	Multiple Linear Regression (Outlier removed)	$y = a_o + a_1X_1 + a_2X_2$ $+a_3X_3 + a_4X_4$	X_1 = Water Content X_2 = Liquid Limit X_3 = Plasticity Index X_4 = Effective stress	$a_0 = 31.392$ $a_1 = -0.098$ $a_2 = -0.341$ $a_3 = 0.330$ $a_4 = -0.050$	$R^2 = 0.846$ MSE = 41.232 RMSE = 6.421	Model acceptable
7	Multiple Power Regression (Outlier removed)	$y = a_oX_1^{a_1}X_2^{a_2}X_2^{a_3}X_4^{a_4}$	X_1 = Water Content X_2 = Liquid Limit X_3 = Plasticity Index X_4 = Effective stress	$a_0 = 203.728$ $a_1 = -0.487$ $a_2 = -1.584$ $a_3 = 1.208$ $a_4 = 0.41$	$R^2 = 0.890$ MSE = 29.37 RMSE = 5.419	Model acceptable
8	Multiple Power Regression No Outlier	$y = a_oX_1^{a_1}X_2^{a_2}$	X_1 = Water Content X_2 = Effective stress	$a_0 = 175.797$ $a_1 = -0.833$ $a_2 = 0.286$	$R^2 = 0.861$ MSE = 29.105 RMSE = 5.395	Model acceptable
9	Multiple Quadratic Regression (Outlier removed)	$y = a_o + a_1X_1 + a_2X_2$ $+a_3X_3 + a_4X_4$	X_1 = Water Content X_2 = Effective stress X_3 = Water Content X_4 = Effective stress	$a_0 = 66.497$ $a_1 = -1.098$ $a_2 = 0.0696$ $a_3 = 0.0049$ $a_4 = -7E-5$	$R^2 = 0.828$ MSE = 46.03 RMSE = 6.785	Model acceptable

Table 4. Predicted Undrained shear strength using testing dataset from other sites for general model.

Model	Site	Soil Type	WC	Z	Unit weight	Effective stress	LL	PI	Pred. USS	Actual USS	% Diff.
$USS = 29.230 - 0.205WC + 0.043\sigma_v$ (Model 4)	Cawthrone	MH or OH	252.00	4.5	12.25	55.13	273	156	−20.06	12.00	−267.2
	Cawthrone	CH	69.00	12.8	16.42	209.36	52	29	24.09	25.00	−3.65
	Cawthrone	CH	23.00	18.0	19.60	352.80	64	46	39.69	39.00	1.76
	Chanomi	CH	32.00	22.5	18.09	407.03	110	84	40.17	51.00	−21.23
$USS = 66.49 - 1.10WC + 0.070\sigma_v + 0.0049WC^2 - 0.00007\sigma_v^2$ (Model 5)	Cawthrone	MH or OH	252.00	4.5	12.25	55.13	273	156	104.10	12.00	767.5
	Cawthrone	CH	69.00	12.8	16.42	209.36	52	29	25.51	25.00	2.04
	Cawthrone	CH	23.00	18.0	19.60	352.80	64	46	59.77	39.00	53.26
	Chanomi	CH	32.00	22.5	18.09	407.03	110	84	53.20	51.00	4.31
$USS = 31.39 - 0.098WC - 0.341LL + 0.33PI + 0.050\sigma_v$ (Model 6)	Cawthrone	MH or OH	252.00	4.5	12.25	55.13	273	156	−32.16	12.00	−368.0
	Cawthrone	CH	69.00	12.8	16.42	209.36	52	29	26.98	25.00	7.91
	Cawthrone	CH	23.00	18.0	19.60	352.80	64	46	40.13	39.00	2.91
	Chanomi	CH	32.00	22.5	18.09	407.03	110	84	38.82	51.00	−23.89
$USS = 203.728\, WC^{-0.487} LL^{-1.584} PI^{1.208} \sigma_v^{0.410}$ (Model 7)	Cawthrone	MH or OH	252.00	4.5	12.25	55.13	273	156	4.40	12.00	−63.29
	Cawthrone	CH	69.00	12.8	16.42	209.36	52	29	25.95	25.00	3.82
	Cawthrone	CH	23.00	18.0	19.60	352.80	64	46	68.86	39.00	76.58
	Chanomi	CH	32.00	22.5	18.09	407.03	110	84	54.57	51.00	7.00
$USS=175.80\, WC^{-0.83} \sigma_v^{0.286}$ (Model 8)	Cawthrone	MH or OH	252.00	4.5	12.25	55.13	273	156	5.53	12.00	−53.92
	Cawthrone	CH	69.00	12.8	16.42	209.36	52	29	23.85	25.00	−4.59
	Cawthrone	CH	23.00	18.0	19.60	352.80	64	46	69.07	39.00	77.10
	Chanomi	CH	32.00	22.5	18.09	407.03	110	84	54.65	51.00	7.15

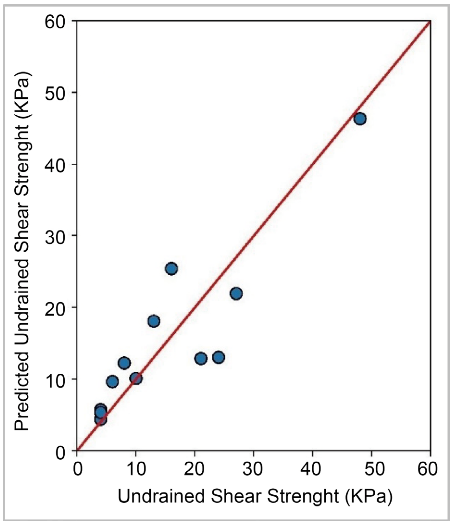

Figure 4. Cross Validation Plot for Escravos model prediction.

with two independent variables (water content and effective stress) seems to be the best model for predicting the undrained shear strength of soft clay found in the Niger Delta region of Nigeria.

4. Discussion

4.1. Soil Classification at Escravos Site

The result from the classification of the soils showed that the soil samples at Escravos site were predominantly inorganic clay of high plasticity. Inorganic clay of high plasticity which are also known to be fat clay are expansive soil that tends to be problematic. [15] stated that inorganic clay is not just problematic due to its low shear strength but the problem is compounded by the drastic change in the volume of the clay. This drastic change in the volume of the clay causes the clay to swell when water is added to the clay and shrinks when water leaves the clay. This drastic swelling and shrinking of the clay cause the lifting of structures which will lead to cracking in the structure and also subsidence [15]. [16] stated that fat clays are subject to extreme change in shear strength as a result of extreme moisture content change. When the void of fat clays are filled with water the strength of the clay drops significantly but when water is dissipated from the void the strength increases significantly. [17] stated that very high plastic clay usually contains smectites and as the plasticity in the clay decreases clay minerals like illitic and kaolinitic can be found in the clay. The statement by [17] gives an indication that the clay minerals at Escravos site might be predominately smectites. The stabilization of fat clay can help improve the usability of the clay as a construction material. [18] reported in their study that the strength of the fat clay found in the Niger Delta region was improved by stabilizing it with cement binder.

The undrained shear strength (USS) obtained for Escravos site ranged from 4 to 48 KPa and is classified as either soft or very soft clay. [14] stated that soil with USS less than 25 KPa are considered to be very soft clay while soil that their USS is between 25 to 50 KPa are considered to be soft clay [19]. Finding of USS of Escravos soil by [19] corroborated with the finding from the present study that the USS at Escravos site was relatively low. [15] stated that the strength of the soils found on the western side of the Niger Delta were predominantly weak soil. The range of cohesion of the soils found in the western side of the delta ranged from 6.9 to 27.5 KN/m^2. However, the USS of the soils at other regions of the Niger Delta that are not close to the coastal region are relatively high. [20] stated the cohesion of soil found in Choba region ranges 50 to 61 KPa, while cohesion for soil found in Eagle Island ranged from 97 to 107 KPa. Similar values of the USS obtained in this study were also obtained for soil in other coastal regions in the World. [3] reported that the USS for sensitive alluvial soil found in the Nile River ranged from 5 KPa to 45 KPa. [20] reported a USS of 19.21 KPa which gave indication of soft clay. The result from the study showed that Escravos site which had soil samples that were predominantly high plastic clay had the lowest USS. [21] reported that high-swelling clay minerals (e.g smectites) tend to reduce the shear strength of the soil significantly. This might be the reason for the low shear strength found on Escravos site which had highly plastic clay. The result from the present study and other studies provide evidence that the soil found in the coastal region of the Niger Delta are predominantly soft weak soft clay.

The liquid limit of the soil found at Escravos site ranged from 52% to 150%. The liquid limit of most of the soils at Escravos had liquid limit above 100%, which is a strong indication of the plasticity of the clay soil. The relatively high liquid limit found in the soil indicates that the problem of compressibility will be experienced at Escravos site. [17] stated that a high liquid limit normally indicates high compressibility and high shrinkage/swelling potential.

The plastic limit of the soil found at Escravos ranged from 17% to 51%. The plastic limit of the soil tends to measure the ease of which soil can be deformed without breaking. Soil with low plasticity tends to break easily upon the application of an external force or pressure while soil with high plasticity tend to deform with external force applied on it.

4.2. Pearson Correlation on Clay Properties

The relationships between the clay properties were investigated using Pearson correlation coefficient which measure the degree of linear relationship between two variables. The linear relationship of the clay properties showed that there was a negative linear relationship between the USS and the liquid limit at the three sites. The result shows that as the liquid limit of the soil increase the USS of the soil tends to decrease. The decrease in the USS of the soil with increase in liquid limit can be attributed to the fact that the soil exhibit high plasticity. An increase in the plasticity of the soil result in a higher tendency of absorption of water by the clay which result in decrease in the strength of the soil. The more water content in the soil the less resistant the clay become to external forces which will result in the shearing of the soil. Also, as the water content of the soil reduces the soil becomes less plastic and more resistance to external forces. The result of the relationship between the liquid limit and USS was not statistically significant at the Escravos site which indicates that the negative relationship observed in the soil samples might not be existing in the population. This might be attributed to the number of soil samples used for the study, as several researchers have established that a negative relationship exist between the liquid limit and USS but some suggested that the relationship is not entirely linear.

The relationship between the plastic limit and the USS was negative, which indicate that as the plastic limit of the soil tends to increase the USS of the soil tend to reduce and *vice versa*. The increase in the plastic limit indicates that the soil sample have more water in its voids which will eventually lead to easier deformation of the soil which result in decrease in the USS of the soil. Several researchers have opined that there is no really established relationship between the plastic limit and USS. The relationship between the plastic limit and the USS can be affected by several factor such as the soil type, grain size distribution and the stress history. No significant relationship was established between the plastic limit and the USS for the three sites. [21] stated that the USS is almost independent of the liquid and plastic limit which was also observed in the present study.

The relationship between the water content and the USS was negative, which implies that an increase in the water content will result to decrease in the USS of the soil. The increase in water in the clay soil will cause the soil to be more cohesive which will reduce the ability of the soil resist deformation. The relationship between the water content in the soil and USS at Escravos site was statistically significant.

4.3. Predictive Models for USS

The result from model development showed that model 4 was the best model in predicting the undrained shear strength of the soil based on the water content and the effective stress of the soil. The validation of the model with second input data set provided sufficient evidence in stating that model 4 was significantly better than the other model developed.

5. Conclusion

This study presents the models that relate the undrained shear strength with the soil properties of soft clays found in the Niger Delta region. The study showed that most of the soil found in the coastal region of the Niger Delta is predominantly inorganic clay of high plasticity which indicates that they are expansive soil. The strength of the soil within this region were either soft or very soft clay which signifies very low shear strength. The relationship showed that the undrained shear strength of the soil had a statistically significant negative linear relationship with the moisture content and a positive linear relationship with the unit weight. The model developed provided good predictive power in forecasting the undrained shear strength of the soil if the moisture content and effective stress are known.

6. Limitation

The predictive power of the developed model can be improved if more soil properties that affect the undrained shear strength are included as predictor variables. Very few studies including the present study have considered how mineralogy of clay affects the USS. Measurement of the amount of kaolinite and illite which affect the USS can be included as predictor variables which may lead to a better predictive model. The soil samples used to develop the model in this study was quite small, more soil samples can be collected to establish the true relationship which may enhance to a better predictive power of the model. More advance Machine learning algorithms can also be used for the model development.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Gagliardi, L. (2013) Why Oil and Gas Drilling Is Going Deeper and Further Offshore. https://www.csmonitor.com/Environment/Energy-Voices/2013/0702/Why-oil-and-gas-drilling-is-going-deeper-and-further-offshore#:~:text=Offshore%20oil%20and%20gas%20drilling,%2Drisk%20areas%2C%20Gagliardi%20writes

[2] D'Ignazio, M., Phoon, K.-K., Tan, S. and Länsivaara, T. (2016) Correlations for Undrained Shear Strength of Finnish Soft Clays. *Canadian Geotechnical Journal*, **53**, 1628-1645. https://doi.org/10.1139/cgj-2016-0037

[3] Elsawy, M., Alsharekh M., and Shaban M. (2022) Modeling Undrained Shear Strength of Sensitive Alluvial Soft Clay Using Machine Learning Approach. *Applied Sciences*, **12**, Article 10177. https://doi.org/10.3390/app121910177

[4] Persson, E. (2017) Empirical Correlation between Undrained Shear Strength and Preconsolidation Pressure in Swedish Soft Clays. Royal Institute of Technology, Stockholm. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-213848

[5] Skempton, A.W. (1954) Discussion: Sensitivity of Clays and the c/p Ratio in Normally Consolidated Soils. *Proceedings of the American Society of Civil Engineers*, Separate 478, 19-22.

[6] Hansbo, S. (1957) New Approach to the Determination of the Shear Strength of Clay by the Fall-Cone Test. http://urn.kb.se/resolve?urn=urn:nbn:se:swedgeo:diva-356

[7] Enewugwem, J.H. (2010) The Niger Delta of Nigeria: A World Class Oil-Rich Region in Africa 2000-2006. Africana, 165-181.

[8] Amaechi, R. (2009) Phases in the Manifestation and Management of Niger Delta Crisis. http://www.unilorin.edu/.ng/downloads/speech_Gov%20Amaechi.pdf

[9] Stewart, N.F. (2006) Deprivation, Environmental Degradation and Armed Conflicts: Need for Sustainable Development of Niger Delta Wetlands. Department of Public law, University of Benin, Benin City. http://www.nigerianlawguru.com/articles/environmental%20law/DEPRIVATIONS,%20ENVIRONMENTAL%20DEGRADATION%20AND%20ARMED%20CONFLICTS,%20NEED%20FOR%20SUSTAINABLE%20DEVELOPMENT%20OF%20THE%20NIGER%20DELTA%20WETLANDS.pdf

[10] World Bank (2008) Niger Delta Social and Conflict Analysis. Document of the World Bank on "Report of Nigeria".

[11] Omofonmwan, S.I. and Odia, L.O. (2009) Oil Exploitation and Conflict in Niger-Delta Region of Nigeria. *Journal of Human Ecology*, **26**, 25-30. https://doi.org/10.1080/09709274.2009.11906161

[12] NDDC (2006) Niger Delta Regional Development Master Plan (NDRDMP). NDDC, Abuja.

[13] Semiama, I. (2007) Crisis in the Niger Delta Area of Nigeria.

https://www.bayelsa.org.uk/pdf/bsup-crisis-in-theniger-delta-of-nigeria.pdf

[14] Murthy, V.N.S. (2002) Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering. Marcel Dekker Inc., New York.

[15] Okagbue, C. (1989) Geotechnical and Environmental Problems of the Niger Delta. *Bulletin of the International Association of Engineering Geology*, **40**, 119-126. https://doi.org/10.1007/BF02590349

[16] Gibbs, H., Hilf, J., Holtz, W. and Walker, E. (1960) Shear Strength of Cohesive Soils. *Proceedings of ASCE Research Conference in Shear Strength of Cohesive Soils*, University of Colorado, Boulder, Colorado, June 1960, 33-162.

[17] Wagner, J.F. (2013) Mechanical Properties of Clays and Clay Minerals. *Developments in Clay Science*, **5**, 347-381. https://doi.org/10.1016/B978-0-08-098258-8.00011-0

[18] Alayaki, F., Al-Tabbaa, A. and Ayotamuno, M. (2017) Stabilization of Niger Delta Fat Clay with Blend of Binders for Subgrade Application. *Nigeria Journal of Technology*, **36**, 740-748. https://doi.org/10.4314/njt.v36i3.12

[19] Nwankwoala, H., Amadi, A., Jimoh, M. and Warmate, T. (2015) Geotechnical Properties of Sub-Soils in Escravos Estuary, Western Niger Delta, Nigeria*. American Journal of Civil Engineering and Architecture*, **3**, 8-14.

[20] LongJohn, T. and Tom, J. (2022) Characterization of Marine Clays of the Niger Delta. *Journal of Architecture and Civil Engineering*, **7**, 16-24.

[21] Prinz, H. and Straub, R. (2006) Abriss Der Ingenieurgeologie*.* Rev. Ed, Springer, Berlin.