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Predicting Soil Strength using Electrical Resistivity Measurements in Clays

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ABSTRACT
This paper presents an experimental study that investigates the effects of stress history and mineralogy on the use of electrical resistivity to predict soil strength. Recent experimental studies show that the electrical resistivity, ρ, is promising in predicting the undrained shear strength, S_u, for a given soil type under the same conditions (e.g., pore fluid and stress history). When employing ρ in surveying seabed sediments, the effects of natural variability in the soil, such as different stress histories and mineral compositions, need to be addressed. This study utilizes a special-made triaxial setup that can measure the electrical resistance, R, at any stage of a consolidated undrained test on reconstituted clay samples, which is used to calculate the electrical resistivity of the clay samples. Multiple triaxial tests are performed on specimens of varying plasticity indices (PI) and stress histories (represented by the overconsolidation ratio, OCR). The results provide a correlation of S_u relating to ρ, PI, and OCR, which is useful in geotechnical engineering applications where the determination of soil strength using geophysical methods is an option.

RÉSUMÉ
Cet article présente une étude expérimentale qui étudie les effets de l'historique des contraintes et de la minéralogie sur l'utilisation de la résistivité électrique pour prédire la résistance du sol. Des études expérimentales récentes montrent que la résistivité électrique, ρ, est prometteuse pour prédire la résistance au cisaillement non drainé, Su, pour un type de sol donné dans les mêmes conditions (par exemple, fluide interstitiel et historique des contraintes). Lors de l'utilisation de ρ dans l'étude des sédiments du fond marin, les effets de la variabilité naturelle du sol, tels que les différentes histoires de contraintes et les compositions minérales, doivent être pris en compte. Cette étude utilise une configuration triaxiale spéciale qui peut mesurer la résistance électrique, R, à n'importe quel stade d'un test consolidé non drainé sur des échantillons d'argile reconstituée, qui est utilisé pour calculer la résistivité électrique des échantillons d'argile. Plusieurs tests triaxiaux sont effectués sur des échantillons d'indices de plasticité (PI) et d'histoires de contraintes variables (représentés par le rapport de surconsolidation, OCR). Les résultats fournissent une corrélation de Su relative à ρ, PI et OCR, ce qui est utile dans les applications de génie géotechnique où la détermination de la résistance du sol à l'aide de méthodes géophysiques est une option.

1 INTRODUCTION

The purpose of this investigation was to evaluate the effectiveness of using a geophysical parameter, electrical resistivity (ρ), along with two geotechnical parameters: plasticity index (PI) and overconsolidation ratio (OCR), individually and combined, in estimating undrained shear strength (S_u) for reconstituted clay specimens. A comprehensive laboratory testing program utilizing consolidated undrained triaxial tests was performed at California State University, Los Angeles, to study the relationship between measured geophysical values and corresponding soil strength. Employing electrical resistivity as a geophysical parameter has shown advantages when surveying soil properties of near-surface soils because of the potential for rapid coverage rates and non-contact ability. This research is essential because non-contact methods may potentially advance technology in surveying the earth's resources located both on- and offshore. Custom-made triaxial caps were used to allow for resistivity measurements to be made at any stage of a triaxial test. The obtained laboratory results are used to develop a S_u-ρ-PI-OCR relationship, and regression methods were used to evaluate the effectiveness of individual and combined geophysical and soil parameters in the estimation of soil strength. The results show that when only ρ and PI are used, the correlation is relatively weak, but significantly improves when combined with OCR.

2 BACKGROUND

Electrical resistivity can be used in geotechnical subsurface exploration locating earth resources such as oil and gas in both the on- and offshore environments. The Electrical-resistivity survey has shown the potential to manifest the spatial variability of soil properties (e.g., water content, density, and shear strength) in geotechnical site characterization (Samouëlian et al. 2005). Compared with the body wave surveying methods (p- or s-wave), the resistivity approach is less prevalent because of the limited and perceived weak correlations between electrical resistivity and soil properties.

Electrical conductivity in fine-grained soils also depends on the mineralogy because of electrical current flow through the charged surfaces of the clay minerals. The Cation Exchange Capacity (CEC) can explain the conductivity in clayey soils (Mitchell and Soga 2005). Kibria and Hossain (2019) show that the electrical resistivity of clay is affected by the dominant mineral of clay material. Compared with sand, the electrical conductivity levels of clays are generally higher, because the diffuse double layer is more conductive, with the exception when salt content is present in the pore fluid. (Fukue et al. 1999; Kwan et al. 2019b). Electrical conductivity is the reciprocal of resistivity.

Electrical current flow in soil depends on the hydraulic gradient, i_h, and electrical gradient, i_e, which can be described by the following equation (Mitchell and Soga 2005):

$$I = \left[\frac{k_e \gamma_w}{n}\right] i_h + \left[\frac{\sigma_e}{n}\right] i_e \quad [1]$$

Where I is the electrical current, k_e is the coefficient of electroosmotic hydraulic conductivity, γ_w is the unit weight of water, n is the soil porosity, and σ_e is the bulk electrical conductivity of the soil.

To further improve the feasibility of using electrical resistivity in surveying soil strength, improved correlations between the two are desired. There are some correlations that exist from field testing research programs (Cosenza et al. 2006; Oh and Sun 2008); while very few exist from correlations developed from laboratory investigations (Long et al. 2012). Nevertheless, those correlations are generally weak and there are no strength-resistivity correlations attempted to incorporate information from clay mineralology and stress history. Such development is limited due to the expensive and time-consuming cost of soil lab testing and the need for special equipment that can measure electrical resistivity and shear strength on the same specimen.

Another approach to increase the accuracy of using electrical resistivity to predict soil strength is to incorporate additional independent predictors. Kwan et al. (2019a) finds that combining two geophysical parameters, shear wave velocity and electrical resistivity, increases the correlation with soil undrained shear strength compared with considering only one at a time. For cohesive soil, past studies have shown that there are correlations between undrained shear strength and both the overconsolidation ratio (OCR) and the plasticity index (PI) of certain clays. Skempton (1957) has shown a correlation between the undrained shear strength of normally consolidated clays and the plasticity index of the clay.

$$\frac{S_u}{\sigma_i} = 0.11 + 0.0037PI \quad [2]$$

where S_u is the undrained shear strength and σ_i is the vertical effective stress. Chandler (1988) has suggested that this correlation could be modified to allow for overly consolidated clays of low OCR. This modified correlation was used to study multiple case studies but found to fail often. Studies from Bjerrum and Simons (1960) suggest that high liquidity index clays would not fit the modified correlation. For sensitive clays, the correlation of undrained shear strength was better with the liquidity index rather than the plasticity index. Wroth and Houlsby (1985) proposed a correlation for normally consolidated clay using the modified Cam clay model:

$$\frac{S_u}{\sigma_i} = 0.129 + 0.00435PI \quad [3]$$

Studies have shown that as overconsolidation increases, the undrained shear strength ratio increases. This is addressed by the concept of SHANSEP (Stress History and Normalized Soil Engineering Parameters) (Ladd and Foott 1974). However, there is no attempt to incorporate electrical resistivity along with PI or OCR to predict soil strength.

This study tested two types of commonly used clays: Kaolinite and Bentonite. Variation in the mixing ratio of the two gives different PI values.

Kaolinite originates from the weathering of feldspar and mica in granite rocks. Kaolinites tend to develop in high precipitation areas but have proper drainage that enables the percolating of Mg, Ca, and Fe cations (Mitchell and Soga 2005). The range of liquid limit of Kaolinite is 30 to 110, plastic limit of 25 to 40, and has a particle size of 0.2 to 210 μm. For the electrical properties of Kaolinite, CEC is in the range of 3-15 meq/100 g, and k_e is 5.7×10^{-5} cm^2/s-V.

Bentonite is a highly plastic and swelling clay that contains significant amounts of Montmorillonite or smectite and is widely used as a grout material or backfill during the construction of slurry trench walls and soil admixture for seepage barriers. Montmorillonite has a range of liquid limit of 100 to 900, plastic limit of 50 to100, and has a particle size of 0.1 μm. It also has unusually high surface conductance. For the electrical properties of Montmorillonite, CEC is in the range of 80-150 meq/100 g, and k_e is 2.0×10^{-5} cm^2/s-V.

Abu-hassanein et al. (1996) developed a testing procedure using electrical conductivity to determine bentonite content in soil-bentonite mixtures. They concluded that when more Bentonite is added to the soil slurry, its conductance increases as a result of additional surface conductance and an increase in ionic strength of the fluid.

3 TESTING PROGRAM

3.1 Clay Specimen Reconstitution

In this study, nine Isotropic Consolidated Undrained (ICU) triaxial tests were performed on reconstituted clay specimens that were reconstituted using the slurry-based consolidation method on Edgar Plastic Kaolin (EPK) powder and Volclay 325 Mesh Bentonite powder. Three specimens were reconstituted by mixing EPK powder with distilled water, aiming for the initial water content of 120%. Three specimens were reconstituted with 95% EPK powder and 5% Bentonite powder and three specimens with 90% EPK powder and 10% Bentonite powder. The slurry mixture was stored for 24 hours, in closed, sealed containers, to allow moisture homogenization and then gently poured into an assembled stainless-steel reconstitution box, shown in Figure 1a. They were then subjected to a gradual increase of consolidation stress to 100 kPa on a triaxial frame. Adding a small portion of Bentonite significantly slowed the consolidation process. For the consolidation stage after reaching 100 kPa, the coefficient of consolidation, c_v, for the mix of 100 % Kaolin and 0 % Bentonite is 2.37×10^{-03} cm^2/sec and for the mix of 95 % Kaolin and 5 % Bentonite is 7.96×10^{-04} cm^2/sec. With a square area of 324 cm^2, the reconstituted clay block, shown in Figure 1b, is trimmed into four columnar specimens, each with an area of 81 cm^2, sealed in two layers of plastic bags, and preserved in a moisture-maintained storage room.

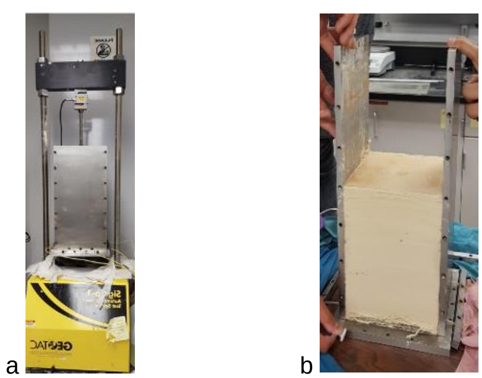

Figure 1 a. Clay Reconstitution Box and b. Reconstituted Clay Block after Consolidation with sides removed.

3.2 ICU Triaxial Test

The nine ICU tests were performed according to ASTM D4767-11 with custom-made triaxial caps. The custom-made triaxial caps were used to allow for resistivity measurements to be made at any stage of a triaxial test. When conducting a test, the reconstituted clay specimen is taken from the storage room and trimmed into a cylindrical shape with a diameter of 7.1 cm and a height to diameter ratio of 2.0. The specimen is placed on the triaxial cap, and a 0.35 mm thick latex membrane is placed over it. The cell of the triaxial apparatus is filled with distilled water and the pore stones of the triaxial caps are flushed with CO_2, followed by distilled water to remove as much air as possible from the specimen. The specimen is back pressure saturated to a target saturation ratio of 95% and then consolidated to the desired maximum pressure (100, 200, or 400 kPa) and then brought back down to 100 kPa for the shearing phase. Table 1 summarizes the test plan.

Table 1. Summary of the experimental testing program (%B = % Bentonite).

Test #	%B	OCR	Test #	%B	OCR
1	0	1	6	5	4
2	0	2	7	10	1
3	0	4	8	10	2
4	5	1	9	10	4
5	5	2			

While the triaxial test is in progress, the cables of the custom-made resistivity triaxial caps are attached to a Miller 400A resistance meter (Figure 2) so that measurements can be taken throughout the testing process. The resistance meter manually sends a 12V, 97Hz current through the soil from current terminals, C1 and C2, and the potential terminals, P1 and P2, measure the drop in the voltage and the resistance, R, is displayed on the resistance meter. With additional information from the triaxial test about the deformation of the specimen, the resistivity of the specimen can be calculated. Typical triaxial test results are illustrated in Figure 3.

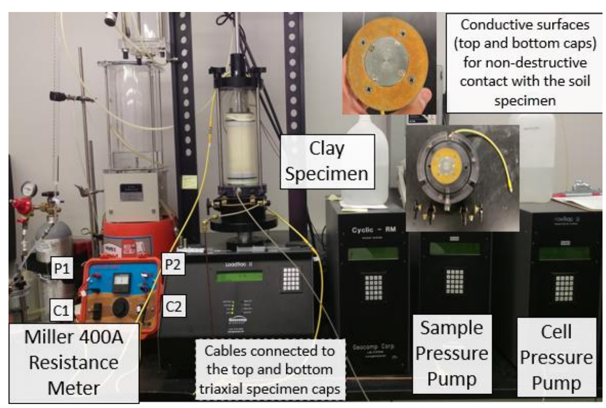

Figure 2. Triaxial Test Setup and Custom-Made Triaxial Caps (Kwan et al. 2019b)

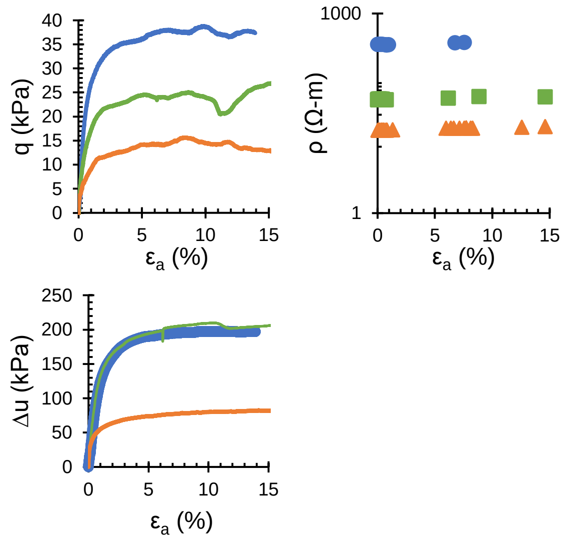

Figure 3. Triaxial test results and electrical measurements during the shear phase for samples of OCR=1. Test 1 (Blue), 4 (Green), and 7 (Orange)

3.3 Liquid Limit and Plasticity Index

Before mixing the clay slurry, Atterberg limit tests were performed on sample batches of the Bentonite and Kaolin powder. The desired ratio of Bentonite to Kaolin is mixed with distilled water and used in Atterberg limit tests to determine the liquid limit and plastic limit. Figure 4 shows that as the Bentonite content increases, the liquid limit and plasticity index also increase.

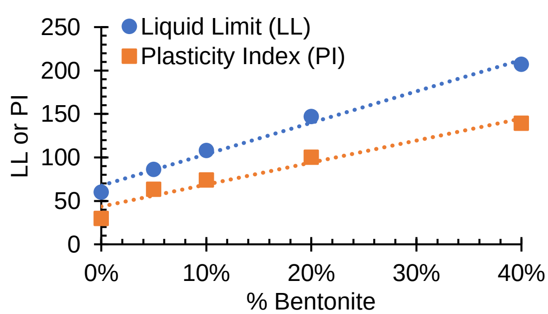

Figure 4. Atterberg test results for varying Bentonite concentrations

4 TEST RESULTS AND ANALYSIS

4.1 Results of electrical resistivity

Using the Miller 400A resistance meter, the electrical resistance of reconstituted clay specimens is measured as the specimen is subjected to consolidation and shearing during triaxial testing. The resistance is used to calculate the resistivity of the soil in relation to the height and cross-sectional area of the specimen. The electrical resistivity is calculated as

$$\rho = \left(\frac{R}{H}\right)(A) \quad [4]$$

$\rho = Electrical\ Resistivity\ [\Omega - m]$
$R = Electrical\ Resistance\ [\Omega]$
$H = Height\ of\ Specimen\ [cm]$
$A = Area\ of\ Specimen\ [cm^2]$

The results of electrical resistivity of the soil in Figure 5 indicates a decrease relative to the amount of Bentonite used in the mixing process of the soil as well as in a drop in the normalized undrained shear strength due to the overconsolidation ratio of the soil.

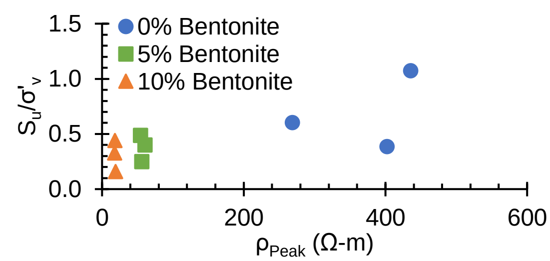

Figure 5 Normalized Undrained Shear Strength (S_u /σ'_v) vs. pre-shear electrical resistivity (ρ)

The presence of the 5% Bentonite significantly reduces the electrical resistivity (average 57.14 Ω-m) by 6.5 times. At 10% Bentonite, the average ρ is 18.34 Ω-m. The observation of decreasing ρ with increasing Bentonite content agrees with the results from the literature. Adding the Bentonite content increases the surface conductance of the clays and ionic strength of the pore fluid.

4.2 Results of plasticity index

After a triaxial test is performed, the soil specimen is used in an Atterberg limit test to determine whether the plasticity index of the sample matches the plasticity index from the trial batches. Because a 100% Kaolinite sample would have little to no change in the homogeneity of the soil, it was assumed to maintain a plasticity index of 30. While the plasticity index of the soil specimens varies slightly, they are within the expected range of tested plasticity index (Figure 6).

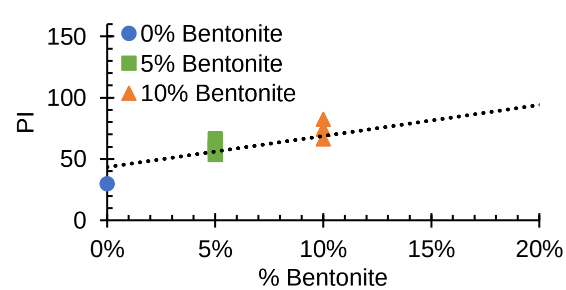

Figure 6. Atterberg Limit test results of triaxial specimens

Table 2 summarizes the results from the nine ICU tests, including the resistivity taken at the start of the shearing phase, ρ_{pre}, and at the peak of the principal stress ratio curve, ρ_{peak}, during the shearing phase. While ρ_{peak} measurements were taken at the specimens' failure condition, ρ_{pre} corresponds to the specimen's intact condition.

Table 2. Summary of experimental testing program results

Test #	OCR	PI	ρ_{Pre} Ω-m	ρ_{Peak} Ω-m	ε_a %	S_u/σ'_v kPa
1	1.01	30.0	344.2	402.1	9.7	0.387
2	2.01	30.0	271.9	268.9	6.2	0.603
3	4.01	30.0	385.5	435.6	9.4	1.074
4	1.01	53.7	51.5	56.2	8.6	0.250
5	2.01	58.6	54.9	60.7	7.9	0.400
6	4.01	66.4	53.3	54.5	8.3	0.489
7	1.02	82.4	17.7	19.1	8.4	0.160
8	2.02	74.2	17.0	17.9	9.2	0.329
9	4.11	66.5	16.4	18.1	7.1	0.441

4.3 Regression Analysis

Simple linear regression analysis with one variable (ρ or PI), regression analysis with two independent variables (ρ and PI, ρ and OCR, PI and OCR) and multivariable regression analysis with three independent variables (ρ, PI, and OCR) were performed to study the correlations between the parameters representing geophysical, mineralogic, and stress history with undrained shear strength of the soil. Using the fitlm function in MATLAB, the adjusted R^2 (R^2_{adj}) values and correlation coefficients were obtained for each regression analysis and are presented in Tables 3 and 4. R^2_{adj} is preferred to R^2 value to avoid overfitting the data points when multiple independent predictors are included. The independent variables to be considered for correlating normalized undrained shear strength (S_u/σ'_v) in this analysis are electrical resistivity (ρ), OCR, and plasticity index (PI).

Simple linear regression analysis results are summarized in the first three rows of both Table 3 and Table 4. Since the pore fluid type used in all tests was distilled water, we can assume that the electrical resistivity of the soil specimens is only affected by the Bentonite content and stress histories.

When using only a single variable to correlate undrained shear strength, the simple linear regression result indicates that the stress history (OCR) has the highest correlation (R^2_{adj} = 0.42) with S_u. This observation is well documented in the design procedure of SHANSEP (Ladd and Foott 1974). The test results also show that the correlation between ρ and S_u (R^2_{adj} = 0.34) is as good as between PI and S_u (R^2_{adj} = 0.35), which justifies that the electrical resistivity is a decent parameter to estimate the undrained shear strength of clayey soils.

When the overconsolidation ratio is added into the regression, R^2_{adj} significantly increases to around 0.8. However, if the PI is added, the R^2_{adj} remains low at approximately 0.4.

Table 3. Adjusted R^2 Values and Parameter Coefficients for correlating S_u/σ'_v using Peak Shear Resistivity

	Adjusted R^2	S_u/σ'_v Correlation
PI	0.34	$0.92 - 0.0084\,PI$
ρ_{peak}	0.42	$0.30 + 0.0011\,\rho_{peak}$
OCR	0.33	$0.16 + 0.1271\,OCR$
PI, ρ_{peak}	0.32	$0.35 - 0.0007\,PI + 0.0001\,\rho_{peak}$
ρ_{peak}, OCR	0.83	$0.02 + 0.0010\rho_{peak} + 0.1215\,OCR$
PI, OCR	0.77	$0.62 - 0.0083\,PI + 0.1258\,OCR$
PI, ρ_{peak}, OCR	0.80	$0.16 - 0.0020\,PI + 0.0008\,\rho_{peak} + 0.1224\,OCR$

Table 4. Adjusted R^2 Values and Parameter Coefficients for correlating S_u/σ'_v using Pre-Shear Resistivity

	Adjusted R^2	S_u/σ'_v Correlation
PI	0.34	$0.92 - 0.0084\,PI$
ρ_{Pre}	0.44	$0.293 + 0.0012\,\rho_{Pre}$
OCR	0.33	$0.16 + 0.1271\,OCR$
PI, ρ_{Pre}	0.35	$0.21 + 0.0011\,PI + 0.0014\,\rho_{Pre}$
ρ_{Pre}, OCR	0.85	$0.015 + 0.0012\rho_{Pre} + 0.1208\,OCR$
PI, OCR	0.77	$0.619 - 0.0083\,PI + 0.1258\,OCR$
PI, ρ_{Pre}, OCR	0.82	$0.063 - 0.00069\,PI + 0.0011\,\rho_{Pre} + 0.1211\,OCR$

With all test data, a multivariable regression analysis is performed to determine if the R^2_{adj} value improves. Incorporating all parameters generates an R^2_{adj} of 0.81, which is like considering ρ and OCR, but significantly higher than using the parameters separately. The correlation is

$$\frac{S_u}{\sigma'_v} = 0.160 - 0.0020\,PI + 0.0008\,\rho_{peak} + 0.1224\,OCR \quad [5]$$

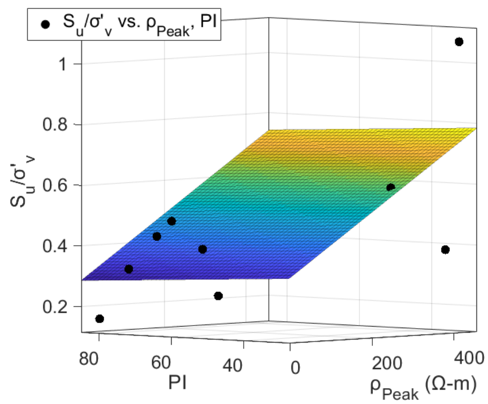

Figure 7. Multivariable linear regression (S_u/σ'_v vs. PI and ρ_{Peak})

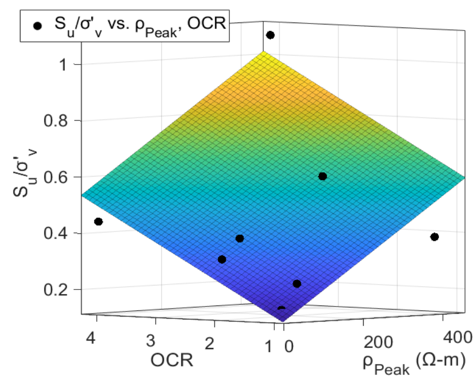

Figure 8. Multivariable linear regression (S_u/σ'_v vs. OCR and ρ_{Peak})

5 Conclusion

This experimental study utilized advanced triaxial tests to investigate whether using electrical resistivity along with the Plasticity Index and stress history of the soil could be used to determine the undrained shear strength of the soil. Correlations between the undrained shear strength of clay and Electrical Resistivity along with the Plasticity Index and Overconsolidation Ratio are established in this study. The results show that, when the parameters are considered individually, Electrical Resistivity has a similar, but slightly higher performance than the Plasticity Index. The relationship significantly improves when combined with the stress history, represented by the Overconsolidation Ratio of the soil.

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7 References

Abu-hassanein, Benson, C. H., Wang, X., and Blotz, L. R. (1996). “Electrical Resistivity of Compacted Clays Determining Bentonite Content in Soil-Bentonite Mixtures Using Electrical Conductivity.” *Geotechnical Testing Journal*, 19(1).

Bjerrum, L., and Simons, N. E. (1960). “Comparison of Shear Strength of Cohesive Soils.” *ASCE Research Conference on Shear Strength of Cohesive Soils*, Boulder, 711–726.

Chandler, R. (1988). “The In-Situ Measurement of the Undrained Shear Strength of Clays Using the Field Vane.” *Vane Shear Strength Testing in Soils: Field and Laboratory Studies*, 13–44.

Cosenza, P., Marmet, E., Rejiba, F., Jun Cui, Y., Tabbagh, A., and Charlery, Y. (2006). “Correlations between geotechnical and electrical data: A case study at Garchy in France.” *Journal of Applied Geophysics*, 60, 165–178.

Fukue, M., Minato, T., Horibe, H., and Taya, N. (1999). “The micro-structures of clay given by resistivity measurements.” *Engineering Geology*, 54, 43–53.

Kibria, G., and Hossain, S. (2019). “Electrical resistivity of compacted clay minerals.” *Environmental Geotechnics*, 6(1), 18–25.

Kwan, W. S., Tuazon, J., Tufenkjian, M., and Kam, T. (2019a). “Combining Shear Wave Velocity and Electrical Resistivity for Improving Predictions of Soil Strength Properties.” *Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR)*, Taipei, Taiwan, 170–175.

Kwan, W. S., Tufenkjian, M., Tuazon, J., Peralta, N., Khov, K., and Garcia, F. (2019b). “Electrical Resistivity Measurements in Advanced Triaxial Tests.” *Geo-Congress 2019: Eighth International Conference on Case Histories in Geotechnical Engineering*, Philadelphia.

Ladd, C. C., and Foott, R. (1974). “New Design Procedure for Stability of Soft Clay.” *Journal of Geotechnical Engineering Division*, 100(GT7), 763–786.

Long, M., Donohue, S., L’Heureux, J.-S., Solberg, I.-L., Rønning, J. S., Limacher, R., O’Connor, P., Sauvin, G., Rømoen, M., and Lecomte, I. (2012). “Relationship between electrical resistivity and basic geotechnical parameters for marine clays.” *Canadian Geotechnical Journal*, 49, 1158–1168.

Mitchell, J. K., and Soga, K. (2005). *Fundamentals of Soil Behavior*. Wiley.

Oh, S., and Sun, C. G. (2008). “Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam.” *Environmental Geology*, 54, 31–42.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G. (2005). “Electrical resistivity survey in

soil science: A review." *Soil and Tillage Research*.
Skempton. (1957). "Discussion on Airport Paper No. 35." *The Planning and Design of the New Hong Kong Airport*, Institution of Civil Engineerings, 305–307.
Wroth, C. P., and Houlsby, G. T. (1985). "Soil Mechanics - Property Characterization and Analysis Procedures." *11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, CA, 1–55.