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Major Goals: The overall goal of the research is to understand how geophysical measurements can be used to predict near-surface seafloor soil properties accurately and reliably. The objectives of the study are to develop correlations relating geophysical properties to engineering properties of a variety of near-surface sediments through controlled laboratory and field trials.

A Database Study was conducted to provide information and background on completed investigations related to geophysical measurements to geotechnical properties. Information from this task was used to help guide development of the subsequent tasks.

A Laboratory Testing Program was conducted at Cal State LA's geotechnical research laboratory to study the relationships between measured geophysical and engineering properties on small scale soil specimens in controlled test environments. Measurements of geophysical and engineering properties on the same soil specimens in the triaxial cell allowed interrelationships to be examined and established. The geophysical soil properties measured were the P- and S-wave velocity as well as electrical resistivity. The strength parameters measured were drained peak secant friction angle for sand and the undrained shear strength for clay; both determined in triaxial compression and Direct Simple Shear.

A Field Study was to be conducted at a controlled test site where near surface in-situ soil characterization and strength would be measured and correlated with measured geophysical properties. However, given that a no-cost extension on the grant was denied and because of the needs of the collaborating Navy Lab this task was eliminated. More focus was placed on the laboratory investigation. The field study was meant as a complementary piece while the laboratory investigation was seen as the task that would produce the most significant and meaningful results.

Another goal of the grant was to actively involve undergraduate engineering students in the research effort and provide mentorship.

Accomplishments: Database Study: A thorough review of the geotechnical literature on the use of non-invasive geophysical methods to evaluate soil properties was conducted. Approximately 40 lab and field studies were evaluated to find correlations between shear wave velocity, compression wave velocity, electrical resistivity, and soil properties particularly focused on drained and undrained shear strength. Although the results of the review discovered that some useful studies have been conducted; it also showed that there is a lack of knowledge in this area. A final report: "Background on Use of Geophysical Methods to Predict Soil Properties," was written and submitted to our Navy collaborator. Based on this information and in collaboration with our Navy partner two test soils and a lab testing plan was developed. A post-doctoral researcher was hired and helped in this phase of the project.

Laboratory Testing Program: Significant modification of some of our lab equipment was needed before the lab testing portion of the grant could commence. Even though the majority of lab equipment was in place prior to the start of the grant; many pieces of the ancillary equipment needed to be modified to work properly. We received full support and understanding from our Navy collaborator. The equipment modifications that were needed were related to the Triaxial Device, which was being used as the centerpiece of the laboratory investigation. Specifically, the equipment was the Bender Elements, Resistivity Cell, and Toxic Water Interface. Because of the unique and specialized nature of this equipment they are produced as one-of-a-kind components. This resulted in modifications and iterations to get the equipment to function as intended. Once the equipment was working properly, it took additional time to test and calibrate the components.

Major accomplishments of the lab testing program included:

Development of detailed written lab test procedures for all of the test types conducted. This will allow future testing of this type to be much more easily carried out by students and researchers in our lab.

Developed a procedure to successfully use saline as the pore fluid in the triaxial tests to better replicate behavior and response of seafloor soils.

Conducted more than 30 index tests on the investigated soils for soil characterization. Conducted more than 50 geophysical and strength tests using the triaxial and simple shear test setups. Of those, 32 tests (19 on sand and 13 on clay) have been used as the basis for the correlations developed thus far. Each geophysical and strength test usually takes between 2 and 14 days to setup and another 1 to 2 days to test.

Based on the results we have identified three major areas of research success. We have developed preliminary correlations between resistivity and soil strength properties. We have developed preliminary correlations between resistivity plus shear wave velocity and soil strength properties. And finally, identified that the effects of membrane penetration correction may be an important factor to consider for drained triaxial tests on sand. Based on the results of our lab investigation we have finalized submission of a paper to be presented and published at the ASCE Geocongress in 2019; and submitted another for publication at the 7th International Symposium on Geotechnical Safety and Risk also in 2019. A final report summarizing our findings will be submitted to our Navy collaborator.

Because of our initial delays in getting the lab equipment to work properly, we asked DoD for a 12 month no-cost extension. This extra time would have allowed us to conduct additional lab tests and an opportunity to validate our correlations with soils from a field test site. Our request was supported by our Navy collaborators at NAVFAC EXWC and the program manager at ONR. However, our request was denied by the DoD HBCU/MI program managers. Nevertheless, because of the success of our project, we are committed to continuing the lab testing program through the end of Spring 2019 even if unfunded. We will consider additional variables in our correlations including salt content and stress history of the soils.

For the last 1.5 years we have had four committed undergraduates students working on the lab testing program. They have been mentored by faculty in the geotechnical laboratory and have learned unique skills in laboratory testing usually reserved for graduate students in a Ph.D. program. All have indicated that their experience on this project has helped them professionally. Two of the students are strongly considering graduate school because of their experiences on this project.

Training Opportunities: Nothing to Report

Results Dissemination: The research project and laboratory work has been disseminated to many different groups. For the past 3 years the laboratory equipment has been showcased at our annual open house where we have talked about the project to more than 100 high school students. Also, we have provided a demonstration of our equipment and project to Navy engineers from NAVFAC EXWC, the Director of Education and Workforce at ONR, as well as the Program Director for the Navy's HBCU/MI program. The research results are now being disseminated through two publications at conferences in 2019.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: The project was developed in collaboration with Navy engineers at NAVFAC EXWC in Port Hueneme, California. They have been involved since the beginning of the project and will benefit from the results of the research.

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Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Other Collaborators:

Electrical Resistivity Measurements in Advanced Triaxial Tests

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ABSTRACT

A custom made triaxial apparatus that can measure electrical resistivity at any stage of a triaxial test has been developed for determining the feasibility of establishing correlations between electrical resistivity and soil properties. Reconstituted Golden Flint Sand and Kaolin Clay specimens are tested in consolidated drained (CD) and undrained (CU) conditions, and about fifty measurements of electrical resistivity were made for each test to shed light on how the electrical resistivity changes from specimen mounting to the end of shearing. The results show that electrical resistivity changed on the order of 10^4 times during the water flushing stage of sand specimens and that resistivity decreases with increasing degree of saturation. Depending on the soil type, clay or sand, electric resistivity increases or decreases with increase in mean effective stress during the consolidation stage. For the investigated soil types, using saturated saline at a defined salt content as the pore fluid, two empirical correlations for predicting the drained friction angle or undrained shear strength are established. These findings imply that the electrical resistivity can work toward advancing characterization of soil properties.

INTRODUCTION

The purpose of the research project is to develop a fundamental understanding of how resistivity (a non-destructive geophysical method) can be used to predict geotechnical properties of near-surface sediments in near-shore and deeper water ocean environments through advanced laboratory triaxial testing. A comprehensive laboratory testing program is being conducted at California State University, Los Angeles's Naval Seafloor Research Laboratory to study the relationships between the measured resistivity and soil properties on triaxial specimens in controlled test environments. The research is important because non-destructive methods have the potential to be used to collect important mission specific information autonomously if for example they are mounted to Unmanned Undersea Vehicle (UUV) platforms.

The use of geophysical methods is appealing due to the non-destructive nature of the measuring devices, improved coverage rates, and potential adaptability to UUV platforms that can be used to collect information autonomously. However, despite the advances in overall geophysical sensor technology and data processing techniques, the basic understanding of how to utilize geophysical measurements to determine accurate soil sediment properties (e.g. soil type and strength) is poor. The uncertainties of the few existing correlations are generally unacceptable for engineering design (Schneider and Maynard, unpublished study report, 2012). The goal of this research is to seek the feasibility of using resistivity to predict soil properties accurately and reliably in triaxial setups. Consolidated Undrained (CU) and Drained (CD) tests were conducted on reconstituted Kaolin and Golden Flint sand specimens. A custom-made resistivity cell that can measure soil resistivity at any stage of a triaxial test was fabricated. The results show that, for both fine- and coarse-grained soil saturated with the same pore fluid, strong correlations exist between the strength parameters (undrained shear strength and drained friction angle) and electrical resistivity.

BACKGROUND OF RESISTIVITY MEASUREMENTS

Electrical resistivity is adopted in many different industries for surveying purposes such as medical testing to locate bone fractures, and oil and gas geophysical testing for searching hydrocarbon bearing formations. For geotechnical engineering, electrical resistivity has shown the potential to adopt as a proxy for the spatial and temporal variability of soil properties (e.g., water content and density, undrained shear strength) by performing one-, two-, or three-dimensional surveys (Samouëlian et al. 2005). In order to further improve the geophysical method for the application of geotechnical engineering, better correlations between electrical resistivity and soil properties are needed. Nevertheless, the existing correlations are often limited to a single soil type or site such as Long et al. (2012) focuses only on Norwegian marine clays. Moreover, relatively less attention has been given to the correlation between soil strength characteristics and electric resistivity. There is clearly a lack of knowledge of the relationship between electrical resistivity and drained/undrained shear strength from laboratory testing. This mainly stems from the expensive lab testing in terms of taking undisturbed or reconstituted samples and having a set-up that can measure electrical resistivity and shear strength on the same specimen.

Field studies (Braga A. et al. 1999; Oh and Sun 2008; Sudha et al. 2009) have been performed to investigate the relationships between in-situ electrical resistivity and a shear strength index, also known as the Standard Penetration Test, SPT. Cosenza et al. (2006) performed electrical resistivity measurements along with Dynamic Cone Penetration Test (DCPT). Since a single index cannot enclose the high spatial and temporal variations of other soil properties such as fabric, density, and fluid composition, weak correlations were found between field shear strength indices and electrical resistivity for SPTs and DCPTs. However, the parameters that control the measured resistivity values on soil specimens can be better determined in a controlled laboratory environment. Long et al. (2012) showed that for Norwegian marine clays, there is a strong correlation between the electrical resistivity and remolded shear strength through fall cone tests. The electrical resistivity decreases sharply with an increase in remolded shear strength. Siddiqui and Osman (2013) investigated the drained shear strength of sands and silty sand by utilizing electrical resistivity measurements in direct shear tests. Results shows that a relatively poor correlation exists between the electrical resistivity and friction angle (R^2=0.29 for all samples). The authors further showed that R^2 is increased to 0.45, if water content (w) is included in the empirical correlation for ϕ as follows:

$$\phi = 39.187 + 0.001\rho - 61.336 * w$$

Electrical current is conducted through soil differently based on soil type; therefore, different ranges of electrical resistivity values are expected for distinct types of soil (Figure 1). The electrical properties of clay depend on its soil fabric because the diffuse double layer formed between the clay particles has a more significant effect than free pore water in terms of electrical conductivity, which is the reciprocal of resistivity (Waxman and Smits 1968). In general, the electrical conductivity levels of clay are higher than those from sand because of the relatively high conductivity in the diffuse double layer (Fukue et al. 1999). For coarse grained soil, the electric current flows through the porous fluid (Jackson 1975). If the geo-material media is saturated with more conductive media (i.e., saline) that contains dissolved salts, it further assists in conducting electrical current. When these salts dissolve into ions, they carry an electrical current through the pore fluid. Therefore, electrical resistivity of sand is primarily dependent on the electrical resistivity of pore fluid and the porosity of the soil. Electric current passes mostly through the pore fluid, while the solid particles and air act as insulators. The soil resistivity values of deionized and saline water are estimated to be around 40 and 0.5 Ω-m respectively, (Van Dam and Meulenkamp 1967).

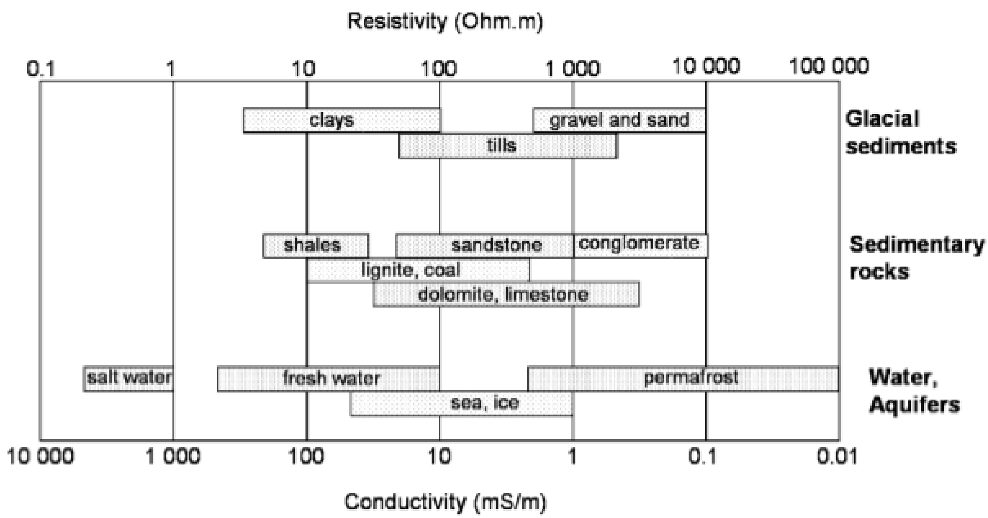

Figure 1. Typical ranges of electrical resistivity of earth materials (original from (Palacky 1987) modified by (Samouëlian et al. 2005)).

Early attempts at distinguishing resistivity come up in Archie's law (Archie 1942) and a correlation with saturation was formed in McNeill (1990). (Archie 1942) provides the important and pioneering study in the topic and comes up with the following widely used unified correlation (known as Archie's law) for both fine- and coarse-grained soils:

$$\rho = a\rho_w n^{-m}$$

where ρ_w is the pore electrical resistivity of the pore fluid, n is the soil porosity, and a and m are constants that depend on the type of soil. The electrical resistivity, ρ, of the soil increases when the resistivity of the pore fluid increases, or porosity decreases. When making the connection to saturation, McNeill (1990) provides an equation with a better understanding of how electrical resistivity of unsaturated soil, the Degree of Saturation, *S*, and an empirical parameter, *B*, are related in the following equation.

$$\frac{\rho}{\rho_{sat}} = S^{-B}$$

The electrical resistivity must be normalized by that of the saturated state in order to see the change of electrical resistivity throughout the soil. The above equation shows that the electrical resistivity decreases with an increase of degree of saturation.

Electrical resistivity surveys provide appealing advantages for quality control in construction of compacted clay liners, because it can scan a larger volume of soil more efficiently. Water content, hydraulic conductivity, and compaction conditions are very important to the performance of compacted clay liners; and therefore, many studies are performed. Past studies (Cosenza et al. 2006; Samouëlian et al. 2005) found that strong correlations exist between electrical resistivity and volumetric water content. Abu-Hassanein et al. (1996) evaluated the electrical resistivity of compacted clays with different plasticity and concluded that a unique correlation between electrical resistivity and hydraulic conductivity can be established for some soils. Moreover, for predicting compaction performance, the electrical resistivity for the soil on the dry side of optimum is high, whereas the electrical resistivity is lower when the soil is compacted to the wet-side of optimum water content.

TESTING PROGRAM

Two types of soil were used in this study: Golden Flint Sand and Edgar Plastic Kaolin (EPK). Nine sand specimens were reconstituted by the dry pluviation method (with the exception of Test#7, which used the wet pluviation method) as documented in (Kwan and El Mohtar 2018). Properties of the Golden Flint Sand include a minimum unit weight (γ_{min}) of 14.2 kN/m^3, a maximum unit weight (γ_{max}) of 16.8 kN/m^3, a specific gravity (G_s) of 2.65, a median diameter (D_{50}) of 0.21 mm and based on the United Soil Classification System (USCS) is considered to be SP which is poorly graded sand. The sand specimens were flushed with CO_2 to replace the air and is more easily dissolved when the saline with a salt concentration of 30 g/L (close to sea water) is introduced. Then, the specimens were back-pressure saturated prior to the stage of consolidation. All sand specimens were sheared under drained conditions. Four clay specimens were reconstituted by the EPK powder, which is commercially available from R.T. Vanderbitt Holding Company, Inc., using the method of slurry-based consolidation as described in (Suzuki and Dyvik 2017). The consolidation box used in this study has a square inner area of 322 cm^2 and can produce four 7.1 cm diameter triaxial specimens. Dry kaolin powder was first mixed in a slurry state, targeting water content of 120 %, with 30 g/L saline. The liquid limit (LL) is 60 and the plastic limit (PL) is 30 and according to the USCS, it is classified as CH which is a high plasticity clay. The slurry was then slowly poured in the box with gentle horizontal vibration to remove trapped air bubbles. For the following two weeks, the soil slurry was consolidated to 50 kPa with at least four loading stages (5, 12.5, 25 and 50 kPa) in a triaxial frame. The consolidated rectangular soil block was then cut into four columnar specimens (9 cm * 9 cm * 23 cm), each sealed with two layers of plastic bags, and then stored in a cooler to preserve moisture. Each columnar specimen was further trimmed into cylindrical shape with a diameter of 7.1 cm before mounting into the resistivity-triaxial cell. All clay specimens were sheared under undrained condition after consolidated to targeted stresses.

The reconstituted soil specimens were tested in a custom made triaxial cell that can measure electrical resistivity as shown on Figure 2 (Geocomp 2016). While working as a cell for typical triaxial testing, the setup allows top and bottom caps to connect to the resistance meter (Miller 400A) through two cables (Figure 2). The Miller400A device can measure electrical resistance through a range of 0.01Ω to 1.1MΩ. From both the top and bottom plates, a cable connects it to the resistance meter and the current is sent and received by the electrodes from inside the resistance meter. This allows for a non-destructive setup as the electrodes are not inserted into the soil specimen, but the current is transmitted through the two caps with flat and conductive surfaces contacting a soil specimen (Figure 2). The two cables pass through the top and bottom plates of the triaxial cell and are divided into a four-array needle probe electrode (P1, P2, C1 and C2) which are connected to the resistance meter. Two input electrodes are connected to a voltage source, P1 and P2, and as the current passes through the soil the signal is received by the other two output electrodes, C1 and C2 (Figure 2). For a parallel circuit, the resistivity, R, is calculated as a function of the measured resistance, ρ, area of the specimen area, A, and distance between each pair of electrodes, specimen height, L, (McMiller 2014).

$$R = \rho * \frac{L}{A}$$

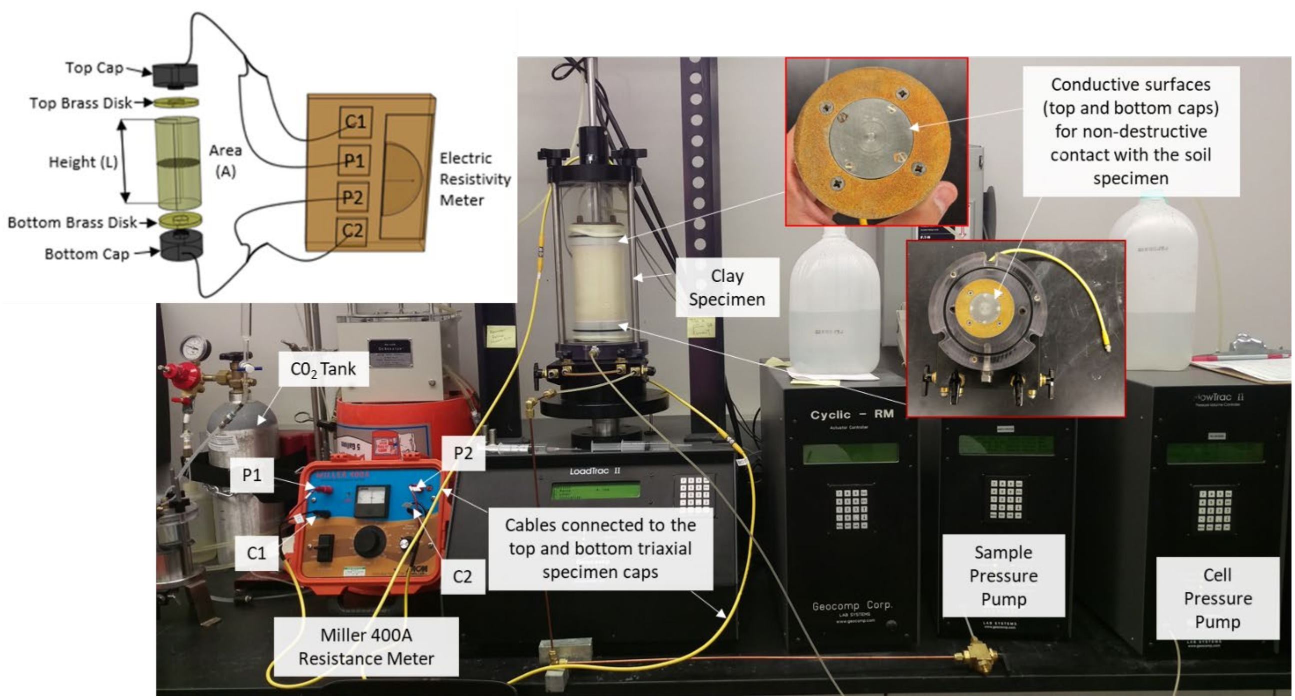

Figure 2. Overall setup of the Geocomp Triaxial apparatus equipped with electrical resistivity measurement.

The assembled resistivity-triaxial cell was then tested using either a Geocomp or Geotac made Triaxial apparatus at the Seafloor Engineering Laboratory at California State University, Los Angeles. Tables 1 and 2 summarize testing conditions and results for the CD tests for the sand specimens, and CU tests for the clay specimens, respectively. Test numbers 1 through 9 refer to tests performed with sand specimens and test numbers 10 through 13 refer to clay tests. In Tables

1 and 2, the variables are defined as follows: SW is salt water, B-Value is the saturation ratio of the soil, D_r is relative density, $\sigma'_{1,max}$ and $\sigma'_{3,max}$ are the maximum vertical and confining stresses applied during consolidation phase respectively, σ'_1 and σ'_3 are the stress levels right before entering the shearing phase respectively, φ'_{cv} and φ'_p are the constant volume friction angle for loose sand and peak friction angle for dense sand respectively. The R values (electrical resistivity) in Tables 1 and 2 are measurements at the time right before shearing started.

Table 1. Summary of Consolidated Drained tests on Golden Flint Sand

Test No.	Pore Fluid*	B-Value	D_r %	$\sigma'_{1,max}$ kPa	$\sigma'_{3,max}$ kPa	σ'_1 kPa	σ'_3 kPa	φ'_{cv} °	φ'_p °	R Ω-m	# of resistivity measurement
1	SW	0.97	24.6	398.9	199.9	398.9	199.9	37.6	-	0.889	59
2	SW	0.97	79.1	50.1	25.1	50.1	25.1	-	46.3	1.093	51
3	SW	0.99	20.4	49.2	25.1	49.2	25.1	38.7	-	1.068	36
4	SW	0.98	19.3	49.1	24.8	49.1	24.8	39.0	-	1.092	52
5	SW	0.98	56.6	49.1	25.1	49.1	25.1	-	44.4	1.069	15
6	SW	0.98	90.7	48.4	25.0	48.4	25.0	-	48.1	1.233	15
7**	SW	0.92	42.6	250.9	199.6	250.9	199.6	38.7	-	2.038	49
8	CW	0.92	27.5	218.6	198.8	218.6	198.8	37.2	-	59.653	45
9	SW	0.93	51.6	370.0	185.0	66.2	24.9	45.7	-	1.171	85

*SW = Saline; CW = Deionized Water

**Reconstituted by Wet Pluviation Method

Table 2. Summary of Consolidated Undrained tests on EPK Clay.

Test No.	Pore Fluid	w.c. %	$\sigma'_{1,max}$ kPa	$\sigma'_{3,max}$ kPa	σ'_1 kPa	σ'_3 kPa	τ_{max} kPa	R Ω-m	# of resistivity measurement
10	SW	40.0	50.3	25.0	48.4	25.0	13.8	1.05	58
11	SW	51.6	51.5	25.1	48.7	25.1	14.6	1.05	45
12	SW	53.3	43.82	23.71	4.35	7.51	9.3	1.05	71
13	SW	55.6	208.7	199.9	208.7	199.9	53.4	1.21	41

Fifty measurements of electric resistivity were made on average for every CU or CD test at various stages (flushing, backpressure, consolidation and shearing) of triaxial tests to seek the feasibility of using resistivity to correlate with soil properties. The first measurement for each specimen was made after placing the top cap and applying a small amount of vacuum (< 10kPa). For coarse grained specimens, the specimens are dry initially; therefore, the resistivity is very high (on the order of 10^4 Ω-m) because there is no pore fluid and the dry solids and air act as insulators. Figure 3a shows the measured electric resistivity versus collected saline (V_{fluid}) normalized by its pore volume (V_v) during the flushing stage. Resistivity measurements were also made during the back-pressure stage, in which the degree of saturation can be indicated by the B-values. During the consolidation stage, various stress levels and histories were applied to the soil specimens and different electrical resistivity behaviors were observed for sand and clay specimens.

RESULTS OF SOIL ELECTRICAL RESISTIVITY AND DISCUSSION

The data collected from the tests show a correlation between a soil's electrical resistivity and soil properties at various stages of triaxial tests (Figures 3 and 4). After one to two pore volumes of saline has been flushed through the soil specimens, the pore fluid is interlinked or partially interlinked from the bottom to top caps; and therefore, the electric resistivity drops significantly to around 1 to 2 Ω-m (Figure 3a), which agrees with typical values reported by Palacky (1987), as depicted on Figure 1. The results confirm that the saline acts as the electrically conducting media. For fine grained specimens, the initial averaged resistivity measurement for the four specimens are 1.35 Ω-m with a standard deviation of 0.46 Ω-m. The results show that the resistivity values decrease with increase in B-values for both sand (Figure 3b) and clay tests (Figure 4b). With a decrease in air void and an increase in degree of saturation, electric resistivity decreases as there is less air void impeding the conducting current. During the consolidation stage, electrical resistivity decreases with increasing mean effective stress (σ'_m) for sand tests (Figure 3c); and increases with increasing σ'_m for clay tests (Figure 4c). Figures 3d and 4d depict the electric resistivity evolutions for sand and clay tests respectively during the shearing stage. There are overall trends that show a decrease in electrical resistivity with the progression of strain increasing during the shear phase of sand specimens, but vice versa for the clay specimen tests.

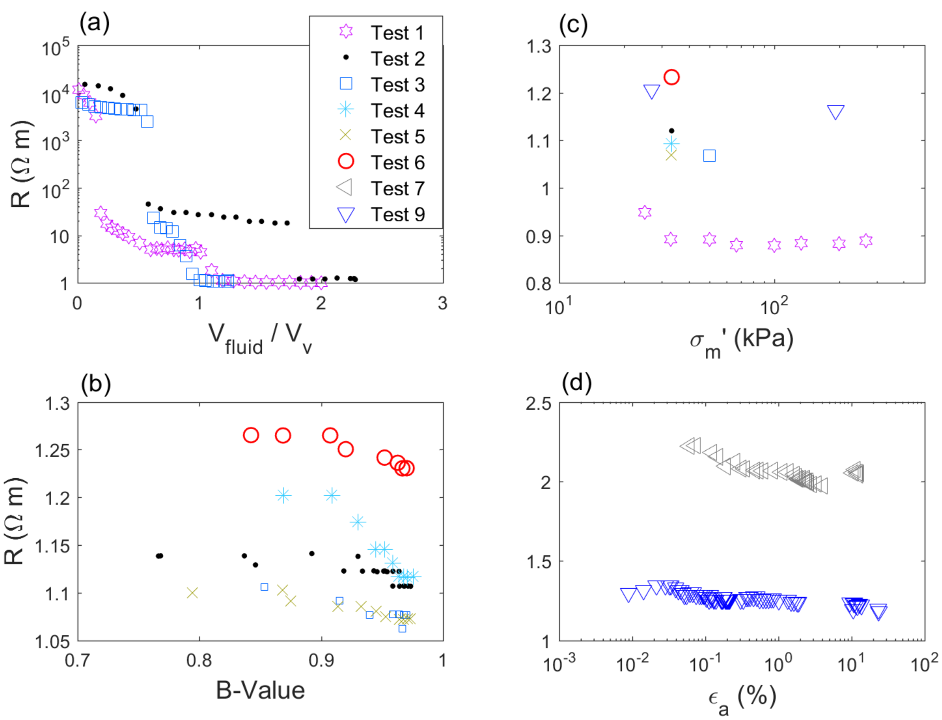

Figure 3. Electrical resistivity measurements at various stages for sand specimens: (a) flushing, (b) back pressure saturation, (c) consolidation, and (d) shearing.

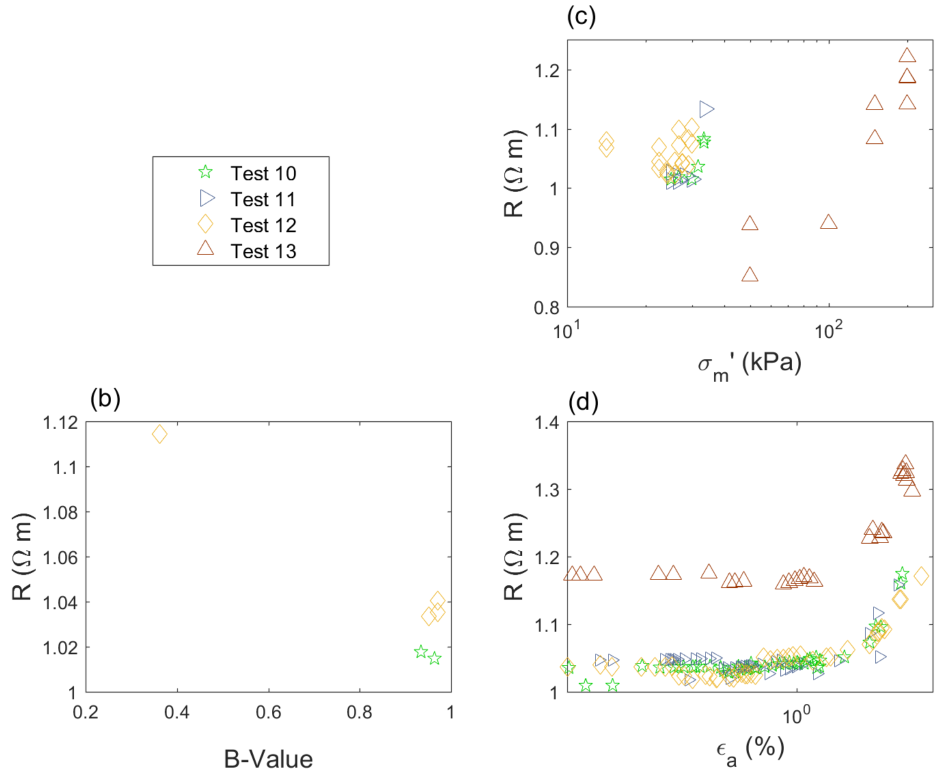

Figure 4. Electrical resistivity measurements at various stages for clay specimens: (b) back pressure saturation, (c) consolidation, and (d) shearing.

For sand samples, the *R*-*φ'* correlations were made based on the *R* values taken right before the shearing stage. While multiple *R* measurements were made during the shearing phase in these two tests: #7 and #9, only one *R* value were taken at the time before shearing in the other tests. According to the figure 3d, the variations of *R* values are within 10% during the shearing phase. Through simple regression analyses, correlations were found between resistivity vs. friction angle (R^2 = 0.53) and resistivity vs. relative density (R^2 = 0.36). Note that seven out of nine sand tests are considered. Test# 7 reconstituted by wet pluviation method and Test# 8 flushed by deionized water are excluded in the regression analyses. The R^2 value significantly improves to 0.95 when both resistivity and relative density are used to predict the friction angle (Figure 5a).

$$\phi' = 26.58 + 0.1217 * D_r + 9.195 * R$$

where *φ'* is in unit of degrees, D_r is in unit of percentage and *R* is in unit of Ω m. The above empirical correlation is established by one type of soil (i.e., Golden Flint sand reconstituted by dry pluviation method) and consistent pore fluid (saline with a salt concentration of 30 g/L). Test#8 contains deionized water as the pore fluid and gives a higher electric resistivity value (60 Ω m) that agree with Figure 1. Wet pluviation method yields fine separation in reconstituted sand specimens (Test#7) and resulted in higher electric resistivity than that those reconstituted by the dry pluviation method.

In the four clay tests, multiple *R* measurements were taken during the shearing phase. Therefore, correlations between the soil strength and electrical resistivity can be established in two scenarios: before shearing and at the failure condition (peak shear stress). While the *R* value taken before shearing can represent the soil condition when geophysical survey is taking place, the R value measured at the peak shear stress is a better representation of the failing condition. Figure 5b shows the two correlations in different scenarios. Based on the four clay tests, the following equation shows the correlation between the maximum shear stress, τ_{max} (or undrained shear strength, S_u in kPa) and its electric resistivity, R (Ω m), at the failure condition:

$$S_u = 154.8 * R - 156.6$$

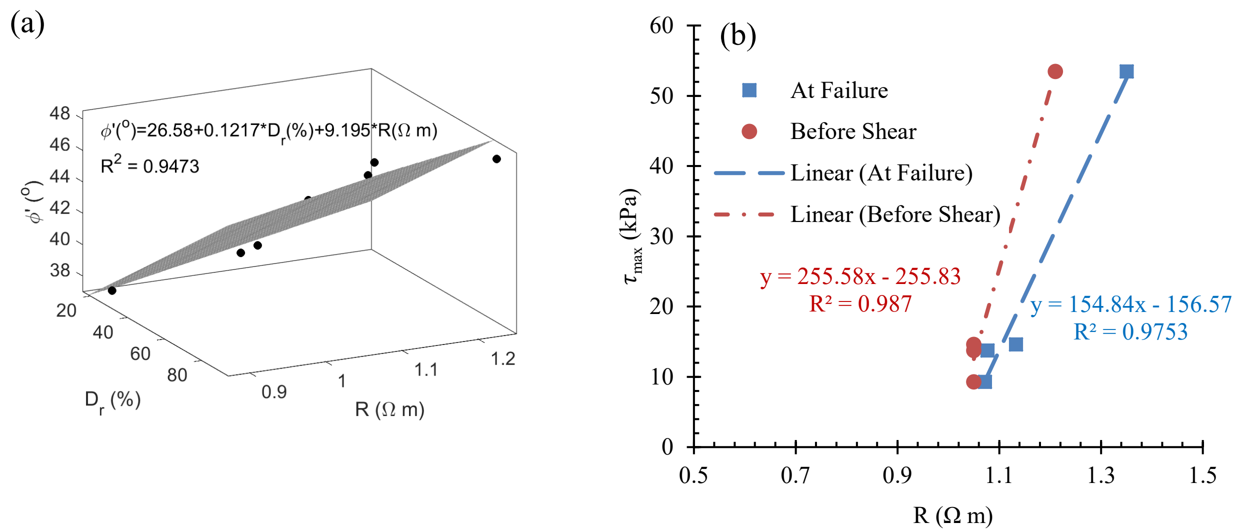

Figure 5. (a) Correlation between sand density, friction angle, and electrical resistivity. (b) Correlation between clay undrained shear strength and electrical resistivity.

CONCLUSION

This study investigated the feasibility of using electrical resistivity to correlate with the soil strength parameters (drained friction angle for sands and undrained shear strength for clays) through a custom triaxial device setup. The experimental program consists of nine consolidated drained tests on reconstituted Golden Flint sand specimens and four consolidated undrained tests on reconstituted Kaolin clay specimens. The experimental results confirm that electrical current conducted through a soil specimen differs depending on the soil type. For coarse grained soils, electrical current conducts through the pore fluid which is reflected during the flushing stage. The electric resistivity decreases by an order of 10^4 times once the pore fluid is interlinked or partially interlinked. Higher values of electrical resistivity were measured for the test that was flushed with deionized water and reconstituted by a different method. An empirical correlation relating drained friction angle with relative density and electrical resistivity is established for the specific Golden Flint sand saturated with saline at a defined salt content. For fine grained soils, electrical current is conducted through the mobilized ions in the diffuse double layer. Empirical correlations between undrained shear strength and electrical resistivity for the reconstituted Kaolin clay are established. Through the preliminary experimental study, the use of electrical resistivity to determine soil strength characteristics is promising for a given soil type and pore fluid. For future studies, the authors recommend to investigate the effect of salt content variation (i.e., different ion strengths) for coarse-grained soil and various types of clay mineral for fined-grained soil.

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REFERENCES

Abu-Hassanein, Z., Benson, C. H., and Blotz, L. R. (1996). “Electrical Resistivity of Compacted Clays.” *Journal of Geotechnical Engineering*, 122(5), 397–406.

Archie, G. E. (1942). “The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics.” *Transactions of the AIME*, 146, 54–62.

Braga A., Malagutti, W., Dourado J., and Chang H. (1999). “Correlation of electrical resistivity and induced polarization data with geotechnical survey SPT measurements.” *Journal of Environmental and Engineering Geophysics*, 4(2), 123–130.

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.

Van Dam, J. C., and Meulenkamp, J. J. (1967). “Some Results of The Geo-Electrical Resistivity Method in Ground Water Investigations in the Netherlands.” *Geophysical Prospecting*, 92–115.

Fukue, M., Minato, T., Horibe, H., and Taya, N. (1999). “The micro-structures of clay given by resistivity measurements.” *Engineering Geology*, 54(1–2), 43–53.

Geocomp. (2016). *Soil Resistivity User’s Manual*. Acton, MA.

Jackson, P. D. (1975). “An electrical resistivity method for evaluating the in-situ porosity of clean marine sands.” *Marine Geotechnology*, 1(2), 91–115.

Kwan, W. S. and El Mohtar, C. (2018). “A review on sand sample reconstitution methods and procedures for undrained simple shear test.” *International Journal of Geotechnical Engineering*.

McMiller. (2014). *Miller 400A Analog Resistance Meter User’s Manual*. Sebastian, FL.

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.

Palacky, G. J. (1987). “Clay mapping using electromagnetic methods.” *First Break*, 5(8), 295–306.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G. (2005). “Electrical resistivity survey in soil science: A review.” *Soil and Tillage Research*.

Sudha, K., Israil, M., Mittal, S., and Rai, J. (2009). “Soil characterization using electrical resistivity tomography and geotechnical investigations.” *Journal of Applied Geophysics*, Elsevier B.V., 67(1), 74–79.

Suzuki, Y., and Dyvik, R. (2017). “Comparisons of Two Reconstitution Methods for Clay Specimens.” *Geotechnical Frontiers 2017: Geotechnical Materials, Modeling, and Testing (GSP 280)*, 347–357.

Waxman, M. H., and Smits, L. M. (1968). “Electrical Conductivities in Oil-Bearing Shaly Sands.” *Society of Petroleum Engineers Journal*, 8(2), 107–122.