concentrators forcing that point to pass the peak strength with a given amount of displacement. Once the peak strength has passed at one point along the failure surface, the stress is shifted to another point, causing it to pass the peak, and so on. In this way, a progressive failure can be initiated, and the strength along the entire length (or majority) of a slip surface will decrease as a function of displacement to a lower strength range bounded by the softened and residual strengths. Figure 6 shows the idealized response of a stiff, fissured clay during a drained direct shear test (Skempton 1970), which illustrates the reduction in shear strength as a function of displacement that would occur at one point and eventually progress to a portion or the entire length of a slip surface. The results obtained from this study (Table 2) shows a 42% reduction cohesion of Yazoo clay soil from its Peak shear strength to fully soften strength and 87% reduction of cohesion to its residual shear strength from Peak shear strength. On the other hand, the friction angle dropped only 8% in fully softened shear strength and 48% in residual shear strength when compared to the peak shear strength.

In this study, an accumulated one-directional displacement of 38mm (1.5 in.) for a single sample (multistage test) were used to mobilize a post-peak strength that appeared to be a relatively steady-state condition. The stress value at this condition is taken as the residual strength. Numerous studies have been conducted to date that examines techniques for determining the residual strength of clay and the amount of displacement required to achieve that minimum strength. Two of these studies, mentioned previously LaGatta (1970) and Lupini et al. (1981), specifically investigated residual strength for a variety of clay soils including Pepper shale, Cucaracha shale, and London clay. Results from these studies indicated that displacement of 12.7 mm (0.5 in.) per normal stress increment would mobilize the post-peak strength, but that as much as 889 mm (35 in.) of displacement was needed to mobilize the true residual strength for some soils. Based on this study, it is observed that the peak shear strength of the Yazoo clay is mobilized with within the 12.7 mm (0.5 in) displacement. However, the residual shear strength test was conducted up to 190 mm ((7.5 in) displacement and reaches to the residual shear strength. However, more study with higher deformation is recommended to determine the residual shear strength of the Yazoo clay.

CONCLUSION

The current study was conducted considering three shear strength of Yazoo clay soil. The study can be concluded as:

1. The Peak drained shear strength is higher at the compacted phase. Typically, with the peak shear strength, the factor of safety of the slope will be higher and should not be recommended in the slope stability analysis on Yazoo clay.
2. A 42% reduction cohesion of Yazoo clay soil from its Peak Shear strength to fully soften strength and 87% reduction of cohesion to its residual shear strength from Peak Shear strength. On the other hand, the friction angle dropped only 8% in fully softened shear strength and 48% in residual shear strength when compared to the peak shear strength.
3. In current practice in Jackson metroplex in Mississippi, the failure of the slope usually takes place at fully soften shear strength, with the presence of rainfall. More study is recommended on these aspects to improve the current design practice of the highway embankments in this area.

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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 an increasing degree of saturation. Depending on the soil type, clay or sand, electrical resistivity increases or decreases with an 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 for collecting 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 and improved coverage rates. However, despite the advances in overall geophysical sensor technology and data processing techniques, the basic understanding of how to

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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 locating hydrocarbon bearing formations. For geotechnical engineering, electrical resistivity has shown the potential to be adopted as a proxy for the spatial and temporal variability of soil properties (e.g., water content, density, and undrained shear strength) by performing one-, two-, or three-dimensional surveys (Samouëlian et al. 2005). In order to further improve geophysical methods for application in 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 (e.g., Long et al. (2012) focusing only on Norwegian marine clays). Moreover, relatively less attention has been given to the correlation between soil strength characteristics and electrical 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 high cost of 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 sands by utilizing electrical resistivity measurements in direct shear tests. Results show 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

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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 that contains dissolved salts (i.e., saline), it further assists in conducting electric current. When these salts dissolve into ions, they carry an electric 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).

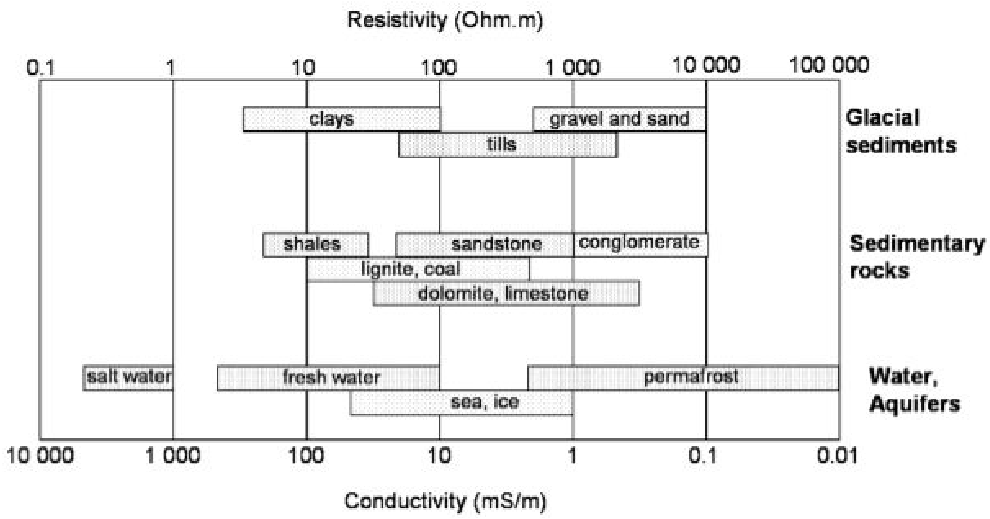

Figure 1. Typical ranges of electrical resistivity of earth materials (original from (Palacky 1987) modified by (Samouëlian et al. 2005)).

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 on 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 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 increasing degree of saturation.

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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, and a median diameter (D_{50}) of 0.21 mm. Based on the United Soil Classification System (USCS), Golden Flint Sand is classified as SP, poorly graded sand. The sand specimens were flushed with CO_2 to replace the air, as CO_2 is more easily dissolved when the saline with a salt concentration of 30 g/L (close to sea water) is introduced. The specimens were then subject to back-pressure saturation prior to the consolidation stage. 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, with a target water content of 120 %, using 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 into 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 a series of 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 a cylindrical shape with a diameter of 7.1 cm before mounting onto 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 connection is made to the resistance meter and a 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 rather the current is transmitted through the two platens with flat and conductive surfaces that contact the soil specimen (Figure 2). The two cables pass through the

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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).

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

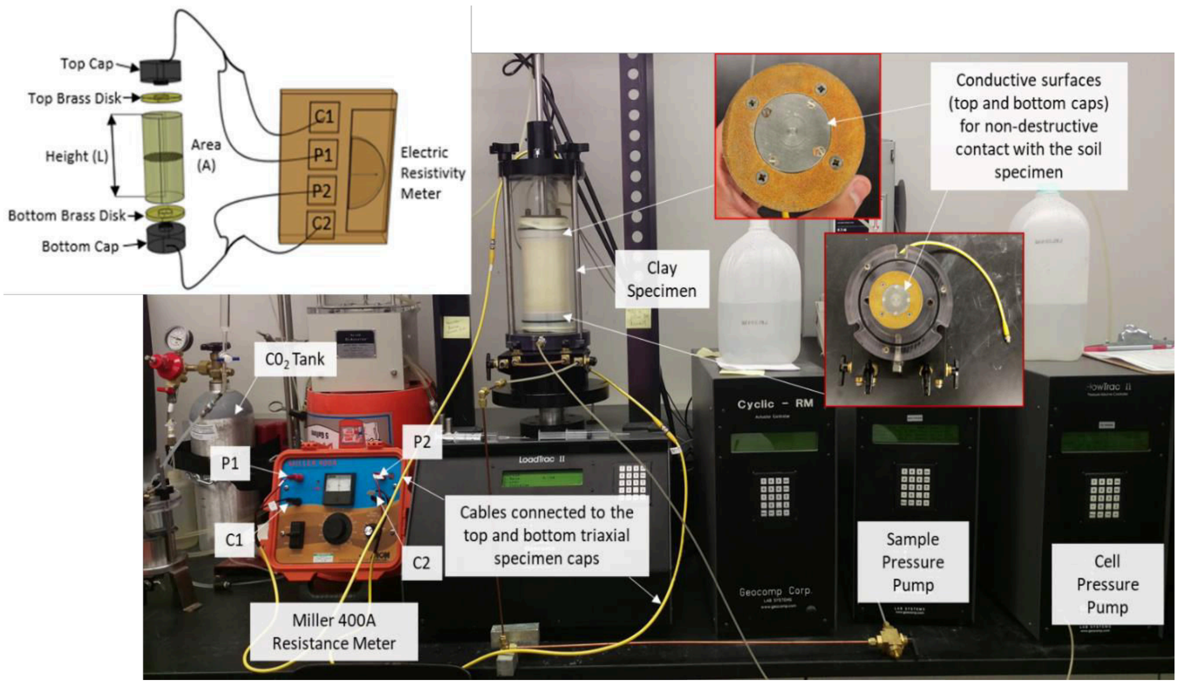

Figure 2. Overall setup of the Geocomp Triaxial apparatus equipped with electrical resistivity measurement.

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

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,

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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, w.c. is water content, $\sigma'_{1,max}$ 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, and τ_{max} is the measured maximum shear stress. The R values (electrical resistivity) in Tables 1 and 2 are measured right before the start of the shearing phase.

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

On average, fifty measurements of electrical resistivity were made at various stages (flushing, backpressure, consolidation and shearing) for every CU and CD triaxial test 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). Coarse grained specimens are dry initially, therefore having a large resistivity measurement (on the order of 10^4 Ω-m) due to the lack of pore fluid and the air voids acting as an insulator. Figure 3a shows the measured electrical 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 relationships between soil electrical resistivity and soil properties at various stages of triaxial tests (Figures 3 and 4). After one to two pore volumes of saline is flushed through the soil specimens, the pore fluid is interlinked or partially interlinked from the bottom to top caps. This causes the electrical resistivity to drop 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 an 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, electrical resistivity decreases as there is less air void impeding the current. During the consolidation stage, electrical resistivity decreases as mean effective stress (σ'_m) increases for sand tests (Figure 3c); on the other hand, electrical resistivity increases with an increasing σ'_m for clay tests (Figure 4c). Figures 3d and 4d depict the electrical resistivity evolutions for sand and clay tests respectively

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during the shearing stage. There are overall trends that show electrical resistivity decreasing with the progression of axial strain during the shear phase of sand specimens, but vice versa for the clay specimen tests.

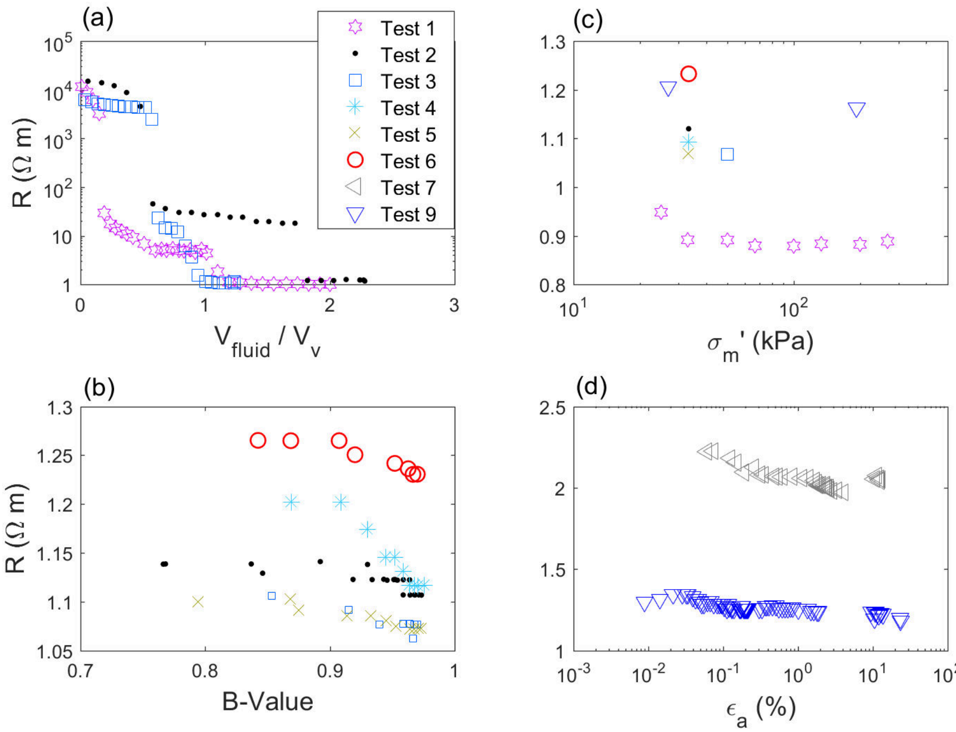

Figure 3. Electrical resistivity measurements at various stages for sand specimens: (a) flushing, (b) back pressure saturation, (c) consolidation, and (d) shearing.

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 tests #7 and #9, only one *R* value was taken at the time before shearing in the other tests. According to the Figure 3d, the variation 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 only 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 through simple linear regression methods 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 electrical 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 a higher electrical resistivity than in specimens reconstituted by the dry pluviation method.

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