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Combining Shear Wave Velocity and Electrical Resistivity for Improving Predictions of Soil Strength Properties

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Abstract: This paper presents a study on determining if correlations between soil strength and a geophysical parameter, shear wave velocity or electrical resistivity, can be statistically improved through considering both. The findings have the potential to be used in ocean applications using an automated unmanned undersea vehicle surveying the seafloor by non-contact geophysical methods. The existing correlations between a geophysical parameter and soil strength are generally too poor for seafloor engineering design. An experimental program consisting of unconfined compression tests and advanced triaxial tests with geophysical measurements on reconstituted Kaolin and Golden Flint sand samples is conducted. Results from simple linear regression and regression with multiple variables identified shear wave velocity to be more effective than electrical resistivity in predicting soil shear strength. It was also found that when combined, the two parameters were more effective than using one.

Keywords: Shear wave velocity; electrical resistivity; shear strength; regression analysis; seafloor engineering.

1 Introduction

The purpose of the investigation was to evaluate the effectiveness of two geophysical parameters, shear (S-) wave velocity (V_s) and electrical resistivity (ρ), individually and combined, in predicting soil shear strength (S_u). A comprehensive laboratory testing program utilizing triaxial tests (unconfined compression, consolidated undrained, and consolidated drained) with geophysical measurement is being conducted at California State University, Los Angeles's Naval Seafloor Research Laboratory to study the relationship between the measured geophysical values and corresponding soil strength. The research is important because non-contact methods have the potential to advance the technology in seafloor engineering, particularly in sediment property characterization through Unmanned Undersea Vehicles (UUV). Two custom-made apparatuses that can measure S-wave velocity or electrical resistivity at any stage of a triaxial test were fabricated. For each unconfined compression test, the two parameters can be measured simultaneously before the shearing phase and, depending on the apparatus, ρ or V_s can be measured throughout the test. The obtained laboratory test results are used to develop a $V_s – \rho – S_u$ relationship which can be very useful for further field demonstration. Regression methods are used to evaluate the effectiveness of the individual and combined geophysical parameters in the prediction of soil strength. The results show that V_s performs better than ρ, and combining V_s and ρ can provide better prediction than V_s alone.

2 Background

Characterization of near-surface seafloor properties is important for trafficability studies, cable routing, and placing of submerged pipelines on soft sediments. Traditional site investigation methods typically use destructive point exploration techniques (e.g., CPT) complemented by a laboratory program. It can be time consuming and costly to cover the area needed for seafloor missions. The use of geophysical methods, on the other hand, is appealing because of the non-destructive or even non-contact nature of the measuring devices, improved coverage rates, and potential adaptability to UUV platforms that can be used to collect information autonomously. However, the few existing correlations that utilize geophysical measurements to predict sediment properties (e.g., soil type and shear strength) have a high level of uncertainty, resulting in unacceptable engineering designs (Schneider and Maynard 2012). To utilize the capability of UUV platforms, it is possible to develop a method that combines body wave profiling with resistivity measurements, the two that show potential in indirectly relating the strength characteristic of soil, to evaluate undrained shear strength of seabed sediments.

Primary (P-) wave velocity and shear (S-) wave velocity are the two body wave techniques in geophysical surveying for soil properties characterization. P-wave velocity is highly sensitive to the characteristics of pore fluid, such as the degree of saturation, but not soil structure (Ayres and Theilen 1999; Kokusho 2000). S-wave velocity, on the other hand, can be indirectly related to the undrained shear strength of soil through the small strain shear modulus, G_{max}. Previous studies (Andersen 2004; Dickenson 1994; L'Heureux and Long 2017) show

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correlations between S-wave velocity obtained from field tests (e.g., multichannel analysis of surface wave, seismic cone penetrometer, cross-hole, and seismic analysis of surface waves) and undrained shear strength, S_u. The bender element technique, documented by Dyvik and Madshus (1985), is a popular method for measuring the S-wave velocity of a soil element in a laboratory setting. Bender elements are small piezoelectric plates (electromechanical transducer) embedded in the top and bottom triaxial caps. The elements can trigger a shear wave transmission from one cap and detect the signal at the other cap after traveling through the mounted soil specimen. S-wave velocity is calculated by dividing the measured travel path length by the recorded travel time. Black et al. (2009) tested compacted specimens of Stepwhite Kaolin clay and found a correlation between shear wave velocity from bender element tests and undrained shear strength from unconsolidated undrained triaxial tests and hand vane shear tests in the lab. The results show that there is a linear relationship between S_u and V_s from bender element measurements before shearing. Chan and Ch'ng (2010) studied the relationship between compressive strength, q_u, and V_s in cement-fiber stabilized kaolin clay, subjecting various specimens to S-wave and unconfined strength measurements throughout a range of curing periods. Plotting q_u against V_s resulted in a power-law function with a correlation factor of nearly 90%, suggesting that S-wave velocity can be utilized for estimating the unconfined compressive strength of cement-fiber stabilized soils.

Electric resistivity, ρ, in geophysical applications refers to a measure of how adequately sediments resist the flow of electric current. In the marine environment, seawater has commonly been known as the most conductive medium. The classic work of Archie (1942) has shown that ρ is proportional to soil porosity and the electrical resistivity of the pore fluid. Since porosity is related to other soil properties such as water content, density, and shear strength, electrical resistivity provides the potential to be used as a proxy for characterization of geotechnical engineering properties. Kwan et al. (2019) utilized the same electrical resistivity apparatus used in this study and confirmed the feasibility of predicting shear strength for a given type of sand (drained friction angle) and clay (undrained shear strength) through advanced triaxial tests. Electrical resistivity can survey a larger volume of ground more rapidly than typical point measurement techniques such as penetrometers. This advantage has attracted many studies in the application of electrical resistivity in the quality control of constructing compacted clay liners. Cosenza et al. (2006) and Samouëlian et al. (2005) established sound correlations between ρ and volumetric water content. Electrical resistivity also has the potential to correlate with hydraulic conductivity. Nevertheless, limited studies have investigated the relationship between electric resistivity and soil strength, and the findings are often too site- or soil-type specific; therefore, it is hard to apply to seafloor engineering designs. For example, Long et al. (2012) established a strong correlation between ρ and remolded shear strength of Norwegian marine clays through acoustic survey and laboratory fall cone test. To date, either from the field or laboratory approach, there is has been no attempt to combine two different types of geophysical surveying methods (body wave and resistivity) to predict the strength characteristic of soil.

3 Testing Program

3.1 Clay specimen reconstitution

In this study, sixteen triaxial tests (12 UC tests and 4 CK_oU) were performed on reconstituted clay specimens using the method of slurry-based consolidation as described in Suzuki and Dyvik (2017). All specimens were reconstituted by mixing Edgar Plastic Kaolin (EPK) powder, with distilled water and a salt concentration of 30g/L (close to seawater) if saline clay was desired, aiming for the initial water content of 120%. The slurry mixture was stored for 24 hours to allow moisture homogenization and then gently poured into an assembled stainless-steel reconstitution box with an inner square area of 324 cm^2 and subjected to a series of consolidation stages on a triaxial frame, stopping at the desired stress level (50, 100, or 200 kPa). The reconstituted clay block was then revealed by disassembling the walls of the box, trimming into four columnar specimens (area = 81 cm^2), sealing within two layers of plastic bags, and preserving in moisture-maintained storage.

3.2 Unconfined compression test

The twelve UC tests (Tests #1 to #12 in Table 1) were performed according to ASTM D2166-16 taking both ρ and V_s measurements before the shearing phase and taking measurements of one of the two parameters throughout the shearing phase. For Tests #1 to #6, three specimens were mixed using a saline mixture of 30g/L and Kaolin powder (Test #1 to #3), and another three were mixed using Kaolin powder and distilled water (Test #4 to 6). Each specimen was trimmed into a cylindrical shape with a diameter of 7.1 cm and a diameter to height ratio of 0.5 and placed on a bender element setup (Figure 1c). The pre-shear V_S reading was taken using a signal waveform generator (Figure 1d), before the sample was transferred to the triaxial frame (Figure 1e) and subjected to shearing. Before and during the shearing phase, resistivity measurements were taken through a resistance meter (Figure 1b) and recorded. When shearing, the electrical resistivity was measured approximately every 20 seconds so that the corresponding ρ values to the peak and residue strengths can be recorded.

Electrical resistivity, R, is measured from the Miller 400A Resistance Meter (Figure 1b), and the electrical resistivity, ρ, is calculated as the following:

$$\rho = R * \frac{A}{L} \tag{1}$$

where L is the specimen height and A is the cross-sectional area.

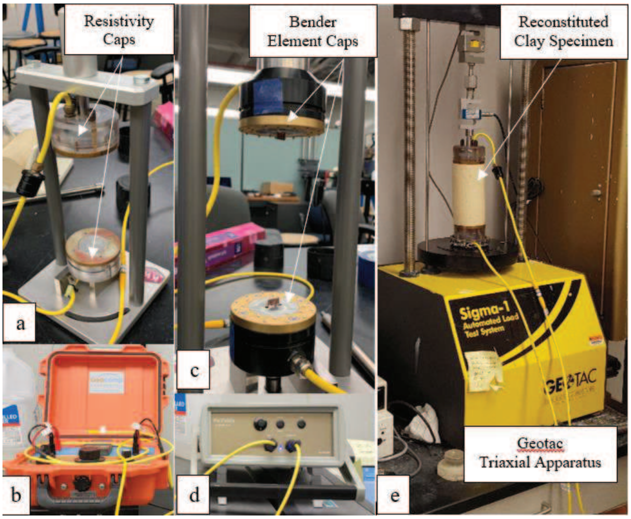

Figure 1. Overall Test Setup for the UC Testing Procedure along with V_s and ρ measurements. (a) and (b): Setup of pre-shear ρ measurement, (c) and (d): Setup of pre-shear V_s measurement, (e) A clay specimen during the shearing phase with continuous ρ measurements.

Table 1. Summary of Triaxial Tests (Background Information and Results). Test No. 1-12: UC tests; Test No. 13-16 CK_oU tests; Test No. 17-18 CK_oD tests.

							Pre-Shear		Peak			Residue		
Test No.	Salt Conc. g/L	F.C. %	σ'_v / σ'_m kPa	γ g/cm³	W.C. %	G kPa	ρ_{pre} Ω-m	$V_{s,pre}$ m/s	$S_{u,max}$ kPa	ρ_{qmax} Ω-m	$V_{s,qmax}$ m/s	$S_{u,resid}$ kPa	ρ_{resid} Ω-m	$V_{s,resid}$ m/s
1	30	100	45	1.60	53.3	191.3	3.2	57.4	6.5	2.0	-	5.9	2.28	-
2	30	100	100	1.72	45.9	3652	2.1	79.7	16.6	1.5	-	10.3	1.55	-
3	30	100	200	1.75	41.2	5922	2.9	86.9	32.9	1.6	-	20.5	1.73	-
4	0	100	50	1.63	57.4	1725	410	52.5	7.1	398	-	5.2	434	-
5	0	100	100	1.59	54.7	2355	465	71.3	14.2	449	-	9.1	485	-
6	0	100	200	1.73	44.8	2815	1238	91.7	35.7	485	-	11.2	560	-
7	30	100	50	1.67	49.7	140.5	1.50	59.1	7.7	-	66.1	5.5	-	61.5
8	30	100	100	1.69	47.1	478.8	2.73	79.2	15.1	-	72.8	11.4	-	60.2
9	30	100	200	1.75	41.3	741.0	8.42	80.8	39.7	-	119.2	27.2	-	109
10	0	100	50	1.62	57.0	273.1	652	52.2	7.6	-	48.3	8.2	-	44.4
11	0	100	100	1.64	52.3	1315	759	77.5	17.0	-	78.3	16.6	-	74.3
12	0	100	200	1.73	43.2	1337	731	100	39.2	-	108.6	27.2	-	82.9
13	30	100	32.8	1.69	46.4	4235	-	68.4	14.3	-	64.4	12.1	-	76.0
14	30	100	33	1.68	47.4	10657	1.05	-	14.6	1.13	-	15	1.14	-
15	30	100	5.4	1.67	51.2	12462	1.05	-	9.25	1.07	-	6.7	1.17	-
16	30	100	27.7	1.66	53	2024	-	64.3	8.62	-	55.5	6.9	-	42.9
17	30	0	33.1	1.53	-	28723	1.066	-	21.1	-	-	19.3	-	-
18	30	0	32.8	1.51	-	46421	-	97.7	20.5	-	131.9	19.6	-	91.0

For UC Tests #7 to #12, V_s values were measured during the shearing phase. The clay samples were trimmed to a diameter of 6.4 cm, fitting the bender element caps and using the resistivity setup to measure the pre-shear resistivity (Figure 1a). The specimens were then transferred to the triaxial frame with the bender element caps installed. V_s readings were continuously taken during each test to capture the readings at the peak and residual strengths. The frequency of the wave generator (Figure 1d) was adjusted until a clear response signal could be seen. On average, seven V_s measurements were taken during the shearing phase for each test. The response time of the wave passing through the test specimen was measured, and the velocity of the wave was calculated by dividing the height of the specimen by the response time.

3.3 Anisotropic consolidated undrained and drained test

Four anisotropic consolidated undrained (CK_oU) tests (Test #13 to 16) were performed on clay samples, for which the reconstitution procedure is the same as the UC tests described above (slurry-based consolidation box with targeted stress of 50 kPa). Two anisotropic consolidated drained (CK_oD) tests (Tests # 17 and 18) were performed on sand samples that were reconstituted using a dry pluviation method and flushed with saline solution. The six tests have a k_o value of 0.5, and the specimens were subjected to low-stress levels to mimic the shallow sediments of the seafloor environment. Due to the limitations of the testing apparatus, only one type of geophysical parameter could be measured for each test; therefore two trials were run for each test condition (Tests #13 and 14; Tests #15 and 16; Tests #17 and 18). For Test# 15 and 16, the two tests were subjected to the same maximum mean effective stress (σ'_m), 33.3 kPa, but were unloaded to different stress levels of 27 kPa and 5 kPa. The S_u values obtained from each pair are comparable. Table 1 summarizes all test information. SW (Saline Water) clay specimens contain 30g/L saline water, and DW (Distilled Water) clay specimens contain pure distilled water (i.e., salt concentration = 0). W.C is the water content of the specimen after testing, G is the shear modulus, S_u is the undrained shear strength, ρ is the electrical resistivity, V_s is shear wave velocity.

4 Data Analysis and Discussion

4.1 Results of electrical resistivity and S-wave velocity

The independent variables to be considered for correlating undrained shear strength (S_u) in this analysis are resistivity (ρ) and shear wave velocity (V_s). Table 1 shows that the ρ values are inconsistent depending on the pore fluid types (Saline, SW vs. Distilled water, DW) and test types (UC vs. CK_oU and CK_oD). The calculated ρ values were very low for salt pore water and very high for clean pore water. This phenomenon can be explained through Archie's Law, that states that the electrical resistivity of soil increases or decreases along with the electrical resistivity of the pore fluid (Archie 1942). SW is more conductive than DW. The calculated pre-shear V_s values for the 18 tests generally agree with the values obtained from correlations relating to undrained shear strength reported in the literature (Andersen 2004; Dickenson 1994; L'Heureux and Long 2017).

4.2 Regression analysis

Using the data recorded for each of the aforementioned geophysical parameters, simple linear regression analysis with one independent variable (V_s or ρ) and regression analysis with two independent variables (V_s and ρ) were performed in Matlab utilizing the curve fitting tool to study the correlations between the geophysical parameters and undrained shear strength of soil. Depending on the test type and test phase (pre-shear, peak, and residue), the number of data points per regression may vary between 6 to 15 points. As previously stated in the testing program, under the UC test setup, ρ and V_s are both able to be measured before shearing phase. However, while the shearing stage is in progress, only one type of measurement can be taken depending on the type of custom-made triaxial caps being used (e.g. not able to take bender element readings with the resistivity caps). This leads to different data quantities when considering before shear, during shear, and residual data points.

For this paper, the analysis will compare each regression according to the adjusted correlation coefficient (R^2_{adj}) rather than the standard correlation coefficient (R^2). Each time a predictor is added to a model, the R^2 will always increase but never decrease. After a certain number of predictors are incorporated, the regression will tend to overfit the data points, causing it to model the noise within the data set. Using R^2_{adj} will allow us to effectively compare regression analyses involving varying numbers of predictors while still accounting for overfitting effects resulting from the addition of multiple predictors.

To separately evaluate the performance of ρ and V_s in predicting S_u, the effect of the pore fluid type is isolated. The conductivity of each soil specimen is dependent on the concentration of dissolved ions within the pore fluid, and the electrical resistivity of a specimen decreases as the conductivity of the pore fluid increases (Samouëlian et al. 2005). This phenomenon can be seen in results shown in Table 1, the resistivity measurements between each pore fluid type at each respective target stress level vary by a factor of 100. Combining the data collected from samples with differing pore fluid types will lead to a low correlation value. Therefore, V_s has advantages over ρ in predicting soil strength, because the correlation between the geophysical parameter and soil strength is independent of the pore fluid type. Considering all data for correlating undrained shear strength, the R^2_{adj} value for using pre-shear V_s is 0.649 and ρ is 0.017. When samples of each pore fluid type are isolated, the variation between each resistivity measurement is significantly reduced.

Table 2 summarizes the result of first-order simple linear regression analysis correlating each and combined of the two parameters measured at the pre-shear stage with the corresponding peak S_u value. The first two columns show results of UC tests only, and the third column indicates results from UC, CK_oU, and CK_oD tests.

The pore fluid used in the CK$_o$U and CK$_o$D specimens were limited to saline pore fluid; therefore only the UC samples with a saline pore fluid were considered for the combined-test analysis. Only pre-shear geophysical measurements are used in the regression analysis because of relatively copious data points while only one type of pore fluid (Saline, SW or Distilled Water, DW) is considered per analysis. Figures 2 and 3 show two examples of linear regression analysis utilizing the Matlab curve fitting tool. Regression analysis also performed in the UC test results to study the correlations between the parameters of V$_s$, ρ, or V$_s$ + ρ and the rigidity index (G/S$_u$), which is more sensitive to the shear wave velocity. However, very weak correlations ($R^2_{adj} < 0.1$) are found.

Table 2. R^2_{adj} Values for Simple Linear Regression Analysis. (#) Represents the number of data points. SW = Saline; DW = Distilled Water. *UC test data; $^+$UC, CK$_o$U, and CK$_o$D test data.

Test Phase	Parameter	SW*	DW*	SW$^+$
Pre-Shear	ρ	0.430 (6)	0.371 (6)	0.427 (9)
	V$_s$	0.523 (6)	0.911 (6)	0.383 (9)
	ρ + V$_s$	0.816 (6)	0.906 (6)	0.793 (9)

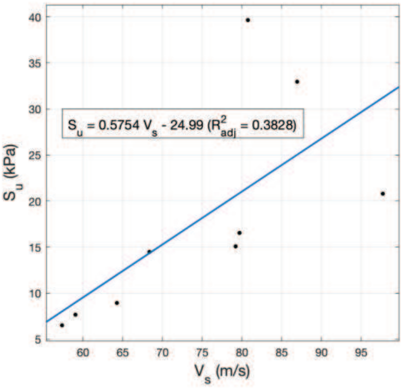

Figure 2. Regression analysis for the correlation between pre-shear V$_s$ and S$_u$ considering all UC, CK$_o$U, and CK$_o$D test data with SW pore fluid.

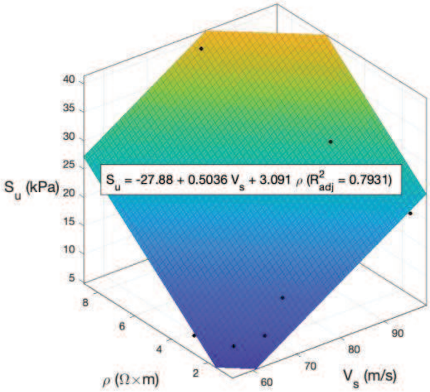

Figure 3. Regression analysis for the correlation between pre-shear V$_s$, ρ, and S$_u$ considering all UC, CK$_o$U, and CK$_o$D test data with SW pore fluid.

It should be noted that the sharp drop in electrical resistivity from pre-shear to shearing phase for the unconfined compression tests, as seen in Table 1 for Tests 1 through 6, may be the result of lack of confining stress and incomplete contact between the soil specimen top and bottom surfaces with the electrical resistivity electrodes. Without confining stress, complete contact may not be achieved until the sample reaches a strain level of around 0.5% during the shearing phase when the sample can deform slightly to close the gap. The experimental results suggest that contact between the electrode and soil surface is crucial for electrical resistivity measurements, but not for S-wave measurements. This observation may also be applicable to UUV development, in that body wave techniques may be preferred to resistivity because the transmission of body waves is relatively independent to the contact between electrode and soil surface than the conduction of electrical current.

A multivariable regression analysis utilizing all collected test data is performed in Matlab using the *fitlm* function (MathWorks 2019) in order to determine if the R^2_{adj} value improves when combining additional independent parameters such as fines content (F.C.) and Salt Concentration (S.C.), for which the values for each test are summarized in Table 1. While the two parameters are independent of the undrained shear strength of soil, F.C. can identify the soil type, and S.C. can detect the pore fluid type. After incorporating the two additional parameters, the R^2_{adj} value dropped from 0.793 to 0.694 as seen from Eq. (2). As previously stated, when data from both fluid types are used, the R^2_{adj} value will drop due to the distinct variation in resistivity values based on pore fluid. Eq. (3) and (4) are the results of the multivariable regression analysis separating the data between saline pore fluid and distilled pore fluid respectively. The results show that R^2_{adj} improved from 0.793 to 0.806 for saline solution specimens and to 0.916 for distilled water specimens.

$$S_u = -51.4245 + 0.0038 \cdot \rho + 0.7199 \cdot V_S + 0.0588 \cdot S.C. + 0.1556 \cdot F.C.\ (R^2_{adj} = 0.694) \tag{2}$$
$$S_u = -46.4238 + 2.6276 \cdot \rho + 0.6585 \cdot V_S + 0.0921 \cdot F.C.\ (R^2_{adj} = 0.806) \tag{3}$$
$$S_u = 0.0071 \cdot \rho + 0.6141 \cdot V_S - 0.3021 \cdot F.C.\ (R^2_{adj} = 0.916) \tag{4}$$

where S$_u$ in kPa, ρ in Ω-m, V$_s$ in m/s, and F.C. in %.

5 Conclusion

This study identified shear wave velocity as the better geophysical parameter in the prediction of soil shear strength than electrical resistivity through an experimental program utilizing triaxial setups with V_s and R measurements. The results also show that combining V_s and ρ provides a better correlation with S_u (V_s-ρ-S_u) than only considering V_s (V_s-S_u), with the criteria that the salt concentration remains constant within the pore fluid. Adding a third parameter to the regression analysis has shown to improve the R^2_{adj} even further. The results are preliminary but have the potential to combine body wave profiling with resistivity measurements to better characterize seafloor sediment strength using a UUV platform.

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