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Characterisation of Granular Solis with Electromagnetic Waves: Some Exploratory Findings

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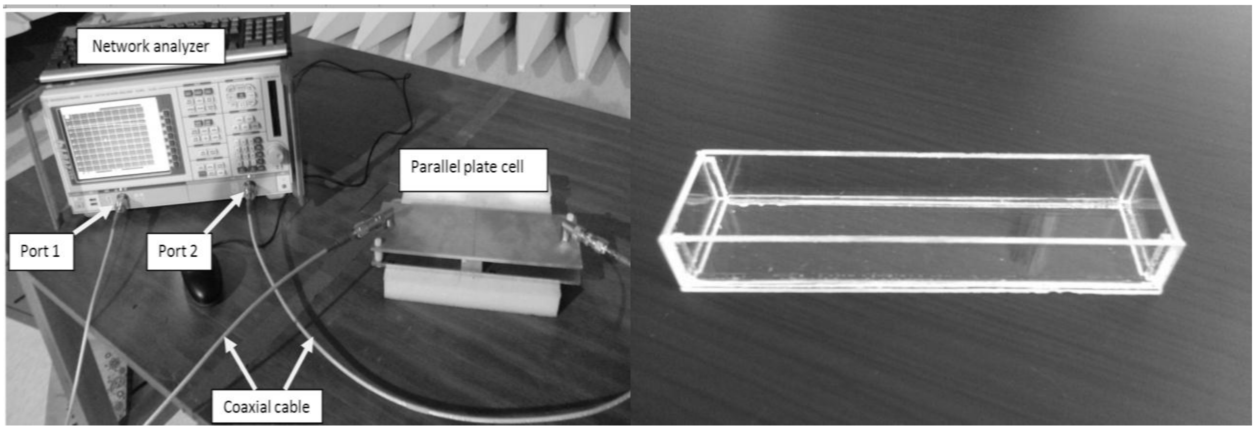
Abstract

A new method is developed for measuring electromagnetic properties of soil using the technique of Network Analyzer (NA). The method is applicable for characterization of granular soil in the laboratory and in the field for various other geotechnical purposes. A network analyzer is an instrument that measures the network parameters of electrical networks. A network analyzer commonly measures s-parameters because reflection and transmission of electrical networks are easy to measure at high frequencies. It is also often used to characterize two-port networks such as amplifiers and filters, but they can be used on networks with an arbitrary number of ports. The type of NA used in this study is NA Rohde & Schwarz (R&S). This study proposes a method of using NA technique for measuring density of soil and for various geotechnical purposes. In order to achieve these goals, the tests were conducted with various density of granular soil to get the dielectric constant, shear strength and shear wave velocity of each density. The result shows a linear relationship between the dielectric constant and the density. Based on this result, the dielectric constant is expected to be increased when the density increasing. For the next step planning, more granular soil specimens with increasing in density will be prepared for the tests to get more accurate results. At the same time, the investigations are carried out to study the effect of sample preparation and density in measurements and experimental result. This significant testing procedure on a variety of soil density is quick, safe and sufficiently accurate for measuring density of granular soils. This study develops the test methodology, and relationships of measured dielectric constant and with density of soil in characterising the granular soils.

Keywords: dielectric constant, shear strength, friction angle, sand

I. INTRODUCTION

The measurement setup for dielectric measurement consists of an in-house developed system at the Electromagnetic Compatibility Research Centre (EMC) of UTHM: a network analyzer (Rohde & Schwarz), a pair of coaxial cable and a parallel plate cell (see Figure 1). The soil sample was placed in an acrylic mould with dimensions of 3 cm in width, 11 cm in length and 2 cm in height. The system was conditioned to measure S-parameters over the frequency range of 10 MHz to 14 GHz. A frequency range of 50- 800 MHz was used in the present study. The measured S-parameters were saved in a Mathlab programme for subsequent computations of the relative permittivity or dielectric constant.



(a) (b)

Figure 1: (a) The electromagnetic properties measurement setup. (b) The acrylic box mould used for holding the test specimen.

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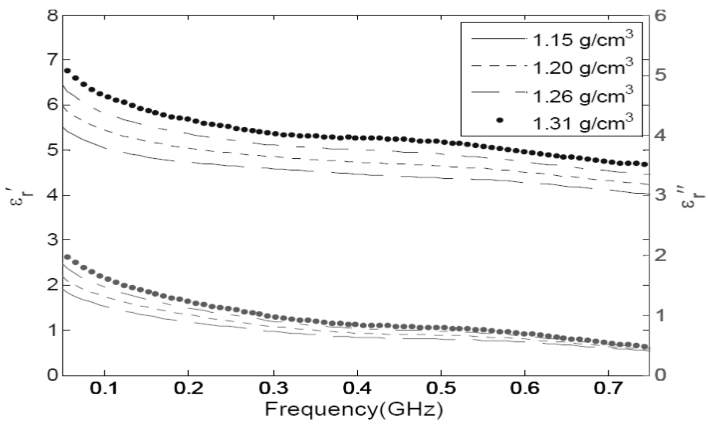


Figure 2: Laboratory-based measurements of dry Hawaiian volcanic red soil showing the electromagnetic properties [1].

Figure 2 shows the relative permittivity (ε'_r) of a dry Hawaiian volcanic soil at different densities. In their attempt to relate the electromagnetic properties to the basic physico-chemical and geotechnical properties of granular soils, Youn et al. [1] concluded that the relative permittivity (ε'_r) increases with increased density (ρ). It can also be observed from Figure 2 that the relative permittivity displays a downward trend as frequency increases. This suggests the frequency-dependency of such measurements on dry granular soils, which should be taken into consideration when taking the readings.

2. MATERIALS USED FOR TESTS

The test specimen consisted mainly of river sand. Figure 3 shows the particle size distribution curve of the sand sample. The uniformity coefficient (C_u) was 3.6 while the coefficient of gradation was 0.95, putting it under the general category of poor graded sands. Classification of the sample is in accordance with BS 1377-1: 1990 [2] and the related tests were conducted with reference to Head [3] too.

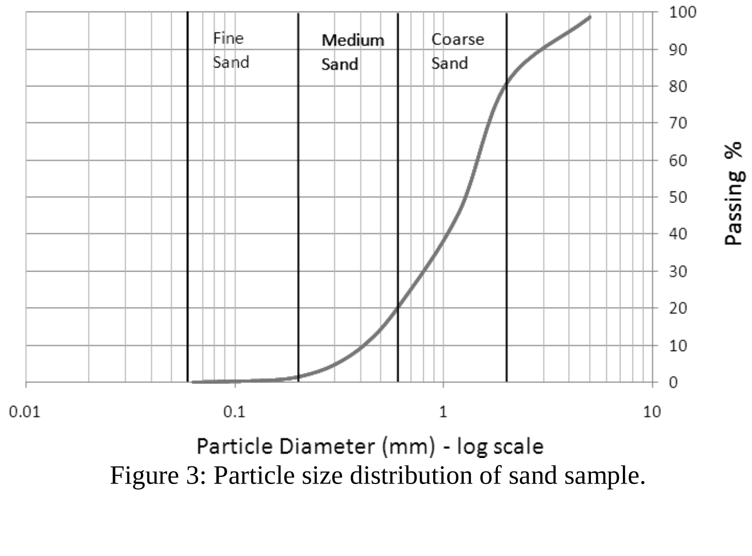


Figure 3: Particle size distribution of sand sample.

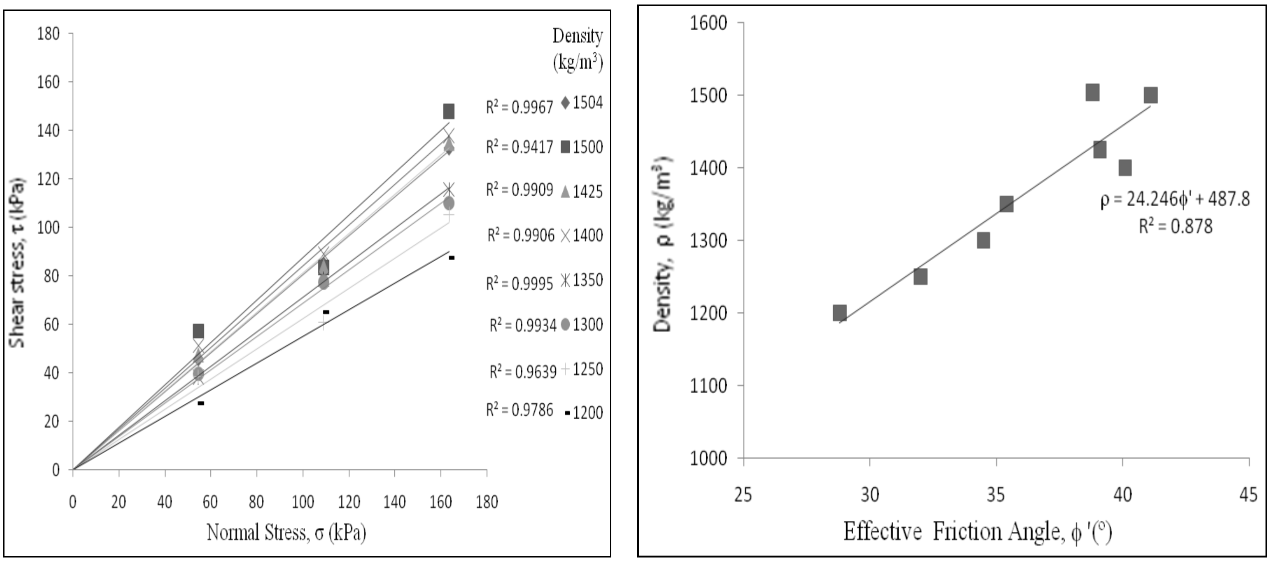
3. MEASUREMENTS

To examine the relationship between electromagnetic properties and engineering properties of granular soil, the relevant laboratory tests were conducted to measure both the engineering and electromagnetic properties. The direct shear tests were conducted to obtain shear strength parameters. The dielectric measurements were conducted with the in-house developed system (Figure 1) in an anechoic chamber. This chamber was suitably insulated to provide an electromagnetic-conducive environment and test conditions for the measurement of communication equipment. The chamber can effectively eliminate outside electromagnetic and other interferences. It can also simulate the free space environment required by the measurements, for obtaining reliable and standardized test data, ensuring the accuracy of signal measurements. Considering that the NA measurements are non-destructive by nature, the same specimens could be tested repeatedly if necessary. This is especially useful for soil specimens with properties which vary with time.

The granular soil used in this research was river sand. The specimens subjected to measurements were prepared at different density, namely 1200 kg/m^3, 1250 kg/m^3, 1300 kg/m^3, 1350 kg/m^3, 1400 kg/m^3, 1425 kg/m^3, 1500 kg/m^3 and 1504 kg/m^3. The specimens were prepared using the funnel pulverisation method, where the sand was gently placed in the mould or shear box through a funnel. The spout of the funnel was maintained at a fixed height from the surface of the placed sand, while the funnel was moved along the length of the mould or shear box to lay the sand in layers. The procedure was indeed repeated several times to ensure consistency in the execution, so as to produce uniform and homogeneous specimens for the tests.

4. DIRECT SHEAR TESTS

Direct shear tests were carried out on natural dry specimens in a standard 60 x 60 x 24.5 mm shear box. Specimens with different densities were prepared and each specimen was subjected to a normal stress (σ) of 55, 110 and 165 kPa. Figure 4a shows typical results from the direct shear tests. For each specimen, the relationship betw een shear stress (τ) and normal stress (*σ*) can be approximately fitted with a straight line through the origin. The effective friction angle of a soil (ϕ') is determined from the inclination of the linear fit.



(a) (b)

Figure 4: (a) Shear stress versus normal stress for specimens at different densities. (b) Relationship between soil's density and effective friction angle.

Table 1: Effective friction angle and R^2 value (coefficient of correlation) from direct shear test

Density (kg/m^3)	Effective friction angle, ϕ' (°)	R^2-value
1504	38.8	0.9967
1500	41.1	0.9417
1425	39.1	0.9909
1400	40.1	0.9906
1350	35.4	0.9995
1300	34.5	0.9934
1250	32.0	0.9639
1200	28.8	0.9786

Table 1 shows the effective friction angle (ϕ') increasing with density (ρ). This observation is consistent with the results of Lim et al. [4]. Figure 4b shows the effective friction angle (ϕ') plotted against the density (ρ) for all the specimens. As expected, the effective friction angle (ϕ') is the lowest for the loosest soil specimen, and increases as the specimen was prepared at greater densities. This confirms that the packing of a sand specimen has a significant effect on the shear strength of the soil.

5. ELECTROMAGNETIC (EM) MEASUREMENT

The electromagnetic properties and geotechnical properties of a granular soil are obviously related as both parameters are density-dependent [1&4]. Thus, the reliability of the EM measurement for geotechnical characterization relies on its capability for accurately determining the soil density. Typically, the EM measurement was repeated ten times for each specimen, and a simple statistical analysis was next conducted to identify any discrepancies. From the results shown in Table 3, the largest standard deviation (S_D) was 0.007309, i.e. the maximum S_D that is considered acceptable in this study. Based on this series of initial calibration measurements, subsequent tests were performed with five times repetition to obtain the S_D values. Table 4 shows the results of measurement from five-time repetition, where the shaded box indicates rejected data due to unacceptable discrepancy (i.e. $S_D > 0.007309$).

Table 3: Dielectric constant (ε) and standard deviation (S_D) from ten-time repetitive measurements.

Density, ρ (kg/m^3)	**Dielectric constant, ε_{AVG}**	**Standard Deviation, S_D**
1317	1.682579	0.005080
1323	1.612653	0.004026
1332	1.690022	0.003708
1363	1.717178	0.005908
1389	1.736167	0.007309

Table 4: Dielectric constant (ε) and standard deviation (S_D) from five-time repetitive measurements.

Density, ρ (kg/m^3)	**Dielectric constant, ε_{AVG}**	**Standard Deviation, s_D**
1200	1.556829	0.002578
1250	1.628419	0.005849
1300	1.661997	0.007228
1327	1.656954	0.004553
1341	1.664527	0.006553
1350	1.619454	0.001686
1376	1.706975	0.005622
1398	1.724719	0.009938
1400	1.671938	0.005207
1403	1.666664	0.002757
1410	1.673794	0.004226
1417	1.675405	0.002722
1421	1.678540	0.008743
1425	1.685908	0.004427
1427	1.717069	0.001399
1431	1.720563	0.008261
1441	1.632155	0.033029
1449	1.726405	0.014682
1452	1.730999	0.004896
1453	1.758237	0.005191
1477	1.785011	0.004729
1486	1.803988	0.001212
1490	1.737105	0.00774
1500	1.791242	0.00507
1504	1.787488	0.002146

The experimental data in Figure 6 clearly shows that the dielectric constant has a linear correlation with soil density. From the same figure, the dielectric constants measured at frequency 541.25 MHz are much lower than those measured at 752 MHz, indicating that the EM's input frequency plays an important role in determining the relationship between the soil densities. Further investigation on these frequency-dependent characteristics is underway.

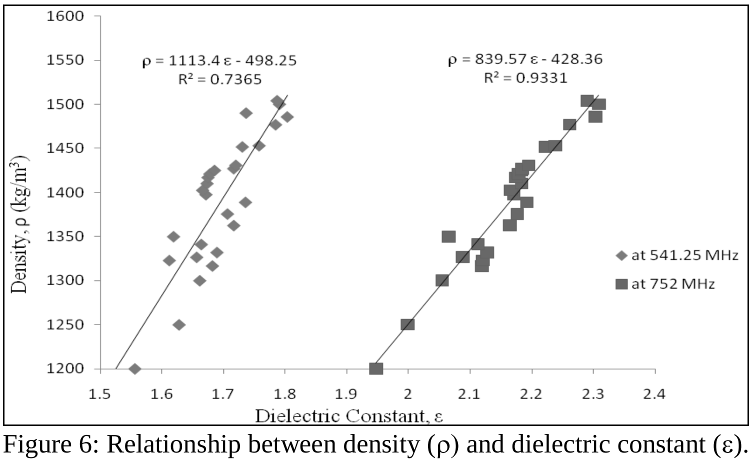


Figure 6: Relationship between density (ρ) and dielectric constant (ε).

6. RELATIONSHIP BETWEEN EM PROPERTIES AND GEOTECHNICAL PROPERTIES

The determination of geotechnical properties of soil is important for civil engineers to predict the behaviour and responses of soils for designing geotechnical structures. The shear strength parameters can be estimated from the measured dielectric constant using correlations as presented in Table 5. The correlation pattern between the parameters can also be inferred from such plots. For instance, the effective friction angle would increase when dielectric constant increases, though as mentioned earlier, the input frequency in the EM measurements could affect the readings obtained. By correlations like these, the effective friction angle of a soil sample could be readily determined.

Table 5: Summary of the equations for all tests.

Figure	Equation		R-squared value, R^2
4b (shear box)	$\rho = 24.246\ \phi' + 487.8$	(i)	0.8780
6 (at 541.25 MHz)	$\rho = 1113.4\ \varepsilon - 498.25$	(ii)	0.7365
6 (at 752 MHz)	$\rho = 839.57\ \varepsilon - 428.36$	(iii)	0.9331

Figure 7 shows the dielectric constant plotted against the effective friction angle. Note that although the plots clearly suggest frequency-dependency, there appears to be an increasingly expanding gap between the two trend lines. This implies that the trend lines could converge at a much lower friction angle (if they are extrapolated backwards), i.e. sand in very loose form. Also, there is a possibility that with higher input frequencies, while the trend line may rise with higher dielectric constants recorded, the relationship may gradually reach a constant inclination or gradient, i.e. the corresponding link between the parameters.

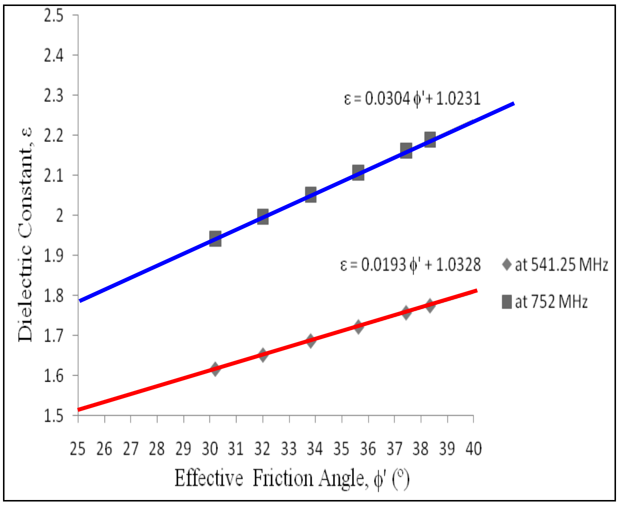


Figure 7: Relationship between dielectric constant, ε and effective friction angle, ϕ'.

8. CONCLUSIONS

The EM properties of soils are not only frequency-dependent but also affected by the soil's density and water content [1&5]. The analyses of S-parameters from the study have shown that the density of granular soils could affect the dielectric constant. The dielectric constant is higher in the frequency range of 700-800 MHz if compared to the frequency range of 500-600 MHz (see Figure 7). In this paper, a new method to measure granular soil's density (ρ) over a specified frequency range of 50-800MHz has been developed. The measured dielectric constant can then be used in the characterization of granular soil by determining the shear strength parameter, i.e. effective friction angle.

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