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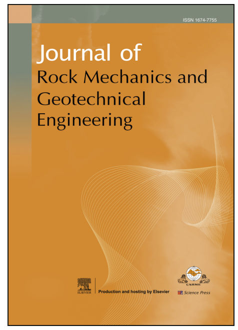

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Non-destructive experimental testing and modeling of electrical impedance behavior of untreated and treated ultra-soft clayey soils

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Abstract: The characterization of ultra-soft clayey soil exhibits extreme challenges due to low shear strength of such material. Hence, inspecting the non-destructive electrical impedance behavior of untreated and treated ultra-soft clayey soils gains more attention. Both shear strength and electrical impedance were measured experimentally for both untreated and treated ultra-soft clayey soils. The shear strength of untreated ultra-soft clayey soil reached 0.17 kPa for 10% bentonite content, while the shear strengths increased to 0.27 kPa and 6.7 kPa for 10% bentonite content treated with 2% lime and 10% polymer, respectively. The electrical impedance of the ultra-soft clayey soil has shown a significant decrease from 1.6 kΩ to 0.607 kΩ when the bentonite content increased from 2% to 10% at a frequency of 300 kHz. The 10% lime and 10% polymer treatments have decreased the electrical impedances of ultra-soft clayey soil with 10% bentonite from 0.607 kΩ to 0.12 kΩ and 0.176 kΩ, respectively, at a frequency of 300 kHz. A new mathematical model has been accordingly proposed to model the non-destructive electrical impedance-frequency relationship for both untreated and treated ultra-soft clayey soils. The new model has shown a good agreement with experimental data with coefficient of determination (R^2) up to 0.99 and root mean square error (*RMSE*) of 0.007 kΩ.
Keywords: ultra-soft clayey soil; bentonite; lime; polymer; shear strength; non-destructive testing; electrical impedance

1. Introduction

In the deep-water seabed, most of the testings are performed to characterize the soft soil within penetration about 3 m to 5 m (Hawkins and Markus, 1998). Several methods such as vane shear test (VST), cone penetration test (CPT) and T-bar method are being used for the downhole testing. In the VST, the torque required to cause failure is a measure of the shear strength of the soil and it is the only stress measured in the test. In addition, the VST assumes the soil to be homogenous and isotropic. Thus, the effect of the intermediate principal stress is ignored compared to other tests such as triaxial compression test (Xiao et al., 2016a, b). The VST has been widely used in offshore site investigations, especially in the Gulf of Mexico (Johnson et al., 1988; Young et al., 1988), while T-bar can be considered as a modified cone penetration device, and both have been used for soft soil characterization (Teh and Houlsby, 1991). However, these methods may face extreme challenges in characterizing the top surface soil of the seabed, since the undrained shear strength of such kind of soil may reach 0.01 kPa (Vipulanandan and Raheem, 2015). The pipelines in the offshore projects are laid off on the seabed soil without any possible fixation (Vipulanandan et al., 2013; Joshaghani and Raheem, 2014; Joshaghani et al., 2016). Hence, characterizing the top soil of the seabed is required.

Many researches have tried to study the shear strength of the soft soil and correlate the shear strength of soft soil with other soil properties such as liquid limit. In 1939, Casagrande proposed average shear strength of soil at the liquid limit as 2.65 kPa taking into account a wide spectrum of values depending on the apparatus used for determining the liquid limit (Casagrande, 1958). Skempton and Northey (1952) described the value of shear strength at the liquid limit of four soils with different values of plasticity index as 0.7-1.75 kPa. Youssef et al. (1965) found that the values of shear strength of clay at the liquid limit of a large number of soils (liquid limit varied from 32% to 190%) ranged from 2.4 kPa to 1.3 kPa with a mean value of 1.7 kPa. Other studies (e.g. Wroth and Wood, 1978; Nagaraj et al., 2012) have indicated that the shear strength of all fine-grained soils at the liquid limit falls within a limited range of about 1.7 kPa to 2 kPa. Dredged nearshore materials exhibit high water contents and low shear strengths, where the shear strength of most clayey soils is less than 0.01 kPa (Bartos, 1977; De Meyer and Mahlerbe, 1987; Raheem and Joshaghani, 2016). Laboratory compression tests have been performed to understand the deformation of ultra-soft clayey soil with water content up to 190% (Bo et al., 2002, 2005). Thus, the existence of the soft soil with very low shear strength is also widespread for onshore soil.

Soft clay deposits are found in various coastal areas and they exhibit poor strength and compressibility. Many methods have been used for improving the shear strength of soft clays. These methods are relied on using lime, cement and fly ash stabilization for treating soft clay soils (Ali et al., 1992; Muntohar, 2004). Some studies used polymer to improve the soft soil properties (e.g. Mohammed and Vipulanandan, 2014). However, few studies have been performed on using polymer to treat ultra-soft clayey soils. Hence, studying the effect of polymer treatment on shear strength of the ultra-soft clayey soil is essential.

Electrical resistivity methods are used to analyze soil properties by measuring the current and voltage between electrodes. Electrical resistivity methods, which were developed in the 20th century, have been used for the examination of geological structures, underground space such as cavities, groundwater contamination, and salinity distribution of aquifer water (Kaya and Fang, 1997). Electrical resistivity survey was first used in the oil/gas exploration and prospecting of conductive bodies. Later it was applied to various engineering fields such as mining, agriculture, environment, archeology, hydrogeology and geotechnics (Siddiqui and Osman, 2012). Different types of soils have different electrical properties due to the composition, structure, water content, and temperature (Bai et al., 2013). Archie (1942) suggested an empirical correlation using laboratory measurements of clean sand stone samples. However, the Archie's law is only appropriate for saturated rock and sandy soil. The electrical conductivity in clayey soil is related to the particle size distribution, where the electric charge density is mainly located at the surface of the clay particles. Electrical current in soils mostly relies on the amount of water remained in the pores. Laboratory tests have shown that the electrical resistivity of soils decreases when water content increases (McCarter, 1984; Fukue et al., 1999). However, the electrical impedance has rarely been used to characterize the ultra-soft clayey soil behavior.

Limited attempts have been made by researchers to explore the phenomenon of electrical resistivity in soils and its relationship with other

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