Geotechnical-Electrical Evaluation of Soil Compaction Parameters, South of Baqubah City

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Abstract

Soil compaction is fundamental for improving the geotechnical properties of a wide range of engineering structures. Evaluation of compaction parameters is crucial for maintaining the long-term performance of these structures. In this study, geotechnical-electrical relationships were adopted to evaluate the compaction parameters of soil south of Baqubah City. Forty-seven soil specimens, collected from eight locations, were prepared and compacted at various conditions that can be found in the geotechnical practice. First, laboratory tests such as sieve analysis, liquid limit, and plastic limit were carried out to characterize and classify the soil based on USCS classification. Second, the specimens were prepared in the lab using different moisture content, dry density, and compaction efforts. Electrical resistivity measurements were then conducted on compacted specimens using Kangda KD2571B2 instrument. All laboratory tests were performed based on ASTM standards. The results revealed that the soil at the site is fine-grained type CL of medium plasticity clay with sand. Optimum Moisture Content OMC and Maximum Dry Density MDD were, respectively, 14.72% and 1.83 g/cm$^3$ for the Standard Proctor compaction test; and 11.08% and 1.90 g/cm$^3$ for the Modified Proctor compaction test. Geotechnical-electrical relationships achieved showed that soil resistivity is strongly influenced by the main compaction parameters; moisture content, dry density, and compaction energy, particularly at low moisture content. A high correlation coefficient (R$^2 > 0.98$) was achieved for the resistivity-degree of saturation and resistivity-volumetric moisture content relationships. These correlations were validated with R$^2$ (0.896-0.934) between the measured and predicted data, which indicates the advantages of adopting the resistivity method as a complementary tool for the preliminary site investigation.

Keywords: Soil compaction; Geotechnical; Electrical Resistivity; Baqubah

1. Introduction

Soil compaction is an essential operation for a wide range of engineering structures, such as earth dams, buildings, slopes, and road embankments. It improves shear strength and reduces the compressibility and subsequent settlement of soils commonly used in these structures (Budhu, 2015).

For a particular soil, the compaction process is affected by key parameters such as moisture content, dry density, and compaction energy. These parameters affect the hydraulic characteristics of soil; hence, evaluation of compaction parameters is crucial for maintaining the performance of engineering structures (Daniel and Benson, 1990). In geotechnical testing, laboratory Standard Proctor ASTM D698, 2012 and Modified Proctor ASTM D1557, 2012 compaction tests have been used to
evaluate optimum compaction characteristics, which serve as criteria to monitor field compaction specifications. However, evaluation of compaction process requires considerable time, effort, and large soil quantity, particularly for large engineering projects (Di Matteo and Spagnoli, 2021). In practice, oven-drying method and soil probes have been applied for measuring soil moisture content (Robinson et al., 2008). Additionally, methods such as the nuclear density gauge, core cutter, and sand cone have been adopted for determining soil density (Al-Shammary et al., 2018). These techniques are destructive and time-consuming with significant drawbacks; therefore, there are ongoing research studies to develop efficient techniques to evaluate these parameters accurately and none destructively (Melo et al., 2021; Shivaparaksh and Sridharan, 2021).

On the other hand, the electrical resistivity method as a geophysical tool has proven successful for geotechnical subsurface characterization (Al-Saadi et al., 2021). Soil resistivity is sensitive to the same factors that control the compaction process such as moisture content, porosity, density, pore structure, and degree of saturation (Samouelian et al., 2005). Therefore, Bryson (2005) concluded in a review paper that several geotechnical properties can be evaluated using this method. Being non-invasive, quick, and cost-effective, this method can be applied at laboratory and field scales. Thus, this technique has increasingly been integrated in site investigation to address a wide range of hydrogeological (Al-Hamedawi et al., 2022) and engineering (Abbas et al., 2022) problems.

In particular, several electrical studies have investigated the relationships between soil resistivity and its properties such as moisture content (Muñoz-Castelblanco et al., 2013), void ratio (Kim et al., 2011), dry density (Beck et al., 2011), degree of saturation (Abu-Hassanein et al., 1996), and compaction degree (Melo et al., 2021). It was found that soil resistivity correlates non-linearly with moisture content, and the resistivity decreases with increasing moisture content (Shah and Singh, 2005). In addition, as air is infinitely resistive, it was reported that increasing dry density lowers soil resistivity particularly dry of optimum, and this influence is less significant wet of optimum (Bai et al., 2013). However, Kibria and Hossain, (2012) stated that soil resistivity is more affected by moisture content than dry density, particularly at low moisture content.

Soil compaction increases its bulk density and degree of saturation and reduces its void ratio. Thus, compacted soils are characterized by low resistivity (Rinaldi and Cuestas, 2002). Number of authors proposed geotechnical-electrical correlations to predict soil properties. For instance, Siddiqui and Osman (2013) presented regression models for predicting moisture content, plasticity index, and friction angle of soil. Similarly, Fallah-Safari et al. (2013) presented correlations between soil resistivity and moisture content, saturation, bulk density, and void ratio of five types of compacted clay soils. They noticed that clays of higher moisture content are characterized by low resistivity, while clays with lower void ratio are found to have lower resistivity, and they concluded that the proposed relationships can be used to predict the geotechnical parameters reasonably well using soil resistivity. Osman et al. (2014) and Hassan and Toll (2015) reported that increasing compaction energy reduces soil resistivity, and this effect is insignificant at moisture content values close to saturation. Roodposhti et al. (2019) and Melo et al. (2021) showed that the resistivity- moisture content relationship is affected by the degree of compaction, and the moisture content has a greater impact on soil resistivity than the degree of compaction. Qiu et al. (2021) reported that increasing dry density causes a decrease in resistivity, and this effect is insignificant at high moisture content.

Recently, new facilities have been proposed at the campus site of the University of Diyala, south of Baqubah City. Soil characterization is vital to evaluate the geotechnical properties at the site. Thus, this work aims to evaluate the compaction parameters of soil specimens sampled from using geotechnical and electrical methods. First, the soil is characterized and classified. Second, geotechnical and electrical relationships are presented and discussed to evaluate soil compaction parameters.
2. Field work

Soil specimens were collected at 1m depth using a hand auger from eight locations distributed in the campus site of the University of Diyala, south of Baqubah City (Fig. 1). The area is flat, with an altitude of 46 m ASL, and is covered by recent sediments made up of fine-grained soil. Once recovered, the specimens were properly sealed in plastic bags and transferred to the laboratory for testing. Forty-seven specimens were prepared and compacted at various conditions that can be found in geotechnical practice.

3. Materials and Methods

Basic index properties tests such as grain size, moisture content, and atterberg limits (liquid and plastic limits) were performed in the lab according to ASTM standards (Table 1). These tests were used to characterize and classify the soil using the USCS system. In addition, Standard Proctor SP and Modified Proctor MP compaction tests (Fig. 2a), were carried out, from which compaction curves were plotted and OMC and MDD were obtained. Furthermore, at different gravimetric moisture content ranging between 5-20%, various compaction efforts using 15-45 blows were applied to additional specimens to examine the influence of compaction parameters (moisture content, dry density/void ratio,
and compaction effort) on soil resistivity. Specimens of location B1 were used to produce the geotechnical-electrical correlations, and other specimens collected from the same area, shown in Fig. 1, were used for validation. Using this method, specimens were compacted wide range of moisture content, dry density, and compaction efforts. Once compacted in the cylindrical ASTM mold, the resistivity of the specimens is measured using Kangda KD2571B2 resistance instrument using the two-electrode method as described in ASTM standard (ASTM G187, 2005), and adopted in the literature (McCarter, 1984; Fukue et al., 1999; Siddiqui and Osman, 2013; Qiu et al., 2021). In this method, schematically shown in Fig. 2b. Two-disc electrodes are attached to the compacted specimen presented in Fig. 2c. The resistivity of the specimen is calculated as follows (ASTM G18, 2005):

$$\rho = \frac{\Delta V}{I \frac{A}{L}}$$  \hspace{1cm} (1)

Where; \( \rho \) (Ohm.m) is the resistivity of the compacted specimen, \( \Delta V \) (volt) is the voltage drop measured between the electrodes, \( I \) (Ampere) is the current applied, \( A \) (m\(^2\)) is the cross-section, and \( L \) (m) is the distance between the electrodes attached to the specimen. This method of resistivity measurement has the advantage of being simple and straightforward with no disturbance to the soil sample, and offers a representative soil resistivity for the whole cylindrical sample (Beck et al., 2011; Qiu et al., 2021).

Table 1. Laboratory tests performed in the current study and the corresponding ASTM standards

<table>
<thead>
<tr>
<th>Laboratory Test</th>
<th>ASTM Standard</th>
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<tbody>
<tr>
<td>Grain size</td>
<td>ASTM D422, (1972)</td>
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<tr>
<td>Moisture content</td>
<td>ASTM D2216, (2019)</td>
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<tr>
<td>Atterberg limits</td>
<td>ASTM D4318, (2005)</td>
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<tr>
<td>Modified proctor test</td>
<td>ASTM D1557, (2012)</td>
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<tr>
<td>Soil Classification USCS</td>
<td>ASTM D2487, (2017)</td>
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Fig. 2. Laboratory work (a) SP and MP compaction tools (b) Schematic diagram of resistivity measurements (c) Laboratory setup for resistivity measurements

The relationships between the measured soil resistivity and compaction parameters (moisture content, dry density/void ratio, and compaction effort) were then explored. Moisture content is a vital physical property that governs the geotechnical characteristics of soils. In geotechnical testing, moisture content can be described using gravimetric (mass) moisture content, volumetric moisture content, and degree of saturation. Gravimetric moisture content \( w \) is measured using the oven drying method, expressed as follows (Budhu, 2015):

$$w = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} \%$$  \hspace{1cm} (2)
Where; \(m_{\text{wet}}\) is the mass of wet soil, and \(m_{\text{dry}}\) is the mass of dry soil. Bulk density of soil \(\rho_b\), directly determined by knowing the specimen’s mass and volume, is used to calculate the dry density \(\rho_d\) of soil expressed as follows:

\[
\rho_b = \frac{m_s + m_w}{V_T} = \rho_d \left(1 + w\right)
\]

(3)

Where; \(m_s\), \(m_w\), and \(V_T\) are the mass of solids, the mass of water, and the total volume of soil specimen, respectively. Increasing dry density of soil due to compaction is associated with decreasing its void ratio \(e\), which can be written as follows:

\[
e = \frac{V_a}{V_s}
\]

(4)

Where; \(V_a\) is the volume of air, and \(V_s\) is the volume of solids. Gravimetric moisture content and dry density are key geotechnical variables that govern the compaction process. These variables are commonly used to generate compaction curves to determine the MDD and OMC of compacted soil. In geotechnical engineering, moisture state can be defined using volumetric moisture content \(\Theta\), which integrates gravimetric moisture content of soil and its dry density, expressed as follows:

\[
\Theta = \frac{\rho_d}{\rho_w}
\]

(5)

Where; \(\rho_w\) denotes the water density. In addition, the degree of saturation \(S\) which relates moisture content, void ratio, and specific gravity of soil, is also used to determine its moisture content. It can be defined as follows:

\[
S = \frac{V_w}{V_p} = \frac{w \cdot G_s}{e}
\]

(5)

Where; \(V_w\) denotes the volume of water that occupies the voids, \(V_p\) denotes the volume of voids, \(G_s\) is the specific gravity. \(S\) ranges from 0-100% or 0-1. Geotechnical-electrical relationships were established between measured soil resistivity and the above-mentioned geotechnical properties related to the compaction process and discussed.

4. Results and Discussion

Conventional geotechnical tests were used to characterize the soil in the study area. Fig. 3 shows the grain size distribution (GZD) of the B1 sample. It was found that the soil can be classified as fine-grained soil with %fines (grains passing through a #200 US Sieve) of about 54%. Percentages of soil contents were gravel 0%, sand 46%, silt 22%, and clay 32%. Therefore, the soil can be considered Sandy Mud. Atterberg limits tests revealed that the Liquid limit (LL) was 39.0%. The plastic limit (PL) was 22.5%, and the plasticity index was 16.5%. Based on the plasticity chart presented in Fig. 4, the soil at the site is fine-grained type CL (medium plasticity clay with sand) according to USCS classification (Budhu, 2015).
Gravimetric moisture content and dry density are fundamental compaction key parameters represented in the compaction curve. Fig. 5 shows compaction curves of SP and MP compacted specimens with the Zero Air Voids (ZAV) line (i.e., $S = 100\%$), and their resistivity data is presented in Fig. 6. Increasing compaction effort from SP to MP compaction increases MDD and lowers OMC (Budhu, 2015). Compaction curves revealed that OMC and MDD were, respectively, 14.72\% and 1.83 g/cm$^3$ for the SP compaction test, and 11.08\% and 1.90 g/cm$^3$ for the MP compaction test. In terms of resistivity, it decreases with increasing moisture content for both SP and MP compaction tests with a high correlation coefficient ($R^2$) of 0.984 and 0.990, respectively. Increasing gravimetric moisture content accelerates electrical conduction, consequently, the resistivity decreases. A similar non-linear trend was reported in the literature (e.g., Shah and Singh, 2005; Qiu et al., 2021). High $R^2$ achieved indicates that the resistivity can reasonably be used to predict the moisture content of soil. It also can be noticed that the resistivity curve of MP compacted specimens is lower than the resistivity curve of SP compacted specimens, and for both compaction procedures, resistivity is high dry of optimum and low wet of optimum. The above behavior can be attributed to fabric changes due to the compaction process (Benson and Daniel, 1990). Increasing compaction effort from SP to MP reduces air void ratio and increases the dry density of soil, hence, soil resistivity of MP compaction curve is lower than that of SP compaction curve, and this effect is clear at low moisture content (i.e., dry of optimum). In addition, when soil specimen is compacted at the dry side of the optimum, soil grains are difficult to remold with a high void ratio and low moisture content, hence relatively higher resistivity. In comparison, when soil specimen is compacted at the wet side optimum, the grains are easily remolded with low voids ratio and high moisture content, hence relatively lower resistivity (Seladji et al., 2010; Hassan and Toll, 2015).

Soil compaction increases the dry density of soil up to the MDD then dry density decreases wet of optimum (Powrie, 2009), as seen in Fig. 5. Therefore, the resistivity is correlated with the dry density in Fig.7, and with void ratio in Fig.8, for specimens compacted using SP and MP compaction. The resistivity decreases abruptly with increasing dry density in Fig. 7, and decreasing void ratio in Fig. 8 up to the MDD (1.83 g/cm$^3$ for SP and 1.90 g/cm$^3$ for MP specimens) then decreases smoothly afterward wet of optimum. Increasing dry density reduces air void, hence, lowers soil resistivity dry of optimum. However, the influence of dry density and void ratio is less significant wet of optimum due to the high moisture content provided for the electrical conduction. Hence, the resistivity is low and governed by the moisture content (Abu-Hassenein et al., 1996; Bai et al., 2013).
The above discussion showed that the resistivity is sensitive and strongly affected by the main compaction parameters; moisture content, dry density (or void ratio), and compaction energy. However, to better investigate these parameters, additional specimens were compacted at different moisture content and dry densities by applying 15-55 blows (Osman et al., 2014). Fig. 9 shows compaction curves of 15-55 blow compacted specimens, and Fig. 10 shows the corresponding resistivity data. As expected, increasing the number of blows increases MDD and reduces OMC (Budhu, 2015). In terms of resistivity, it is none linearly well correlated with gravimetric moisture content, with high $R^2$ ranges between 0.994-0.970. For particular moisture content, increasing the compaction energy applied reduces air voids (increases the moisture content/degree of saturation), which means that electrical paths for the current injected are very well achieved causing a decrease in the resistivity. This behavior is more obvious for specimens compacted at low moisture content (e.g., 4.95%), where changes in compaction effort bridge the air void significantly, therefore, resistivity varied from 122.89 Ohm.m to 88.82 Ohm.m for specimens compacted using 15 and 55 blows, respectively. At higher moisture content (e.g., 19.40%) and close to 100% saturation, soil resistivity is relatively low (< 10 Ohm.m), which indicates...
that the resistivity is less sensitive to the changes in the compaction energy at high moisture levels (Beck et al., 2011).

Furthermore, soil resistivity is plotted against the number of blows in Fig. 11, and against the dry density for different gravimetric moisture content in Fig. 12. Soil resistivity increased linearly with decreasing the compaction energy (or number of blows), and dry density. The slope of the regression lines is relatively high at low moisture and low at high moisture content, which indicates that compaction effort and dry density have a significant impact on soil resistivity at low levels of moisture content, and have a limited effect at high moisture levels (Kibria and Hossain, 2012; Osman et al., 2014).

Fig. 9. Compaction curves using 15-55 blows

Fig. 10. Influence of compaction energy on the resistivity-moisture content relationship

Fig. 11. Soil resistivity versus the number of blows for different moisture content

Fig. 12. Soil resistivity versus dry density for different moisture content

Fig. 13 shows a 3D surface that defines the relationship among the resistivity, gravimetric moisture content and dry density. Increasing dry density and moisture content decreases soil resistivity. Increasing dry density reduces the voids that are filled with air, hence, decreases the resistivity. Similarly, increasing moisture content facilitates the electrical conduction, hence, decreases the resistivity. A similar 3D surface was suggested by Kibria et al. (2012) and Qiu et al. (2021). However, using gravimetric moisture content alone to correlate with soil resistivity, as showed in Fig. 10, can be erroneous as the soil in the field maybe available at different degrees of saturation but the same gravimetric moisture content (McCarter, 1984). Therefore, several authors correlated soil resistivity with the degree of saturation (e.g., Roodposhti et al., 2019) and volumetric moisture content of soil (e.g.,
Beck et al., 2011). Fig. 14 depicts the resistivity-degree of saturation for SP and MP compacted specimens. Soil resistivity decreases with increasing the degree of saturation for both compaction procedures. Increasing the degree of saturation means more moisture is available for electrical conduction, hence, lower soil resistivity. The high $R^2$ of 0.989 and 0.987 for SP and MP compacted specimens, respectively indicates that soil resistivity can be used to predict the degree of saturation. In addition, the resistivity is plotted versus volumetric water content in Fig. 15, for SP and MP compacted specimens. Soil resistivity correlates none linearly very well with the volumetric moisture content with $R^2$ of 0.989 and 0.992 for SP and MP compacted specimens, respectively, which indicates the potential of using soil resistivity for predicting the volumetric moisture content. Moreover, the current findings are compared with previous studies in Fig.16. This indicates a good agreement between the achieved relationships of this study and similar correlations from previous studies for clay soils (McCarter, 1984; Fukue et. al, 1999; Michot et al., 2003; Hassan and Toll, 2015).
To validate the results, the measured (i.e., observed) values of degree of saturation from different locations in the study area were plotted for SP and MP compacted specimens in Figs. 17 and Fig. 18, respectively, versus predicted (i.e., calculated) degree of saturation data using the relationships achieved in Fig. 14. Similarly, the measured values of the volumetric moisture content from different locations in the study area were plotted, respectively, for SP, MP compacted specimens in Figs. 19, and 20, versus predicted values of the volumetric moisture content using the relationships presented in Fig. 15. Blue dashed lines show the 95% prediction interval. High $R^2$ values (0.896-0.934) between the measured and predicted data were achieved which indicate that the geotechnical-electrical relationships presented in this study can be used for preliminary evaluation of the degree of saturation and volumetric moisture.

5. Conclusions

Geotechnical and electrical evaluation of compaction parameters of soil samples collected from south of Baqubah City is presented and discussed in this study. Basic geotechnical laboratory tests showed that the soil in the study area is fine-grained soil type CL with medium plasticity. Standard and modified compaction tests showed that OMC and MDD of the soil are, respectively, 14.72% and 1.83
g/cm³ for SP compaction test; and 11.08% and 1.90 g/cm³ for MP compaction test. Geotechnical-electrical relationships developed using soil specimens prepared at various conditions indicated that the resistivity is affected and sensitive to key compaction parameters; moisture content, dry density, and compaction energy, and this influence is more obvious dry of optimum (i.e., low moisture content). The resistivity decreased none linearly with increasing moisture content. For particular moisture content, increasing dry density causes a linear decrease in soil resistivity. Furthermore, increasing compaction effort abruptly decreases the resistivity, especially at low moisture levels. These findings were explained in terms of variations of pore characteristics due to the compaction process, discussed, and compared with previous studies. It was found that the results of this study are consistent with those reported in the literature. Strong relationships were achieved between soil resistivity and the degree of saturation; and between soil resistivity and the volumetric moisture content with $R^2 > 0.98$. The proposed correlations were validated with high $R^2 (0.896-0.934)$ between the measured and predicted data. The current work demonstrated that the resistivity method can adopted or the preliminary site evaluation. However, it is recommended exploring the influence of different physical and geotechnical properties such as fine content, shear stress, compressibility, etc., on soil resistivity.

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