Academic Science Journal

Geotechnical and Geophysical Methods for Water Content Prediction of Compacted Soil Southern Baqubah City

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Received: 4 July 2023 **Accepted: 10 August 2023**

DOI: https://dx.doi.org/10.24237/ASJ.02.03.777B

Abstract

Water content affects the soil state, consistency, and engineering behavior of various engineering projects. Evaluation of water content is, therefore, crucial to maintain the stability of these projects. Geotechnical and geoelectrical techniques are integrated in this study to characterize the soil, with a particular interest in the water (moisture) content, southern Baqubah City. Twenty soil specimens, manually collected using a hand Auger and the core cutter method, were used. Basic geotechnical tests were first implemented to characterize and classify the soil. Secondly, compaction characteristics referred to as, Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), were determined using Standard Proctor compaction (SPC) and Modified Proctor Compaction (MPC) tests, which are essential to evaluate the compaction process. Thirdly, the resistivity of the compacted specimens was measured and compared with soil water content obtained using the oven drying method. ASTM standards were followed in all laboratory tests. Finally, geotechnical and geoelectrical methods were integrated for water content prediction. The results showed that, based on USCS, the soil is of low plasticity, fine-grained type (CL) and (CL-ML). The average LL, PL, and PI values were 25.50, 18.61, and 6.89, respectively. The average MDD and OMC values were 1.75 g/cm^3, and 17.18%, for SPC tests, and 1.90 g/cm^3 and 13.24%, for MPC tests, respectively. The resistivity was non-linearly correlated with water content with R^2 values (>0.99) for all samples which indicates the potential of using this method, as a non-destructive and low-cost method, for the evaluation of the water content of compacted soils. The relationships between the measured and predicted values for SPC (R^2=0.911) and MPC (R^2=0.934) tests, respectively, confirm the usefulness of using the resistivity method to provide a quick and preliminary evaluation of soil water content.

Keywords: Geotechnical, Geophysical, Resistivity, Water Content, Soil Compaction

استخدام الطرق الجيوتكنيكية والجيوفيزيائية في تقدير المحتوى المائي للتربة المدموكة جنوب مدينة بعقوبة، العراق

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الخلاصة

يعتبر المحتوى المائي للتربة خاصية فيزيائية حاسمة تحدد حالة التربة، قوامها وسلوكها الهندسي. في هذه الدراسة، استخدمت الطرق الجيوتكنيكية والجيوفيزيائية لدراسة التربة وخاصة تقدير محتواها المائي لموقع الحرم الجامعي لجامعة ديالى جنوب مدينة بعقوبة. تم جمع 20 عينة لتحقيق هذا الهدف. أولا، تم القيام بالفحوصات الجيوتكنيكية الأساسية لتحديد نوع التربة وتصنيفها وفق نظام التصنيف الموحد. ثانيا، تم دمك التربة حسب طرق الدمك الاساسية والمحورة لتحديد محتوى الرطوبة المثالي والكثافة الجافة القصوى المهمة لتقييم خصائص دمك التربة وعمل خرائط كنتورية لها في المنطقة، ثالثا، تم قياس المقاومة النوعية الكهربائية لجميع النماذج باستخدام جهاز للمقاومة الكهربائية باتباع طريقة القطبين القياسية. وقد تم الاعتماد على المواصفات القياسية للجمعية الامريكية للفحص والمواد في جميع الفحوصات في الدراسة الحالية. بينت النتائج ان التربة في الموقع هي تربة ناعمة قليلة اللدونة. نوع CL و CL-ML كما بينت ان المقاومة النوعية الكهربائية ترتبط بعلاقة قوية غير خطية مع المحتوى المائي لجميع النماذج التي تم دمكها وفق طريقة الدمك القياسي والمحور وبمعامل ارتباط اكبر من 0.99 والذي يؤكد إمكانية استخدام طريقة المقاومة الكهربائية في تقدير المحتوى المائي للتربة. لقد تم التحقق من هذه العلاقات من خلال مقارنة القيم المقاسة باستخدام طريقة التجفيف بالفرن مع القيم المحسوبة باستخدام طريقة المقاومة النوعية الكهربائية

وبمعامل ارتباط بلغ 0.911 للدمك القياسي و0.934 للدمك المحور وهذا يؤكد امكانية استخدام طريقة المقاومة النوعية الكهربائية كطريقة رخيصة وغير إتلافيه في الحصول على تقييم اولي سريع للمحتوى المائي للتربة.

كلمات مفتاحية : الجيوتكنيكية، الجيوكهربائية، المقاومة النوعية الكهربائية، المحتوى المائي، دمك التربة

Introduction

An accurate evaluation of soil water (moisture) content is fundamental for evaluating the physical and mechanical properties of compacted soils. Water content affects soil state, strength, and hence, the long-term stability of engineering earthworks [1].

Soil water content has been traditionally assessed using a wide spectrum of techniques, such as oven drying method [2] and soil probs [3]. However, these techniques are intrusive, expensive, and of limited spatial resolution [4]. Therefore, in geotechnical testing, there is an increasing need to introduce new low-cost and efficient techniques that can be used to evaluate soil water content non-destructively [5].

The Resistivity method is a cost-effective and non-destructive geophysical method that has been increasingly adopted to address a wide range of geotechnical and environmental problems [6], [7], [8]. In this context, a number of studies have emphasized the usefulness of geotechnical-geoelectrical correlations to predict various geotechnical properties such as dry density [5], water content [9], and the degree of saturation [10]. As the electrical conduction in the soil mainly takes place due to water content, numerous authors have reported a non-linear relationship between the resistivity and water content, and the resistivity increases with decreasing water content and vice versa. However, it increases more rapidly at low water content, where the voids are more filled with air that is ultimately resistive [11],[12], and [13]. In these studies, the resistivity was correlated with gravimetric water content [14], [15] or volumetric water content [12], [16].

Evaluation of water content of compacted soils is essential to characterize the soil for various engineering earthworks. In the laboratory, SPC [17], and MPC [18] tests have been used to evaluate the compaction process. From these, tests, the OMC and MDD are derived to control the compaction specifications. Several authors have investigated the relationships between the resistivity and compaction variables. It was reported that the resistivity decreases with increasing water content and dry density. However, this influence is more significant for soil compacted at the dry side of the optimum [19], [20].

This work aims, first, to characterize the soil at the University of Diyala, southern Baqubah using basic geotechnical tests. Second, to integrate the geotechnical and geoelectrical methods for predicting soil water content. To achieve this goal, soil samples collected from the site were compacted for a wide range of water content using SPC and MPC tests, and the resistivity of compacted specimens was measured and compared with soil water content determined using the oven drying method. Geotechnical-geoelectrical correlations achieved were used for predicting soil water content.

Material and Methods

Twenty soil samples were manually collected from the University of Diyala campus site, Figure (1). Ten samples, collected using a hand Auger Figure (2), were used to characterize the soil at the site. Additional ten samples, collected at the same locations using the core cutter method [21], Figure (3), were used to evaluate the field compaction specifications. Once recovered, the samples were sealed properly and taken to the laboratory for testing. Firstly, basic tests were performed to classify the soil according to USCS [22]. Secondly, Soil specimens were compacted using ASTM SPC and MPC tools, Figure (4). Once compacted, Figure (5), compaction curves were plotted to determine the OMC and MDD of the soil. Thirdly, the compacted specimen was mounted in a plastic tube to facilitate the resistivity measurements with a resistivity meter type Kangda KD2571B2 using the two-electrode method, Figure (6). The resistivity of a compacted soil can be expressed as follows:

$$\rho = \frac{\Delta V}{I}\,\frac{A}{L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

ρ is the resistivity,, ΔV is the voltage difference, I is the current applied, A (m^2) is the specimen's cross-sectional area, and L (m) is the specimen's length. The ASTM standards, listed in Table (1), were followed to carry out all the tests.

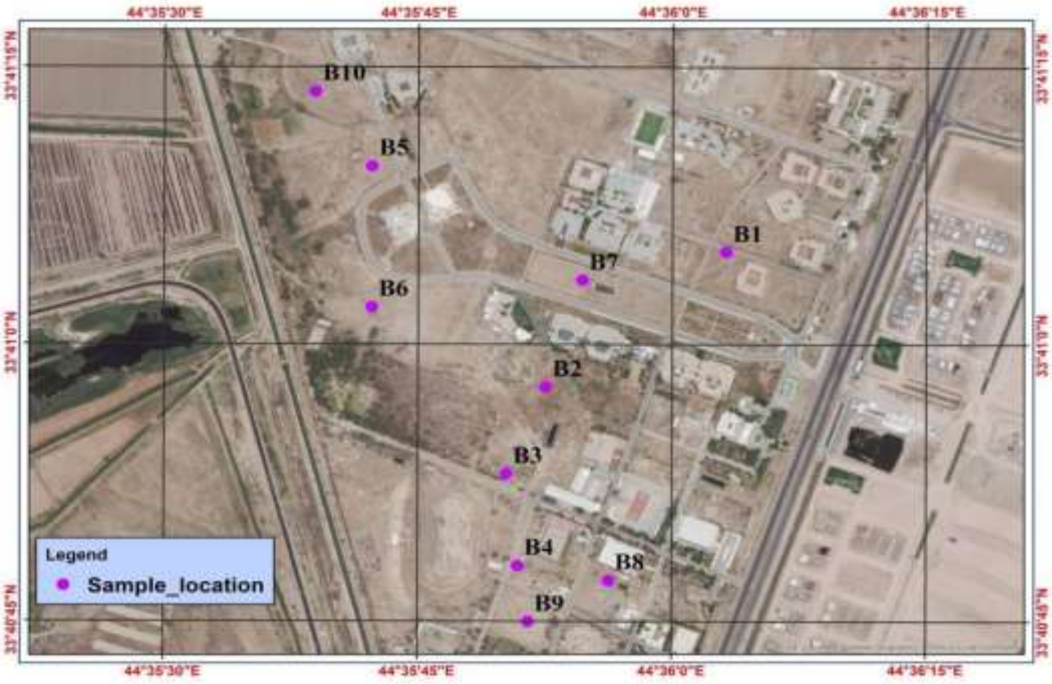

Figure 1: A map showing the locations of soil sampling

Figure 2: Soil sampling using a hand auger

Figure 3: Soil sampling using the core cutter

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Figure 4: Soil compaction tools

Figure 5: Compacted soil specimen

Figure 6: Set up of the ER measurements

Table 1: Laboratory tests and the corresponding ASTM standards followed in this study

LABORATORY TEST	ASTM STANDARD
Water content	ASTM D2216 [2]
Grain size analysisa	ASTM D422 [23]
Atterberg limits	ASTM D4318 [24]
Standard Proctor test	ASTM D698 [17]
Modified Proctor test	ASTM D1557 [18]
Soil resistivity	ASTM G187 [25]

Contour maps of compaction characteristics were drawn using Surfer 11 software. Additionally, the resistivity of compacted specimens was correlated with the corresponding water content, and discussed according to the microstructural changes due to the compaction process. Finally, the integrated geotechnical-geoelectrical relationships achieved were used to predict soil water content.

Results and Discussion:

Geotechnical Characterization:

Table (2) summarizes the results of the geotechnical tests performed in this study. The average natural water content (W%) was 20.89%. The high percentage of fine particles (Silt and Clay) and the low level of groundwater table (less than 2m [26]), contribute to the high W values. The soil's water-holding capacity increases with the high percentage of fine particles, making it more difficult for water to drain from the soil. In addition, the capillary action due to the low level of groundwater contributes to high W values as water fills the voids of the soil. Grain size analysis showed that the average percentages of Gravel, Sand, silt, and clay, were, 0.09%, 17.90%, 64.35%, and 17.67%, respectively. Therefore, all samples were fine-grained as more than 50% of the grains were retained above sieve No. 200 [27]. The averages of the LL, PL, and PI were 25.50, 18.61, and 6.89, respectively. The average Gs was 2.71. According to the plasticity chart shown in Figure (7), LL<50%, therefore, the soil was considered of low plasticity [27]. Therefore, the soil was classified as fine-grained type CL and CL-ML.

Table 2: Geotechnical characterization and classification of soil

NO.	W%	GRAVEL%	SAND%	SILT%	CLAY%	LL%	PL%	PI%	GS	USCS
B1	22.20	0	7.18	80.20	12.60	24.20	17.50	6.70	2.74	CL-M
B2	19.30	0	20.13	71.00	8.87	24.30	18.00	6.30	2.74	CL-M
B3	23.00	0	27.94	61.30	10.80	25.80	18.00	7.80	2.69	CL
B4	18.80	0.16	19.06	54.10	26.70	24.30	18.00	6.30	2.69	CL-M
B5	20.50	0.46	30.29	54.70	14.50	26.00	19.00	7.00	2.68	CL-M
B6	20.50	0	9.25	70.80	20.00	26.50	19.00	7.50	2.68	CL
B7	21.0	0	9.40	73.40	17.20	25.20	18.80	6.40	2.73	CL-M
B8	20.00	0	21.81	67.90	10.30	24.00	17.20	6.80	2.75	CL-M
B9	23.00	0	12.13	57.10	30.80	27.60	20.40	7.20	2.67	CL
B10	20.60	0.26	21.83	53.00	24.90	27.10	20.20	6.90	2.68	CL-M

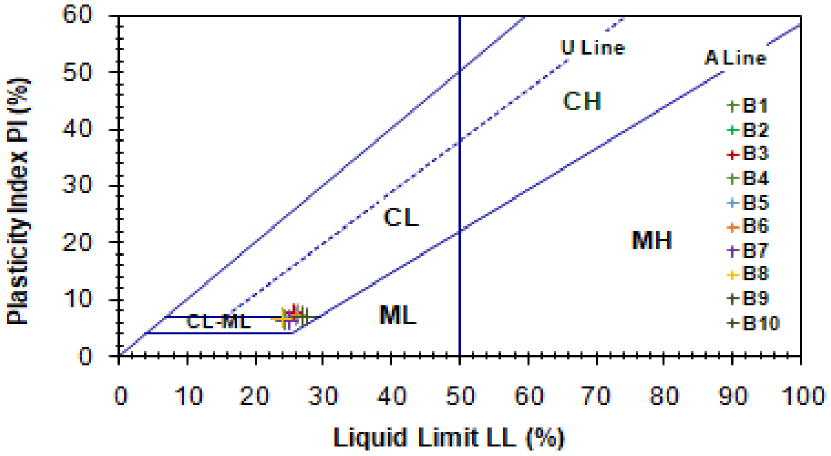
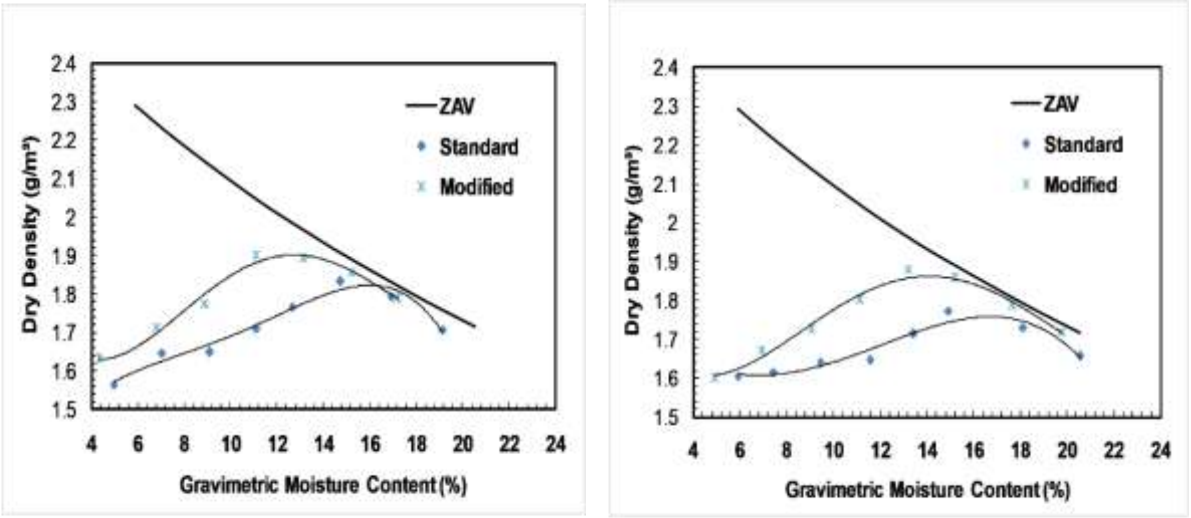


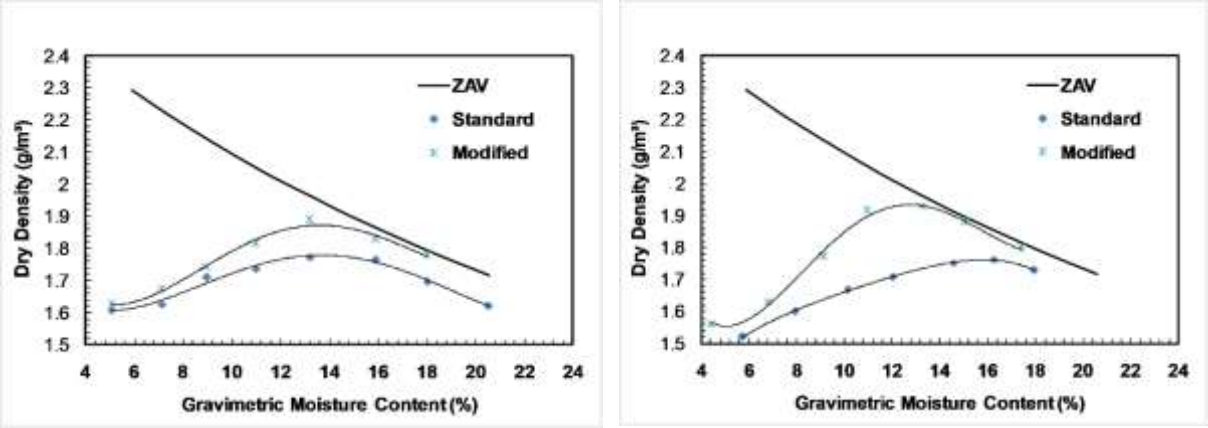
Figure 7: Plasticity chart and soil classification according to USCS

Soil Compaction Characteristics

Compaction characteristics, namely OMC and MDD, are usually determined from compaction curves. The MDD is the highest density that can be achieved at a specific level of compaction energy, while the OMC is the moisture content at which the MDD is achieved [1]. Figure (8) depicts the compaction curves derived from SPC and MPC tests and their Zero Air Void lines (ZAV). The curves reflect the typical bell shape of fine-grained soils. For the SPC tests, the average MDD and OMC values were 1.75 g/cm^3, and 17.18%, respectively. For MPC tests, the average MDD and OMC values were 1.90 g/cm^3 and 13.24%, respectively. As the compaction effort increases from Standard to Modified, the average MDD increases and the OMC decreases [27]. Figures (9) and (10) show, respectively, the MDD variation map using SPC and MPC tests. As expected, increasing the compaction energy increases the average MDD of soil, hence, the average MDD increases. Similarly, Figures (11) and (12) depict, respectively, the OMC variation map of specimens compacted using SPC and MPC tests. Increasing the compaction effort implemented reduces the water content required to reach the OMC [1], hence, the average OMC decreases. Figure (13) presents the compaction ratio [21] map of the study area. It ranged from 78.5 to 92.5%. The high values of the compaction ratio were noticed in locations affected by repeated vehicle movements.

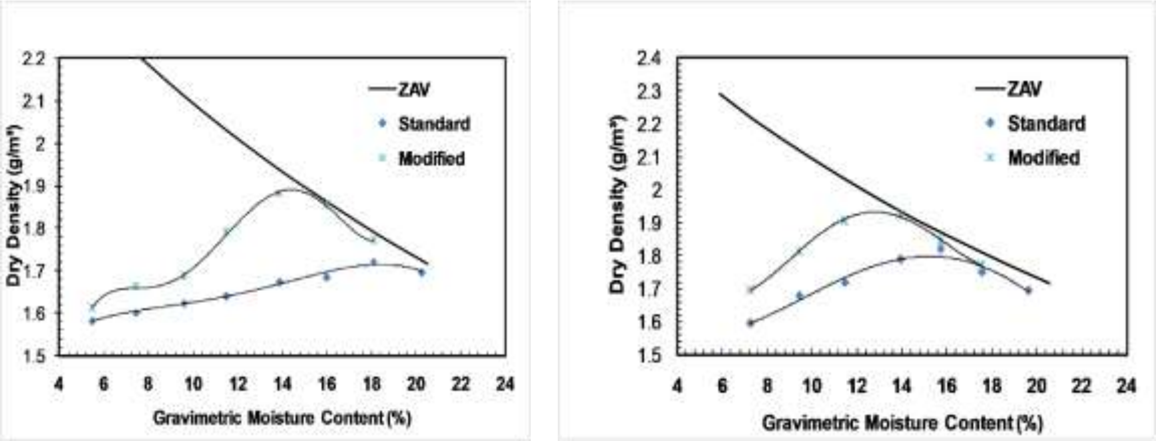


(a) B1 (b) B2



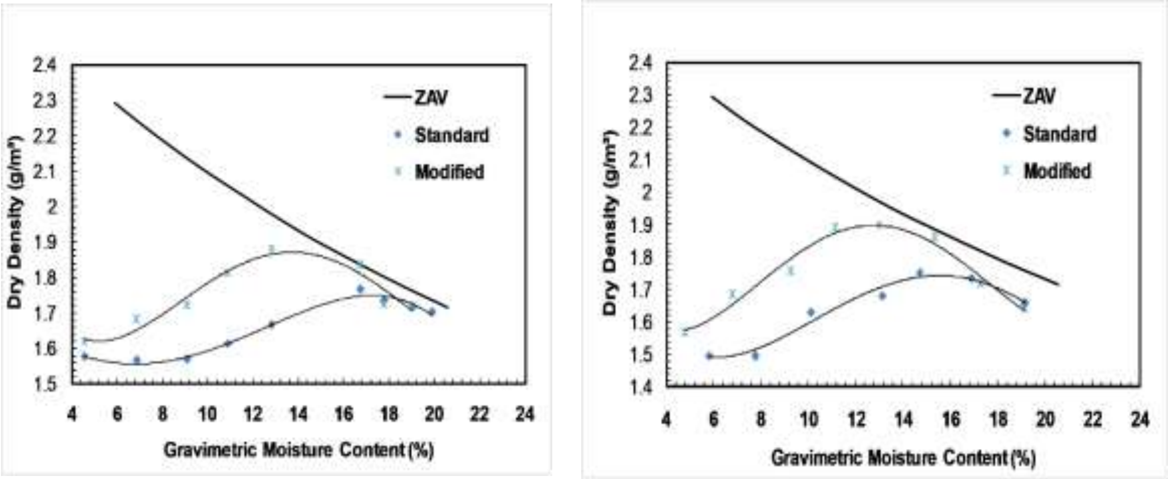
(c) B3

(d) B4



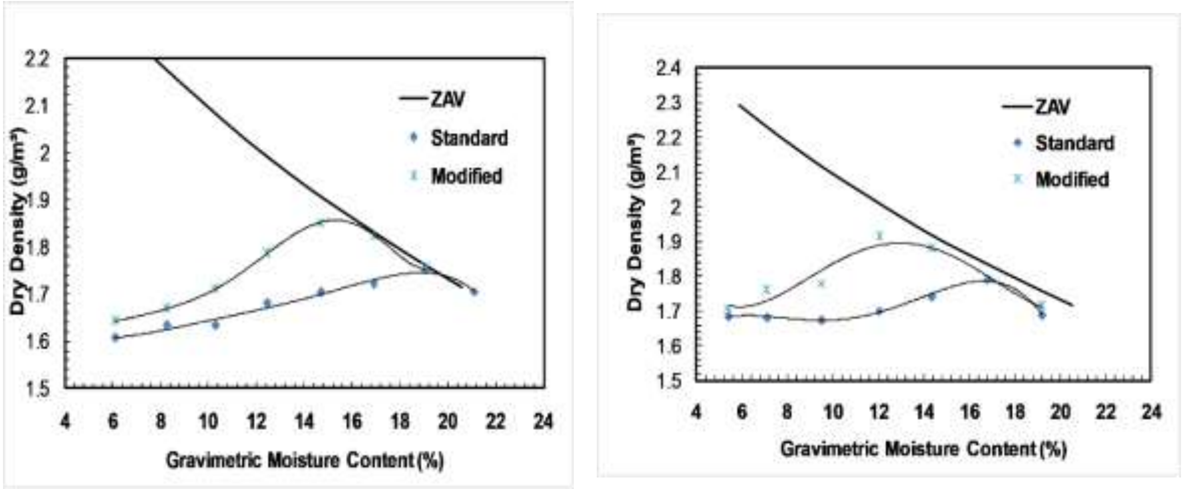
(e) B5

(f) B6



(g) B7

(h) B8



(i) B9 (j) B10

Figure 8: Compaction curves of soil samples

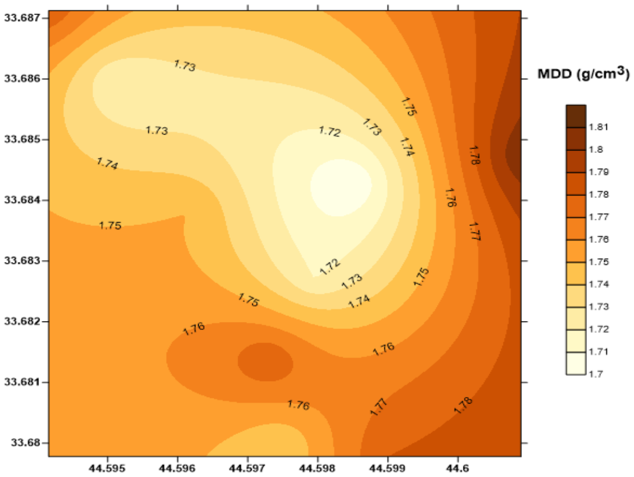


Figure 9: A map showing the MDD variation of SPC tests in the study area

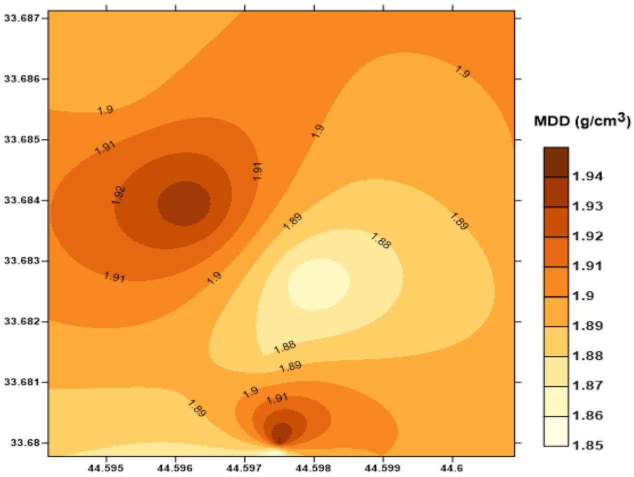


Figure 10: A map showing the MDD variation of MPC tests in the study area

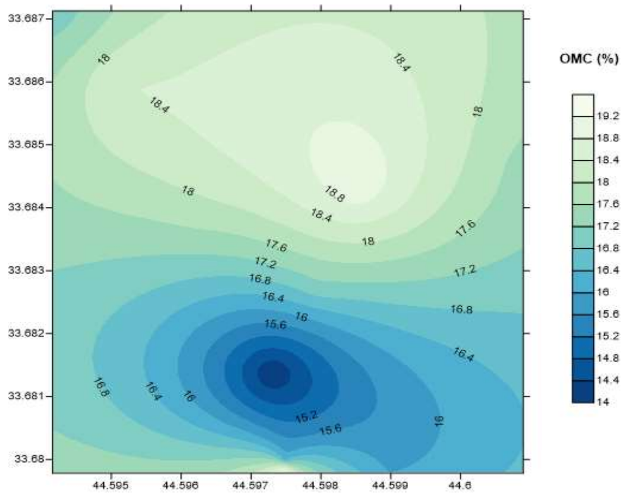


Figure 11: A map showing the OMC variation of SPC tests in the study area

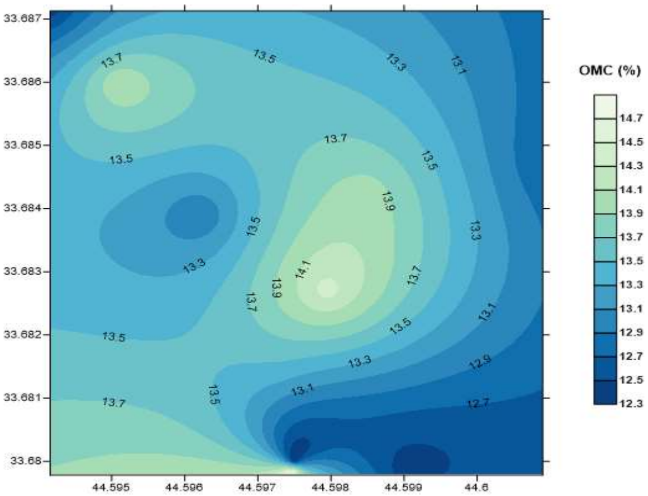


Figure 12: A map showing the OMC variation of MPC tests in the study area

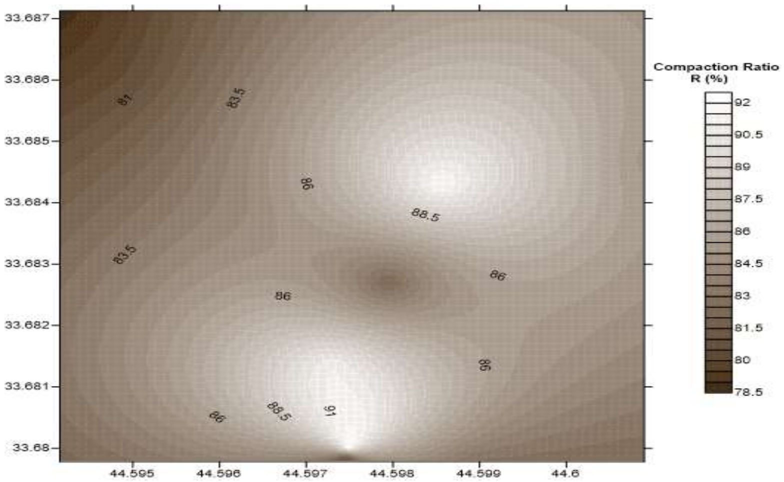
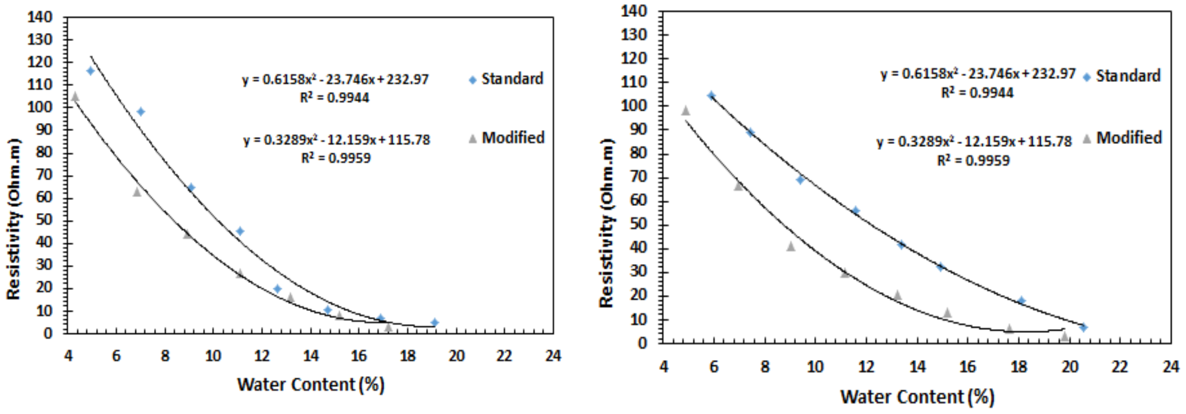


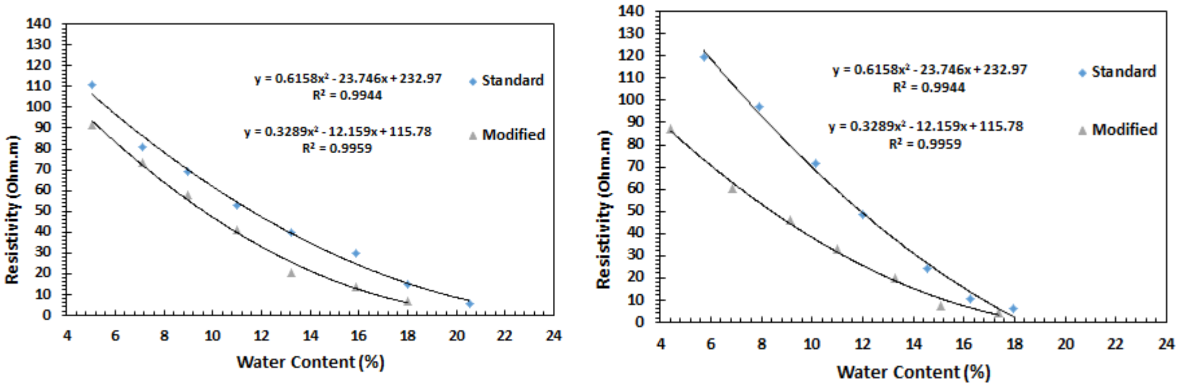
Figure 13: A map showing the compaction ratio variation in the study area

Geotechnical- Geoelectrical Integration

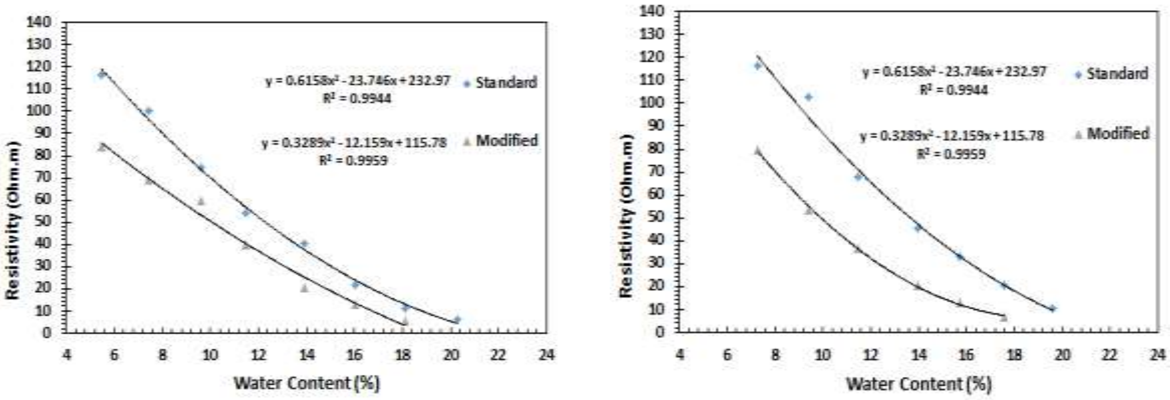
Figure (14) shows the resistivity-water content (measured using the oven drying method) curves of compacted specimens for SPC and MPC tests. The figure indicates typical nonlinear relationships that have been widely reported in the literature [11], [12], [13], and [14]. Increasing the water content decreases the ER, and vise versa, for both SPC and MPC tests, and the resistivity values of MPC specimens are lower than those of SPC specimens [5],[19]. This trend is related to the micro-structural variations of soil particles because of the compaction [5]. At low water content, voids are partially filled with water with high air voids, hence high resistivity. In contrast, at high moisture content, particularly close to saturation, electrical conduction is improved as voids are more filled with water, hence low resistivity [10]. Additionally, the high compaction energy received by MPC specimens reduces air voids and makes soil particles denser, resulting in lower resistivity than SPC specimens [11]. The R^2 values (> 0.99) for all curves shown in Figure (14) demonstrate the potential of the resistivity method for the prediction of soil water content.



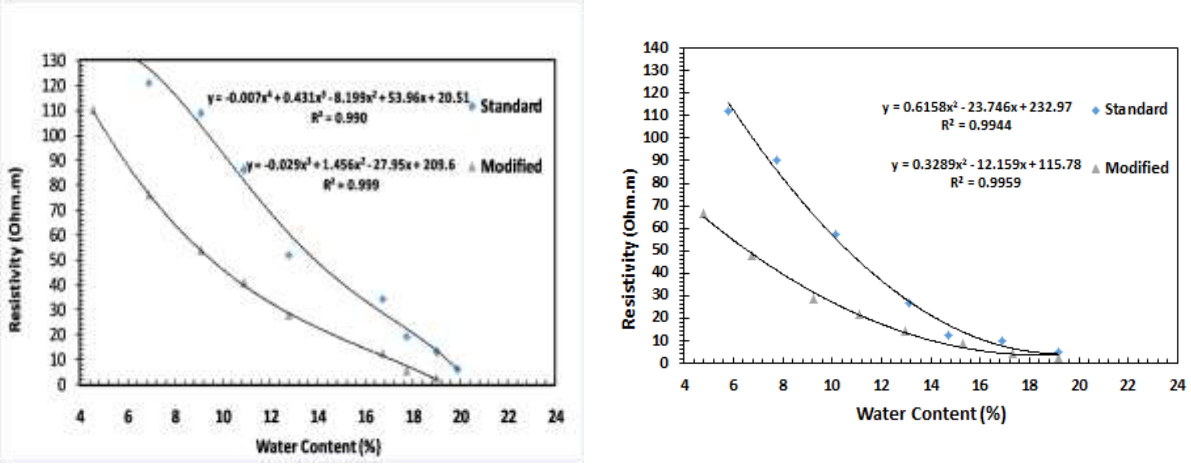
(a) B1 (b) B2



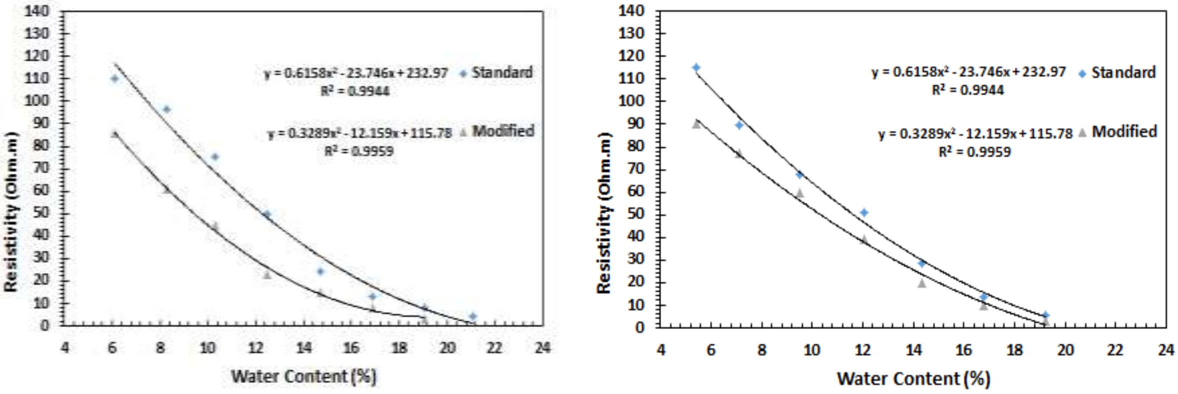
(c) B3 (d) B4



(e) B5 (f) B6



(g) B7 (h) B8



(i) B9 (j) B10

Figure 14: The resistivity-water content relationships

Validation of Geotechnical-Geoelectrical Relationships

In geotechnical testing, water content (gravimetric) and dry density can be integrated into one geotechnical parameter called volumetric water content, which evaluates more precisely the water state in the soil [27]. Therefore, the resistivity was correlated with volumetric water content for SPC and MPC compaction of B1 sample, as shown in Figure (15), and used to validate the above correlations. It can be seen that the resistivity and volumetric water content are well correlated well with $R^2>0.98$. The high R^2 achieved indicates the applicability of using this relationship for predicting soil water content. To validate this finding, the measured volumetric moisture content values using the geotechnical method were correlated with the predicted values using the resistivity method by applying the equations shown in Figure (15). Figures (16) and (17) show the relationships between the measured and predicted values for SPC ($R^2=0.911$) and MPC ($R^2=0.934$) tests, respectively, for a 95% prediction interval. It can be noticed that the majority of data points are within the 95% prediction interval, which demonstrates the usefulness of using the resistivity method, as a low-cost and non-destructive technique, for quick and initial evaluation of the water content of compacted soils.

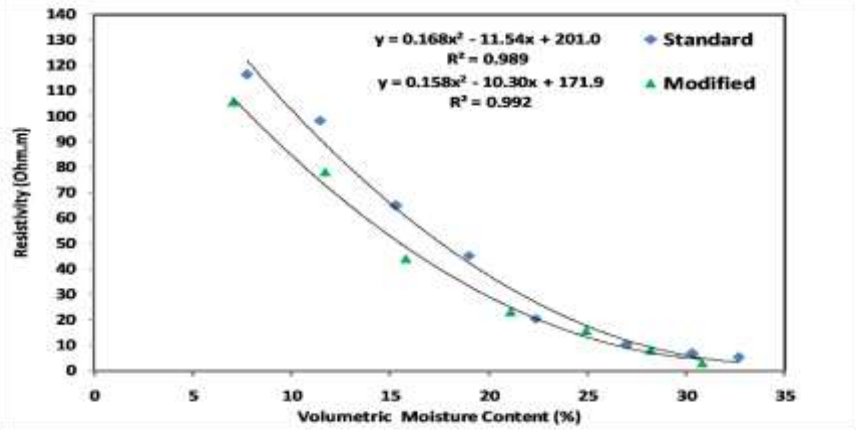


Figure 15: The resistivity-volumetric moisture content relationship for B1 specimen

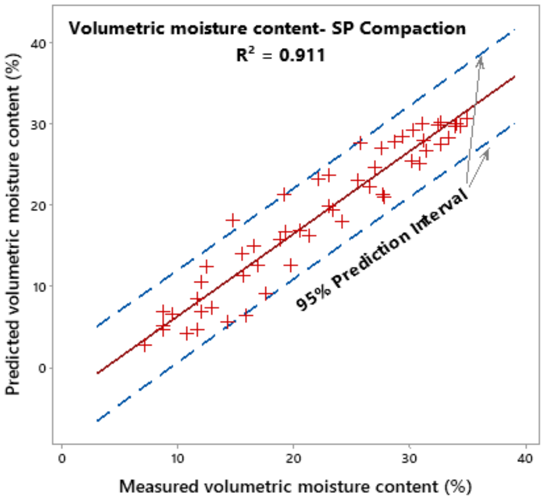


Figure 16: Measured against predicted volumetric moisture content of SPC tests (R^2= 0.911)

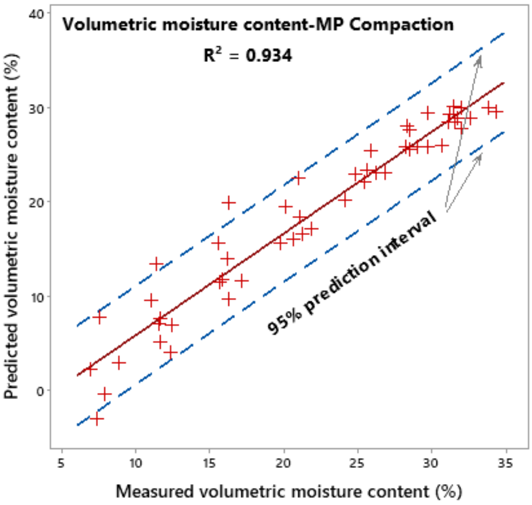


Figure 17: Measured against predicted volumetric moisture content of MPC tests (R^2= 0.934)

Conclusions

Geotechnical and geoelectrical methods were adopted in this study to characterize the soil at the University of Diyala with a particular interest in using the resistivity method for water content evaluation. Laboratory geotechnical tests showed that the soil is of low plasticity fine-grained type CL and CL-ML according to USCS. The MDD and OMC values were obtained and mapped for SPC and MPC tests. Increasing the compaction energy from SPC to MPC increases the MDD and reduces the OMC. It was found that the resistivity was well correlated with water content measured using the oven drying method for all samples with R^2 >0.99 which highlight the usefulness of using the resistivity method for water content prediction. This interesting finding was validated for SPC and MPC tests. The High R^2 values achieved for the relationships between the measured and predicted values for a prediction interval of 95% demonstrated that the resistivity method could be used for a quick preliminary evaluation of soil water content.

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