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Utilization of low-cost water content sensors in compaction tests
Uso de sensores de bajo costo para contenido de agua en pruebas de compactación

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Abstract

The common practice of measuring the water content of any soil mass involves a gravimetric methodology by obtaining the dry and wet mass of a soil-water mixture. In terms of execution, this procedure is simple but time-consuming. Therefore, other techniques could be applied, including devices such as sensors to obtain the water contents of soil. There are plenty of sensors in the market whose purpose is to obtain volumetric water content, which is a fundamental parameter of unsaturated soil mechanics. In the present research, three different low-cost volumetric water content sensors were evaluated in Proctor compaction tests. The soil used in this work corresponds to sandy soil, with a fair amount of gravel and fine material (SM). The interface of the sensors was done via an Arduino UNO board, and the data was processed and displayed using Python code. The findings of this research are presented in terms of calibration curves and linear correlation coefficients. Furthermore, a sensor repeatability test was performed in order to evaluate the accuracy of these types of sensors. The results obtained indicate that these low-cost sensors may not be the most recommended devices to use in sandy soils within the context of this specific geotechnical application.
Keywords: Volumetric water content, compaction tests, moisture sensor, Arduino, Python, sensor accuracy.

Resumen

Comúnmente, la medición del contenido de agua de cualquier masa de suelo se basa en una metodología gravimétrica, evaluando la masa seca y húmeda de una mezcla de suelo y agua. En términos de ejecución, este procedimiento es simple pero muy tardado. Por lo tanto, otras técnicas pudieran ser aplicables para la medición del contenido de agua en suelos, incluyendo el uso de dispositivos tales como sensores. Existen muchos sensores en el mercado cuyo propósito es obtener el contenido volumétrico de agua, el cual es un parámetro fundamental en la mecánica de suelos parcialmente saturados. En esta investigación, se evaluaron tres sensores diferentes de bajo costo para contenido volumétrico de agua, en pruebas de compactación Proctor. El suelo utilizado en este trabajo corresponde a un suelo arenoso, con una moderada cantidad de grava y finos (SM). La interfaz de los sensores se llevó a cabo a través de una tarjeta Arduino UNO, y la información fue procesada y presentada usando un código de Python. Los resultados de esta investigación son presentados en términos de curvas de calibración y coeficientes de correlación lineal. Además, se realizó una prueba de repetibilidad para evaluar la precisión de este tipo de sensores. Los resultados obtenidos demuestran que este tipo de sensores de bajo costo quizá no sean los dispositivos más recomendados para usar en arenas en el contexto de esta aplicación geotécnica específica.
Descriptores: Contenido volumétrico de agua, pruebas de compactación, sensores de humedad, Arduino, Python, precisión de sensores.

Introduction

Water content is one of the most important variables related to soil behavior. Parameters such as Atterberg limits, density, consolidation, and strength, among others, depend significantly on how much water is within a soil mass (Das, 2009). Therefore, measuring water contents is a fundamental task to consider regarding the geotechnical performance of a soil mass. Focusing on the density, the common procedures to obtain it are through laboratory tests where several soil specimens are compacted, varying the water content (ASTM D698, 2012) (ASTM D1557, 2012). Conversely, measuring water contents typically involves the oven drying method, in which the wet soil is dried using an oven until no noticeable mass change is observed. The time of this process will vary depending on the type of material, size of the specimen, oven type and capacity, etc., but in most cases, this procedure may take about 12 to 16 hours (ASTM D2216, 2019). Consequently, this technique is not considered the most efficient due to its duration, and other techniques could be implemented to obtain water content values without spending that much time.

Sensing devices are an alternative to the oven technique, having the advantage of obtaining data in real-time. Although there are different measuring principles (nuclear, hygrometric, tensiometric, etc. (Zazueta & Xin, 1994), many commercial sensors use an electrical principle to estimate the water content of a soil mass, specifically the volumetric water content. These types of sensors are commonly preferred due to their ease of use and direct approach since the amount of electricity that can be stored or conducted through a material is related to its water content (Kumar *et al.*, 2016). However, it has been suggested by different investigations and manufacturers to perform a data calibration specific for each type of soil (Nagahage *et al.*, 2019).

Electrical-based sensors are usually employed in fields like soil physics and agriculture and rarely used in geotechnical testing due to the fact that, for typical civil engineering applications, the gravimetric water content is studied (Fredlund *et al.*, 2012). Besides, some of the most accurate sensors are expensive and only commercially available in some places. Nevertheless, low-cost sensors could be useful, but their precision is still to be proven. Hence, the present research evaluated the applicability and accuracy of non-expensive sensors in conventional compaction tests of geotechnical engineering. To do so, capacitive and resistive sensors were used along with an Arduino UNO board to acquire and transmit data to a computer, where a Python code was implemented to display the voltage values. Then, the voltage readings were plotted against the actual water contents to evaluate their correlation and linearity. Furthermore, a sensor-to-sensor repeatability test was performed to validate its use.

Materials and methods

Sensors

Nowadays, several sensors in the market offer easy implementation and reasonable accuracy, and many of them have been tested successfully in agriculture and irrigation applications. Based on the availability, operation voltage, and cost, three sensors were selected for this research: A capacitive sensor: the Capacitive Soil Moisture Sensor (SKU: SEN0193), and two resistive sensors: The Sparkfun Soil Moisture Sensor (SEN-13322), and the Soil Moisture Hygrometer Detection Humidity Sensor Module Corrosion Resistance Probe (ASIN: B076DDWDJK) (Figure 1). All of these sensors work under the correlation between the electrical current and the moisture level in any material or mass.

The SKU: SEN0193 sensor is an analog device that primarily measures the capacitance of a material, indicating the amount of charge a body can store for a given applied potential (Ida, 2015). Consequently, this sensor acts like a capacitor, sensing how the surrounding soil changes the capacitor's capacity. This sensor operates with a voltage between 3.3 and 5 volts, and its laminar-shaped probes are covered with an anti-corrosion material, improving its serviceability. However, it has electronic components exposed that must be protected to increase their durability. Therefore, the sensor was customized by waterproofing its uncovered elements. This procedure followed suggestions found in online forums and web pages using heat shrink tubing and nail polish to protect the sensor.

The resistive sensors also work under a relatively simple principle. This type of sensor consists of two conductive probes used to pass current through the material, and then the sensor reads the resistance to infer the moisture content. As the water content increases, the soil will allow more electrical current flow, and vice versa (Saleh *et al.*, 2016). Both resistive sensors are analog instruments powered with 3.3 to 5 volts, but they have some key peculiarities. The SEN-13322 probes have exposed pads, which are prone to corrode when exposed to humidity during significant periods of time, and have electrical components exposed, similar to the capacitive sensors. On the other hand, the ASIN: B076DDWDJK sensor has corrosion-resistive probes, and the electronic module is separated from the probe's unit, avoiding the waterproofing problem. However, in the experimentation of this work, the sensors will not be in contact with the soil for a long time, and the electronic components were covered using a procedure similar to that of the capacitive sensor. Figure 1 presents an image of all sensors used.

Figure 1. Sensors used: a) SKU: SEN0193; b) SEN-13322; c) ASIN: B076DDWDJK

Sensor's interface

For the data acquisition and connection of the sensors, an Arduino UNO board was used, powering all the sensors with 5V and receiving the lectures from the analog pins. Even though the ASIN: B076DDWDJK sensor can be used as a digital sensor, it was connected as an analog device in order to have the same conditions for all sensors. Figure 2 shows an example of the schematic connection of a sensor with the Arduino board.

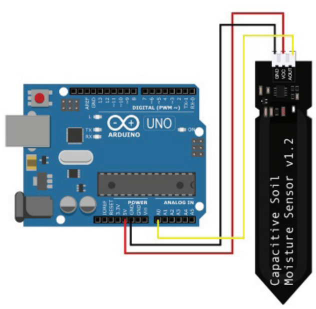

Figure 2. Scheme of connection of the analog sensor with the Arduino board

The Arduino board was connected to a computer via USB; then, as part of the sensor protocol, the sample rate was defined as 1 lecture every 5 seconds. This low acquisition rate was defined because the moisture level of soils does not change quickly; therefore, there is no need to register too much data. The lectures were displayed using the programming language Python through the PySerial package (Van & Drake, 1995), plotting the lectures against time in seconds. It is worth mentioning that lectures collected by the Arduino board are considered raw count values and do not correspond to the actual voltage output of the sensor. The raw count values must be converted to obtain the actual voltage, depending on the Analog-to-Digital Converter (ADC) resolution during data acquisition. Since the Arduino UNO board has a 10-bit resolution, the 0 to 1023 raw counts could be mapped to a 0 to 5 voltage range (voltage supply). This conversion is easy to implement through Equation 1.

$$V_O = \frac{R_{cv}}{1023} * V_{in} \tag{1}$$

Where:

V_O = output voltage
R_{cv} = raw count values obtained from the sensor
V_{in} = powering or input voltage to the sensor, which in this application equals to 5 volts for all the sensors used

Soil characterization

The soil used in this work to test the sensors was sampled from a quarry. Its main application corresponds to a subgrade/subbase layer in a pavement structure. This soil was analyzed through laboratory tests to obtain its index properties. The results of the characterization are presented in Table 1. According to the values obtained, this soil is classified as a sand-silt mixture (SM) with medium mechanical strength and low plasticity.

Table 1. Soil properties

Soil Properties	Results
Specific gravity	1.51
Liquid limit, %	34.4
Plastic limit, %	28.9
Plasticity index, %	5.5
	Gravel = 37.48
Sieve Analysis, %	Sand = 39.57
	Silt and clay = 22.95
Optimum moisture content, %	23.6
Maximum dry density, gr/cm^3	1.42
CBR test, %	19.6
Expansion, %	0
USCS classification	SM

Volumetric water content

Volumetric water content (VWC) is defined as the ratio of the volume of water to the total volume of a soil mass (Fredlund *et al.*, 2012). This concept is widely used in some disciplines, such as agriculture, to describe how much moisture a soil has, and even though it is not often used in ordinary geotechnical practices, most of the theories regarding unsaturated soil mechanics and fluid flow involve VWC analysis. Because of this, and since most compacted soils present an unsaturated condition (for example, a pavement or an embankment), the concept of VWC should be as important as the gravimetric water content in any geotechnical study.

Nevertheless, the volumetric water content cannot be obtained as directly as the gravimetric water content since it is easier to measure weight data than volume data using conventional laboratory equipment. While there are some proposed techniques to evaluate the VWC related to other soil properties, the most accepted and reliable method is to obtain the volumetric value through gravimetric content determination (Smith & Mullins, 2001). To do so, (Fredlund *et al.,* 2012) parts from the concept itself of VWC, mathematically expressed in Equation 2.

$$VWC = \frac{V_w}{V_T} \tag{2}$$

Where:

V_w = volume of water within the soil and
V_T = total volume of the soil mass

Rewriting Equation 2, the VWC could be defined in terms of the gravimetric water content (w) and dry soil and water densities (ρ_d and ρ_w respectively), obtaining Equation 3.

$$VWC = w\frac{\rho_d}{\rho_w} \tag{3}$$

Equation 3 presents an alternative to obtain the VWC using common geotechnical features. Nonetheless, it is well known that the density of the soil greatly depends on its compaction, which also depends on the water content (Das, 2009). This situation implies that different soil compaction produces different volumetric water contents. Therefore, compaction tests are a proper method to assess the functionality of soil moisture sensors at various water contents.

Compaction tests

Soil compaction is a fundamental activity in geotechnical engineering for constructing pavements, foundations, landfills, earth dams, etc. Compaction improves the mechanical properties and decreases undesired settlements. When compacting, water has an important role in the densification process, acting as a lubricant agent on the soil particles, allowing them to slide past each other and occupy the voids in the soil mass. However, beyond a certain water content, water begins to fill the voids that would have been occupied by soil particles (Das, 2009). Through laboratory testing, a compaction curve is determined to obtain the water content that generates the maximum dry density of the soil. Plotting this curve is a well-established methodology in many standards based on the Proctor test (ASTM D698, 2012; ASTM D1557, 2012). This test focuses on conforming soil-water mixtures with various water contents and then compacting them in a mold using a hammer to specific compaction energy. Subsequently, the dry densities and gravimetric water contents data are plotted. These two parameters are needed to obtain the VWC through Equation 2.

Some variations of the Proctor testing involve reusing a drier soil mixture to perform the successive water content-dry density determinations. However, the ASTM procedure suggests avoiding such recycling since it could lead to particle degradation, thus obtaining higher dry density values. Therefore, it is recommended to prepare different mixtures for each determination. This preparation is done by letting the water-soil mixtures rest to achieve homogeneity and even water distribution across the mixture. Reviewing the literature, this practice is relatively usual in common moisture sensor calibration processes (Adeyemi, Norton *et al.,* 2016; Nagahage *et al.,* 2019). Figure 3 shows a typical preparation for a mixture, which was carried out employing various water proportions and stored in a sealed plastic bag to avoid moisture loss. From the previous characterization work, water contents were selected based on values above and below the optimum water content, with varying gravimetric water contents from approximately 12 to 32 %. Afterward, wet soil mixtures were left in plastic bags for 24 hours to form a proper homogenous mass. Then, the compaction test was performed following the ASTM D698 guidelines using the standard compaction energy.

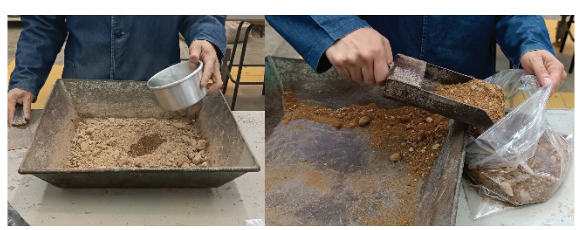

Figure 3. Preparation and storage of soil

Data acquisition protocol

The sensor readings were executed along with the compaction test. According to the ASTM D698 procedure, the soil must be compacted in three layers of approximately equal thickness in the mold. Taking advantage of this procedure, sensors were inserted laterally into the mold once the bottom layer was settled and before the compaction of the second layer since the already compacted layer provided a flat surface to place the sensor. After the sensor was positioned, the following layers were compacted, which improved the contact between the sensor and the soil (Figure 4). This technique was applied for all sensor readings, using only one sensor for each specimen compacted. It should be noted that while the surface of the specimen is exposed to moisture loss due to the environment, the soil mass surrounding the sensor could be considered protected since it was covered with top and bottom layers of soil and encased by the mold. Furthermore, a plastic cylinder was used in the experimentation process instead of the common steel Proctor mold to avoid the possible influence of metal conductivity in the sensor readings.

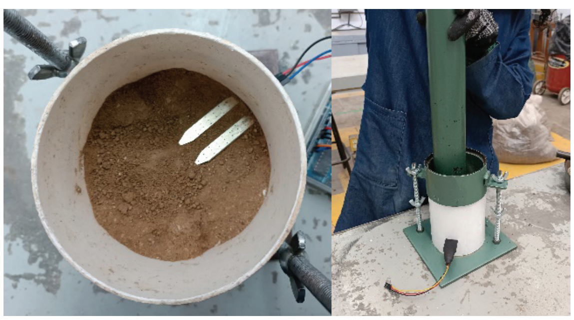

Figure 4. Sensor placement and soil compaction

Once the specimen compaction was completed, the sensor communication was initiated immediately. A minimum period of 5 minutes of sampling was defined, even though, in some cases, the voltage readings stabilized in a shorter lapse to an average constant value. However, in some other determinations, more extended periods of time were needed to obtain constant values in the readings (up to 40 minutes), but no distinguishable pattern regarding this behavior was detected in relation to the type of sensor used or the water content level. It is possible that external factors, such as humidity and room temperature affected the readings stabilization, nonetheless, these factors were not assessed in the experimental protocol.

To finalize the test, the mass of the soil in the mold was registered in conjunction with the volume of the mold, and after obtaining the dry mass of the soil, the results for the density and gravimetric water content were obtained. The mass and volume of the sensors were not considered since they have a pretty low weight and only occupy a small space compared with the soil specimen measurements. Consequently, after calculating the density and water content values, the VWC was obtained through Equation 3 for each specimen, using this parameter to find its correlation with the sensor readings. At least 14 determinations were performed for each sensor used.

Results and discussion

The results obtained with the SKU:SEN0193, SEN-13322, and ASIN: B076DDWDJK sensors are presented in Figures 5, 6, and 7, respectively, where the voltage measurements are plotted against the VWC for each subspecimen. Furthermore, the Pearson squared correlation coefficient (R^2) was calculated for each data set to observe the linear relationship between the sensor output voltages and the actual VWC. This is a simple and common approach to express how well the values obtained by a sensor and its variability are correlated to the magnitude and variability of the parameter that is being measured. In other words, the correlation coefficient proposes a quantitative perspective of the certainty and accuracy of an instrument. Also, many manufacturers suggest applying a linear correlation to calibrate the sensors in terms of a map function.

As observed in Figures 5, 6, and 7, the readings taken with the capacitive sensor yield a better correlation (R2=0.93), implying better reliability and accuracy compared to the results obtained from both resistive-based sensors, with the SEN-13322 sensor producing a coefficient of 0.38, and the ASIN: B076DDWDJK sensor a 0.18 value. This finding is also evident when looking at the plotted results, where the measurements of the resistive sensors do not present a clear pattern (linear or non-linear); instead, they present great dispersion regarding the results of the capacitive sensor.

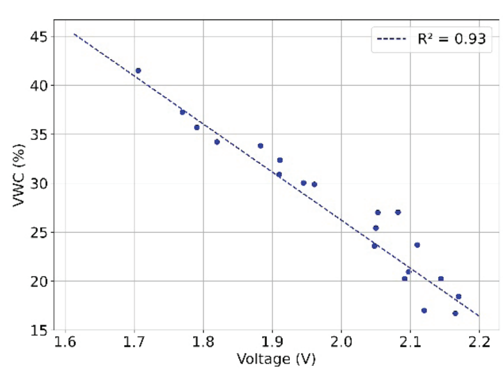

Figure 5. Experimental results of SKU: SEN0193 sensor

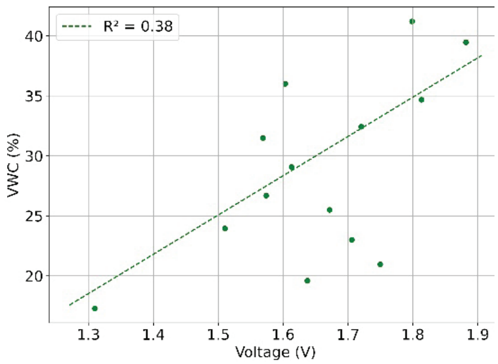

Figure 6. Experimental results of SEN-13322 sensor

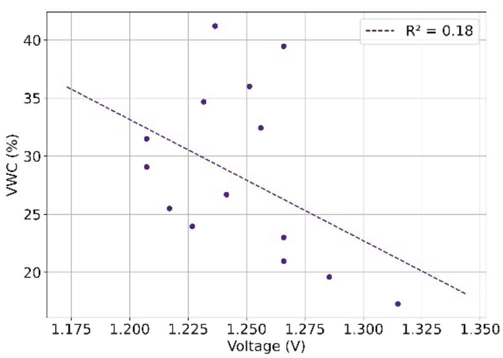

Figure 7. Experimental results of ASIN: B076DDWDJK sensor

From these results, it is possible to partially conclude that the SKU: SEN0193 sensor could be used as a trustworthy instrument within the compaction tests context since its R^2 coefficient is close to 1. However, to validate such an assumption, two more identical sensors (B and C) were tested using the same compaction procedure, achieving a sensor-to-sensor repeatability verification. With these new sensors, more than 20 determinations were executed. The results of these two more capacitive sensors, along with the measurements from the previous sensor (A), are presented in Figure 8. Even though these measurements follow the pattern of the previous sensor (higher volumetric water contents produce low sensor voltage output), a noticeable disparity between sensor measurements is perceived. The calibration curves of the two additional capacitive sensors display steeper slopes, which indicates a higher variability of volumetric water contents in relation to the range of the sensor voltage outputs. Also, the values obtained oppose the acceptable correlation from the original sensor, with correlation coefficients of 0.43 and 0.60. This demonstrates that, despite working with the same soil, a calibration procedure must be performed for every sensor, even when the sensors used are identical and produced by the same manufacturer. Additionally, it is possible to get both fair and low accuracy capacitive sensors, thus implying that these sensors could not be considered entirely reliable for geotechnical applications.

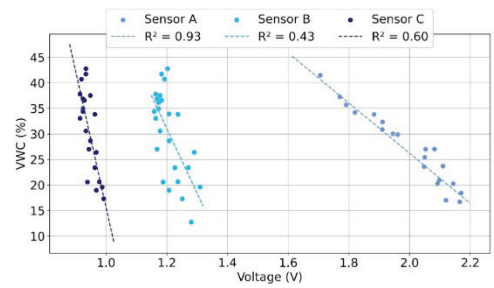

Figure 8. Experimental results of capacitive sensors A, B, and C

Another situation encountered when testing the capacitive sensors was that, in some cases, the shield of the sensor's surface in contact with the soil was progressively peeled off after every compaction test (Figure 8). This condition reduces the durability of the sensor since the exposed copper is subject to corrosion due to the wet environment of the soil, possibly presenting some influence on the sensor readings. Hence, these sensor components should be improved to assure better performance.

Figure 9. Sensor surface wearing

Conclusions

This research examined the accuracy and reliability of three different low-cost moisture sensors used in laboratory compaction tests. Based on the results, none of the tested sensors are recommended for geotechnical applications where fair accuracy is needed. Even though one capacitive sensor presented moderate reliability, other identical sensors yielded less favorable results, proving little consistency between sensors. A possible use of these capacitive sensors would be as an instrument to indicate if the soil is rather wet or dry, but they do not offer accurate measurements. Different considerations are proposed that could improve the utilization of the water content sensors.

Using another soil may produce a different possible scenario, for example, fine-grained soils, which would be less abrasive with the sensor shield and have better contact with it. However, these types of soils would require a thorough calibration process. Another possible outcome could be achieved if the sensor probes are covered or protected with some extra material or shield to enhance its external cover. Nonetheless, the objective of this research was to test the performance of the sensors in their original conditions. Furthermore, it is suggested that external environmental factors (humidity and temperature) may affect the operation of the sensors, hence such factors should be considered in future test runs.

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