2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39220

Design and Application of an Open-Science Electrical Resistivity Meter to Make Geotechnical Laboratory Education More Relevant and Engaging

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Design and application of an open-science electrical resistivity meter to make geotechnical laboratory education more relevant and engaging

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Abstract:
Electrical Resistivity (ER) surveys have been used to investigate soils for over a century, but a "black box" traditionally surrounds commercial ER equipment. This work proposes the design of an intuitive, low-cost ER meter for hands-on geotechnical education. The prototype leverages $40 worth of integrated-circuit modules and less than 80 lines of open-source commands to inject a current into the ground and measure the site's potential response. The device was validated against test circuits with ohmic values ranging over several orders of magnitude and yielded marginal mean absolute percentage error less than 3%. The proposed ER meter was thereafter implemented in a tabletop laboratory setting to perform Constant Separation Traversing (CST) surveys using Wenner array along parallel profiles. The resulting CST matrix showed values of apparent resistivity consistently in agreement with the modeled earth stratum. Over the extent of a buried Styrofoam feature, the device generated measurements up to 70% higher and identified clear lateral disruptions in subsurface conditions. Overall, the proposed ER meter proved to be a tool well suited for tabletop experiments and capable of characterizing complex test beds. Its open-science design addresses the issues of the "black box" surrounding proprietary equipment and makes it accessible to the community at large for a fraction of the cost of commercial units. With practical applications for hands-on teaching and interactive learning, this work makes geotechnical laboratory education more engaging and relevant. As such, it has the potential to modernize STEM curricula and advance the fundamental understanding at the intersection of technology and environment.

1. Introduction

Geophysical methods are useful in subsurface explorations as they are sensitive to contrast in physical properties of soils over continuous coverage. Electrical Resistivity (ER) surveys have been used to investigate soils for over a century and rely on the fact that varying geologic conditions alter the distribution of electrical potential in the ground [1]. Based on this principle, ER methods have a wide array of practical and research applications related to Civil Engineering such as geological and hydrogeological investigations of the subsoil (including testing of porosity, moisture content and saturation degree), the assessment of dam and levee embankments, the monitoring of landfills, and agricultural and post-industrial areas [2]. However, commercial ER equipment has complex inner workings and can act as a "black box", especially to students who lack the understanding of how ER measurements are obtained [3].

Attempts were previously made to construct a simple ER meter for "a mere fraction of the price of commercial units" [4]. Later studies opted for programmable Integrated Circuits (IC) over commercially available units, but the fabrication of their devices remained out of reach of those with little background in electronics [5,6]. The last decade has seen IC- programming become more common and user-friendly with the spread of development boards such as Arduino Uno. This advancement has allowed for the use of more intuitive, affordable ER prototypes [7-10]. However, these instruments were only validated against test circuits, homogeneous soil samples, or uncharacterized field sites. As such, they have showed limited potential to perform actual ground resistivity surveys and teach insights and intricacies of geophysical exploration.

The present work addresses this gap by proposing the design of an ER meter with easy-to-implement, low-cost modules and applying it to a more complex testbed. The open-science framework and hands-on nature of this tool makes it particularly well suited for the interactive teaching/learning of geophysical exploration and engineering design.

2. Design of a low-cost ER meter

Traditional resistivity methods consist of four electrodes linearly placed in the ground (Figure 1). A portable battery serves to deliver a direct-current (DC) between the current source C1 and sink C2 with an ammeter being used to measure the intensity of the injected current. The dipole P1 and P2 is connected to a voltmeter, gauging the potential difference induced in the earth. Following Ohm's law, the earth's resistance is computed based on the current draw and the voltage drop between the potential probes. Note that the measured resistance is dependent on the configuration of a particular measurement. In contrast, resistivity is an intrinsic property that can be calculated based on the resistance and electrode geometry [11]. Essentially, a potential ($V_{P1,C1}$) is induced at probe P1 that is at a given distance r_1 from the power supply C1 of current (I) at the surface of a medium of apparent resistivity (ρ) as given in Equation (1):

$$V_{P1,C1} = \frac{I\rho}{2\pi r_1} \tag{1}$$

In addition, the potential ($V_{P1,C2}$) induced at probe P1 by the power sink C2 at a distance r_2 away is of equal intensity but opposite direction. The amount measured by probe P1 is the sum of the induced potential as expressed in Equation (2):

$$V_{P1,C1} + V_{P1,C2} = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{2}$$

The net potential can be evaluated similarly at a probe P2 that is a distance r_3 and r_4 away from current supply and sink, respectively. For a traditional array, the difference in potential across two electrodes is considered as shown in Equation (3):

$$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right] \tag{3}$$

Different electrode sequences were developed as much for field efficiency as for their accurate results [12]. For instance, the Wenner array consists of a line of four equally-spaced electrodes, with the outer two being the current supply and sink. In this case, distances r_1 and r_4 are of the same length a, and distances r_2 and r_3 are twice as long. Therefore, the general expression above can be simplified for Wenner configuration according to Equation (4):

$$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{a} - \frac{1}{2a}\right) - \left(\frac{1}{2a} - \frac{1}{a}\right)\right] = \frac{I\rho}{2\pi a} \tag{4}$$

The uniformity and symmetry of the Wenner array made it the most straightforward and relevant to this work. Using this approach, the apparent resistivity (ρ) can be computed using only one spatial variable to account for the electrode spacing per Equation (5):

$$\rho = \frac{2\pi a \Delta V}{I} \tag{5}$$

The resistivity reading for a given electrode configuration corresponds a specific depth of investigation. In the case of Wenner arrays, a prior study [3] demonstrated that the effective depth of a measurement takes the simple mathematical form equal to half the spacing between the current probes (i.e. 3a/2). Following a resistivity reading, the dipoles can be maintained at constant spacing and moved along a horizontal line to conduct a unidimensional Constant Separation Traversing (CST) or profiling for a specific depth of interest [13].

The initial step in the fabrication of an ER meter was the selection of an accurate current sensor. DC ammeters consisting of a shunt resistor and precision amplifier have the advantage of offering high resolution and coverage while causing minimal disturbance to the circuit. We found that the specifications of the Adafruit INA 219 IC met study requirements with a maximum error on the order of 1% in the range ± 400 mA.

The creation of a voltmeter was critical in the fabrication of an ER meter that could accurately measure voltage drops between the potential dipole. The input voltage to the development board was scaled down using a two-resistor voltage divider as to not exceed the input pin's 5V limit. We used a combination of 1M- and 100k-ohm resistors to create a voltmeter of high impedance and reduce the loading effect on the circuit, as recommended by others [11].

We also implemented a Liquid Crystal Display (LCD) and SD card module for data visualization and transfer. We powered the development board using a 9V battery. The device was assembled using roughly 20 wires and programmed in less than 80 lines of open-source commands. With a unit cost around $40 and an open-science design, this prototype can be easily reproduced and further advance the use of "interactive computing in teaching geophysics" [14,15].

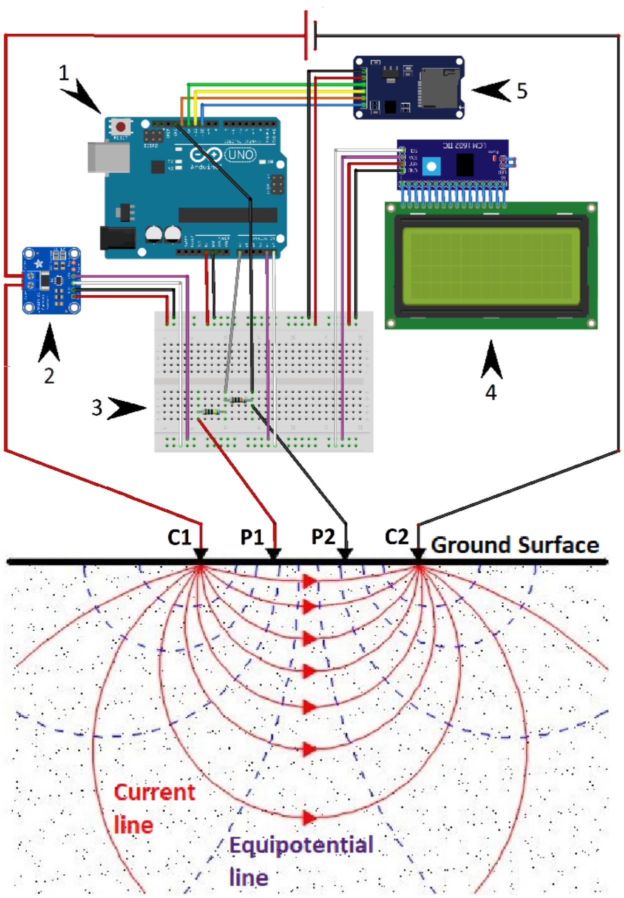

Figure 1: Design of the proposed low-cost ER meter including (1) a development board, (2) DC current sensor, (3) voltage divider, (4) LCD screen, (5) and SD card module.

3. Validation of prototype

The accuracy of proposed device was tested on sets of known resistors. Three identical resistors were placed in series to reproduce a medium of uniform resistance. A 9-volt battery was connected at each end (C1 and C2 in Figure 1) to provide a DC supply. The voltage drop was measured over the middle resistor (P1 and P2 in Figure 1). This process was repeated using various sets of resistors ranging from 30 to 22,000 ohms, all with a 1% tolerance. Each time, 5000 readings of the resistance were collected to capture noise and potential variations. The Mean Absolute Percent Error (MAPE) of the readings was plotted against the true Ohmic values of the resistors, in orders of magnitude as shown in Figure 2. Between 30 and 4700 ohms, MAPE was stable, with values ranging between 1 and 3%. These numbers agreed with the resistor tolerance and the specifications of the current sensor. They also implied that the noise in these 5000 readings was not significant and did not affect the MAPE.

When applied to circuits with a total resistance upward of 20k ohms, the device returned higher MAPE values. According to Ohm's law, when a circuit is exposed to a greater resistance, the current drawn from a constant power supply decreases. Less accurate readings and greater levels of noise can be attributed to values of current in the system approaching the sensitivity of the current sensor (i.e. 0.1 mAmps). This mostly highlights the importance of selecting a suitable power supply, especially against less conductive medium. Overall, the MAPE was negligible for as long as an appropriate current was measured, and the device showed a satisfactory level of accuracy and precision over several orders of magnitude.

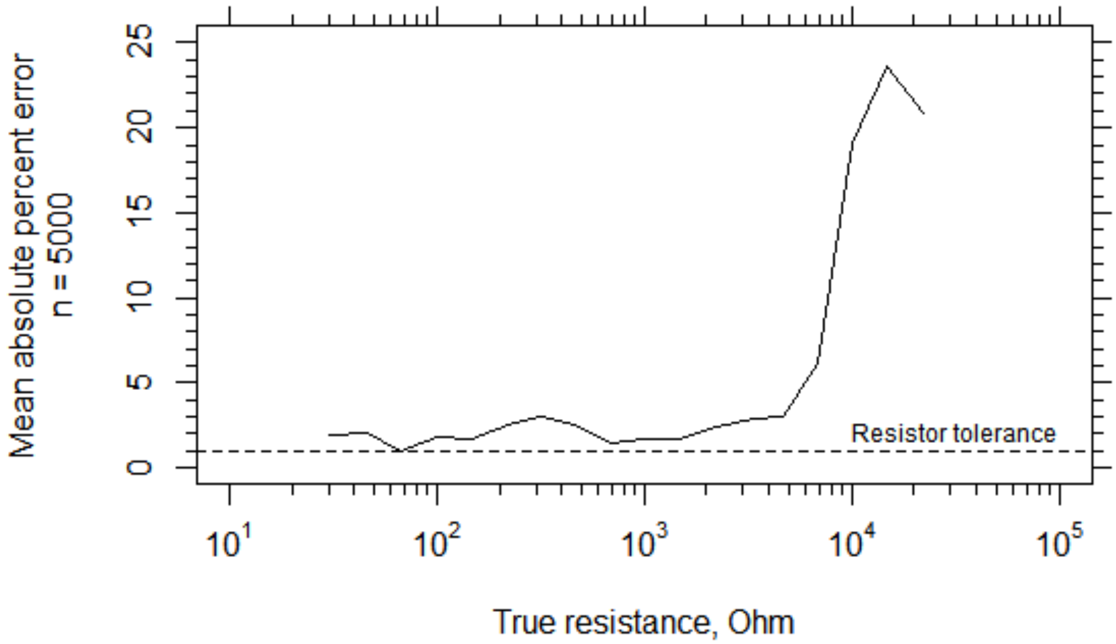

Figure 2: Level of accuracy of the proposed device during validation against known resistors.

4. Tabletop application

4.1. Methodology

This experiment was intended to model the presence of a feature prone to cause disruptions along a horizontal profile. A piece of Styrofoam board (10cm L x 10cm W x 10cm H) of relatively high resistivity was taped to the bottom of a plastic container (60cm L x 43cm W x 45cm H) to simulate an air-filled void such as a developing sinkhole in karstic terrain. The container was filled with silt (MH) to a compacted height of 15cm. CST surveys were performed using Wenner configuration with a 5-cm electrode spacing and two 7-Ah rechargeable batteries connected in series to supply a 24V DC.

The dipoles were installed at successive stations in increments of 5 cm along the traverse line (Figure 3a). Measurements of current and potential were taken at each station to generate a resistivity profile 7.5 cm beneath the center of the CST. Four additional profiles for the same depth of investigation were traced by incrementally shifting the electrode array 5 cm to the right (Figure 3b), resulting in a matrix of results. The Styrofoam void was located on center 25 cm along the first profile and extended 5 cm in x-y directions (Figure 3a,b).

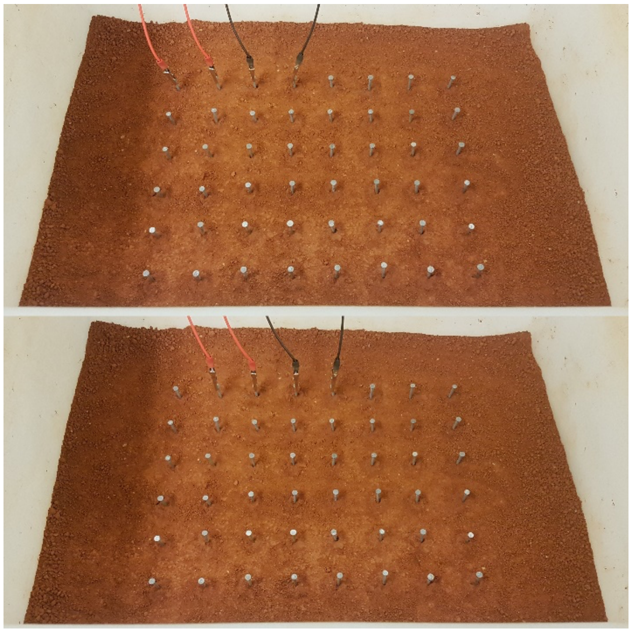

Figure 3: CST along various dashed profiles (a,b) intercepting a void (shaded) buried under 5 cm of soil. The apparent resistivity values to an effective depth of 7.5cm were calculated based on the Wenner array.

4.2. Results

Most measured values of apparent resistivity fell within a range of 400 to 500 Ohm-m., which was in agreement with the material tested [16,17]. However, the CST readings clearly captured a stark contrast in apparent resistivity near the buried Styrofoam piece as shown on Figure 4. The measurements obtained at the tail of the first and second profiles were relatively higher by as much as 30 to 70% than the rest. The three maximum values across the array had in common that at least two electrodes were placed directly above the buried feature.

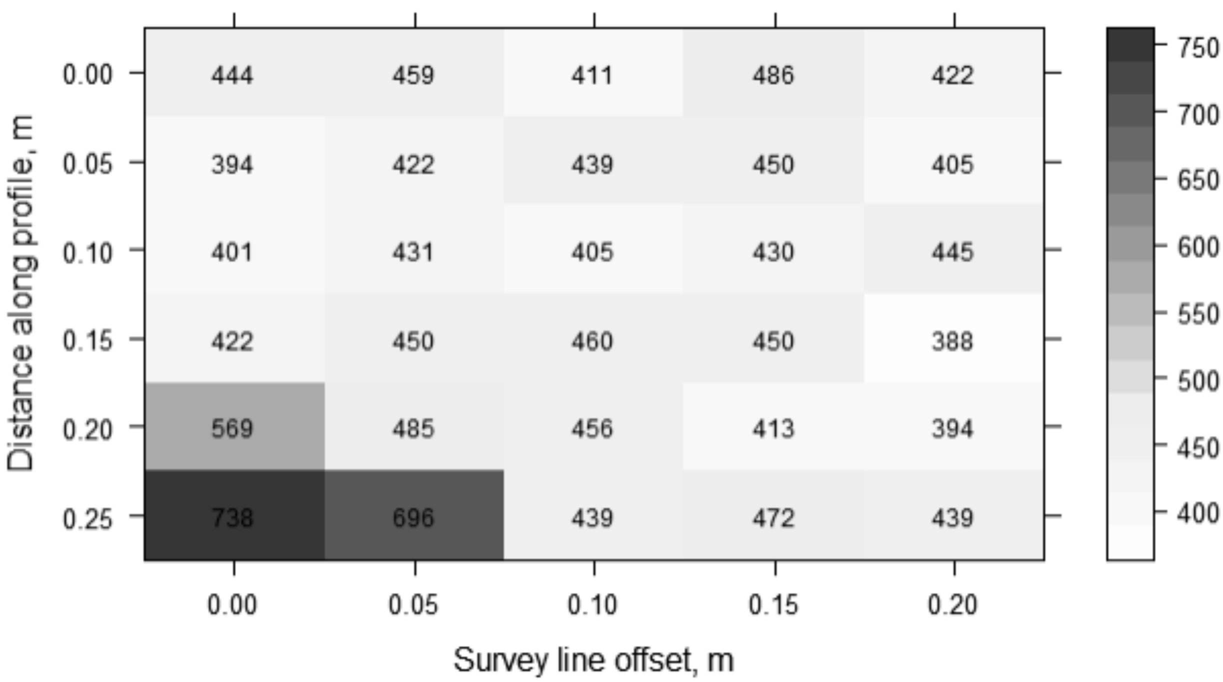

Figure 4: Spatial variation of apparent resistivity (Ohm-m) and anomaly coinciding with the location of artificial void in test bed.

5. Discussion

Most accredited civil engineering programs require a soil mechanics component as part of their curriculum [18]. Soil testing experiments and field trips have often been favored to learn geotechnical engineering practices [19,20]. But undergraduate students rarely have the opportunity to plan, collect and interpret subsoil investigation data [21,22]. So, we propose that our low-cost ER meter be added to the traditional set of geotechnical laboratory experiments to demonstrate the theory and applications of geophysical exploration. This interactive case-study would prepare cross-disciplinary students to develop "an intuitive understanding of the physics controlling the relevant observations and […] an appreciation for how these observations can be used to learn something about the earth" [23].

More and more, engineering graduates are also expected to apply coding and solve complex, interdisciplinary problems. Teaching engineering design is commonly accomplished through project-based learning [24,25]. However, the use and benefits of development boards such as Arduino are still overlooked [26]. Therefore, we also recommend that a device such as ours be further developed and validated by students in a project-oriented capstone course. Using Arduino has been shown to effectively teach programming and strengthen students' engagement [27-29].

At the intersection of both technology and the environment, it has been demonstrated that the implementation of microcomputer-based laboratory could improve the interpretation of physics concept [30, 31]. Specifically, the use of Arduino-based experiments has been promoted to teach the concept of electrical resistance [32,33]. A study found that there was a significant increase in the levels of satisfaction and comprehension among students when Arduino was used in a geotechnical engineering education module [34]. Beyond the positive impacts on learning, the implementation of our prototype also has the potential to expand undergraduate access to hands-on geophysics and provide a sense of belonging to the larger Earth Science community [35]. These engaging additions to the engineering curricula will enhance the recruitment and retention of students into engineering fields [36].

6. Conclusions

This study resulted in the design and implementation of an ER meter that uses inexpensive integrated-circuit modules along with open-source program commands. The prototype was fabricated using a combination of resistors and precision amplifier to measure the current draw and voltage drop with minimal error. A conventional Wenner array with four electrodes was leveraged to simplify geometric factors and resistivity measurements. Beyond test circuits and homogeneous soil samples, the device identified a buried feature in a tabletop setting. Overall, the proposed ER meter is a well-suited tool to be easily replicated by others and address the issues of the "black box" surrounding geophysical equipment. As such, it has the potential to create hands-on learning experience, effectively engage engineering students, and make geotechnical laboratory education more relevant.

Acknowledgments:

The authors would like to thank the anonymous reviewers for their valued input and insightful feedback, which significantly improved the manuscript.

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