Title: **Tracking Soil Saturation in Earthen Embankments Using a Network of Wireless Conductivity Sensors**

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ABSTRACT

Expansive clay embankments along transportation corridors are vulnerable to moisture-driven shrink-swell cycles that threaten their structural integrity. This work presents a low-cost, solar-powered, wireless sensor network designed to monitor soil moisture in real-time using electrical conductivity as a proxy. Five custom-built sensors, deployed 10 cm below the surface, record conductivity, temperature, humidity, and barometric pressure, transmitting data to a solar-powered base station that syncs with a cloud server for remote access. Field testing over seven days validated the system's durability, communication reliability, and power sustainability under variable weather conditions. Spatial moisture maps generated using spatial interpolation demonstrated the system's utility in identifying zones of elevated saturation. This open-source system represents a scalable tool for continuous monitoring of earthen embankments to support early warning and risk mitigation efforts.

INTRODUCTION

Embankments are raised structures designed for numerous functions critical to the development and maintenance of infrastructure such as supporting roadways and railroads or acting as a wall or barrier to hold back water. While earthen embankments constructed from soil, clay, and rock, are cheaper to build than concrete or asphalt embankments, they are more prone to decay, deterioration, and erosion, potentially compromising structural integrity. Studies show that highway embankment failures can be induced by pore water pressure increase, seasonal shrink-swell deformation, and progressive failure due to the age and nature of the dumped clay fill used in their construction can lead to railway embankment failure [1]. Levees, earthen embankments that protect nearby communities and land from flooding, are vulnerable to burrowing animals building habitats, excessive seepage, and internal erosion [2, 3].

Several types of sensors are used to monitor and test the structural health of earthen embankments such as geophones and soil moisture sensors which measure seismic activity and soil water content, respectively [4, 5]. Wired geophone arrays enable techniques such as active and passive seismic interferometry to monitor temporal changes in earthen embankments caused by internal erosion [6]. In addition, tensiometers, sensors that measure the surface tension of fluids, and piezoelectric pressure sensors have been employed to measure pore water pressure. Research into these methodologies suggests that these sensors are effective, individually or combined together, for structural health monitoring (SHM) of earthen embankments. Therefore, a real-time sensor system to monitor an earthen embankment's structural integrity could reduce embankment failure incidents by providing alerts prior to a failure occurrence.

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This paper presents the development and field validation of an open-source [7], low-cost, wireless sensing system designed to monitor soil moisture in earthen embankments. The authors implement a network of five solar-powered spike sensors capable of measuring electrical conductivity, subsurface temperature, ambient environmental conditions, and barometric pressure. Data collected by the sensors are transmitted in real-time to a custom-built base station, which stores the information locally and synchronizes it with a cloud server for remote access. The system is deployed in an outdoor environment for one week to assess its performance in terms of power sustainability, data transmission reliability, and environmental durability. Spatial interpolation methods are then applied to the sensor data to create continuous moisture maps. The contributions of this paper are twofold. First, it establishes a network of wireless solar-charged real-time moisture sensors that measure soil conductivity to track soil saturation in earthen embankments. Second, this paper introduces a wireless base station that stores and syncs the data received from the sensors and syncs the data to a cloud server for real-time monitoring.

Background

Previous versions of these sensors [7] were designed to conduct experimentation that require real-time monitoring of earthen embankments. The initial experiment, which findings were reported by Chowdhury et al [8], utilized a granular earthen levee in a flume under controlled erosion conditions to test the validity of the system. The system was a stand-alone sensor capable of simultaneously measuring ground velocity, conductivity, and temperature in addition to ambient atmospheric pressure and humidity. While the system demonstrated promise, the sampling rate of the geophone was hindered when collected with the other sensor values. Further research will be conducted in the future to determine the best approach for collecting geophone data with other sensor data. However, the experiment did indicate the electrical conductivity sensor's ability to detect increased soil moisture levels as levee failure began to occur [8].

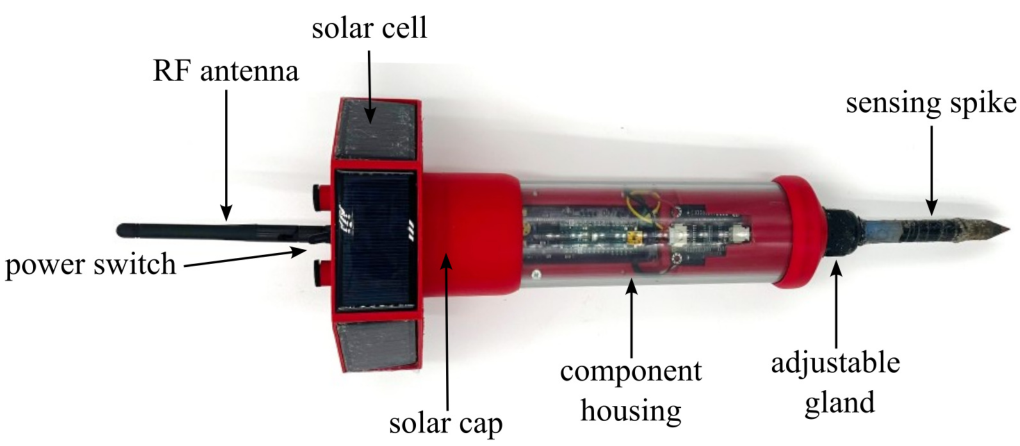


Figure 1. Open-source UAV-deployable wireless spike sensor package with key components annotated.

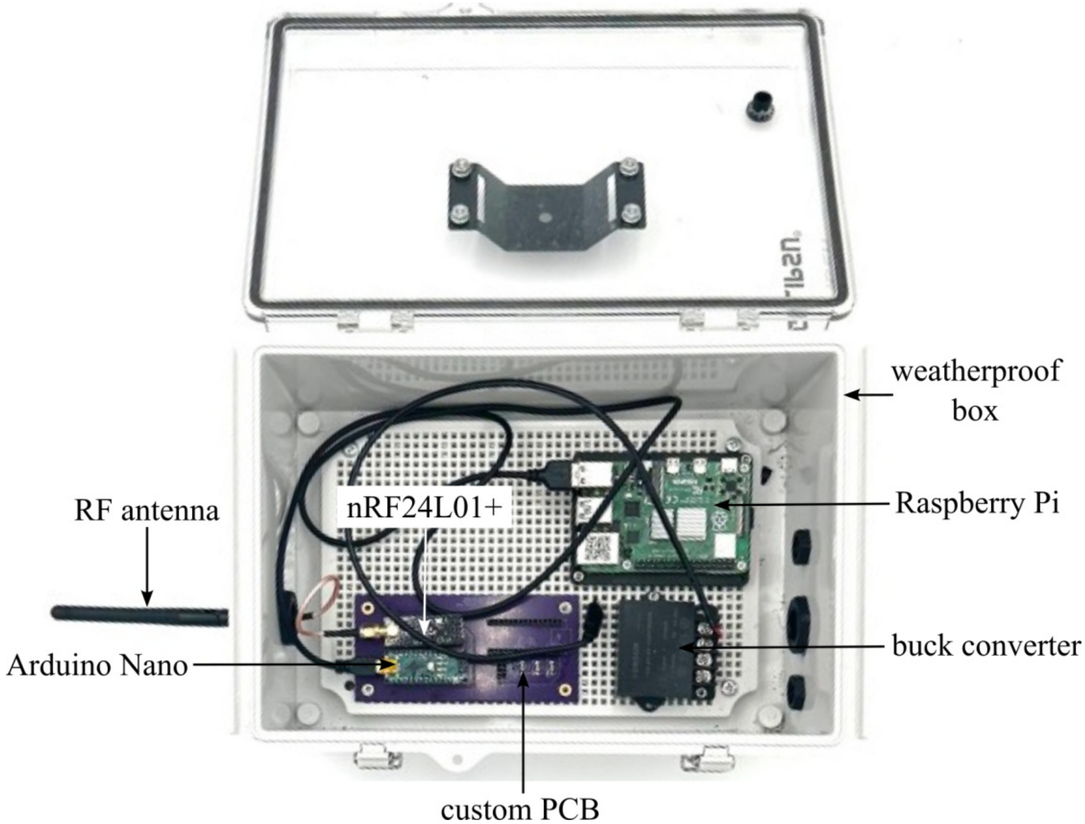
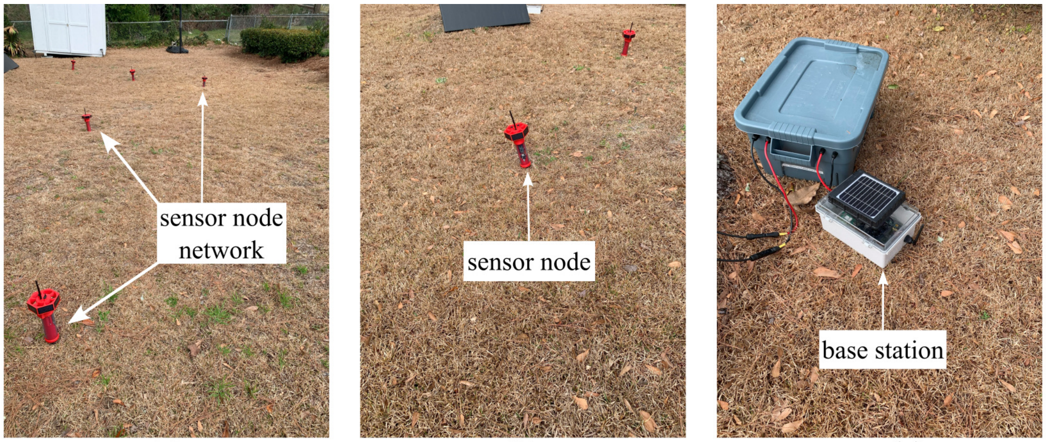


Figure 2. Open-source base station with key components annotated.

Based on the results from the prior experiment, subsequent research focused primarily on the sensor's soil moisture sensing capabilities. In a follow-up work by Chowdhury et al, a version of the sensor was tested that only collected soil moisture data but incorporated wireless data transfer capabilities to a base station [9]. This experiment, which also took place in a flume with a replica levee, tested five wireless sensors' ability to send data simultaneously. Once the base station received the data, it would store the data locally to be analyzed later. The sensors and base station utilized the nRF24L01 transceiver for transmitting and receiving data due to its low cost, long-range, and reliability [10]. The experiment was successful, demonstrating the potential of wireless communication via a network of sensing spike packages for levee monitoring.

Methodology

The version of spike sensors in this paper (see Figure 1) utilize an updated custom Arduino-powered PCB. The sensor incorporates all features from the previous sensor versions while introducing solar charging capabilities to the sensors and base station to increase battery life performance for extended deployment in outdoor environments. The sensors (see Figure 2) are powered by 3.7 V single-cell lithium polymer (LiPO) batteries that are continuously recharged via solar energy. The spike sensors' solar cap consists of six 5V 60 mA solar cells connected in parallel which could potentially produce a maximum of 360 mA of current. A solar charger for single-cell 3.7 V LiPo batteries capable of a maximum charging current of 500 mA converts the power harnessed from the solar cells into usable DC power.



(a) (b) (c)

Figure 3. Experiment setup of sensor spikes, presenting: (a) all five spike sensors deployed in a testing environment, (b) spike sensors in an open area near base station, and; (c) base station with enclosure for battery and solar charger.

The sensor is designed to collect soil electrical conductivity (EC), soil temperature, ambient temperature, humidity, and barometric pressure data. To measure soil electrical conductivity, the sensor utilizes a total dissolved solids (TDS) meter module paired with a custom spike-shaped probe. The spike is a brass rod and brass tube separated by an insulating ABS tube. The end of the spike is chamfered into a point for easier penetration into the ground. A resistance temperature detector (RTD) sensor is embedded inside the spike to measure soil temperature. The dual-sensor probe enables comparing the relationship between EC and soil temperature at the same point. The sensors transmit the data they collect to the base station using nRF24L01+ PA LNA radio transceivers. The base station stores the data of each node in its own designated file. Additionally, the base station's software was updated to not only store the received data locally but to also sync the data with a cloud folder to store the recorded data remotely. These files are located inside the synced folder, which is accessible from the internet via computer, tablet, or smartphone. The base station employs a wireless hotspot to access the internet over the cell network, and the base station's computer powers the hotspot. This allows for real-time monitoring and access to the data online from anywhere during the experiment process. The sensors' and base station designs were enhanced to endure long-term operation in outdoor environments and to ease the assembly of multiple sensors.

EXPERIMENTAL SETUP

A wireless sensor network consisting of five custom sensors and one custom base station was deployed for one week to test their reliability in an outdoor environment (see Figure 3). The functionalities tested were communication from sensors to the base station, communication from the base station to the internet, the ability of the solar power system configuration to maintain adequate power for sensors and base station, and the robustness of the network to withstand the harsh conditions of the environment. To test sensor-to-base station communication, the sensors were placed at differing distances from the base station in a random arrangement (see Figure 4). Several sensors were

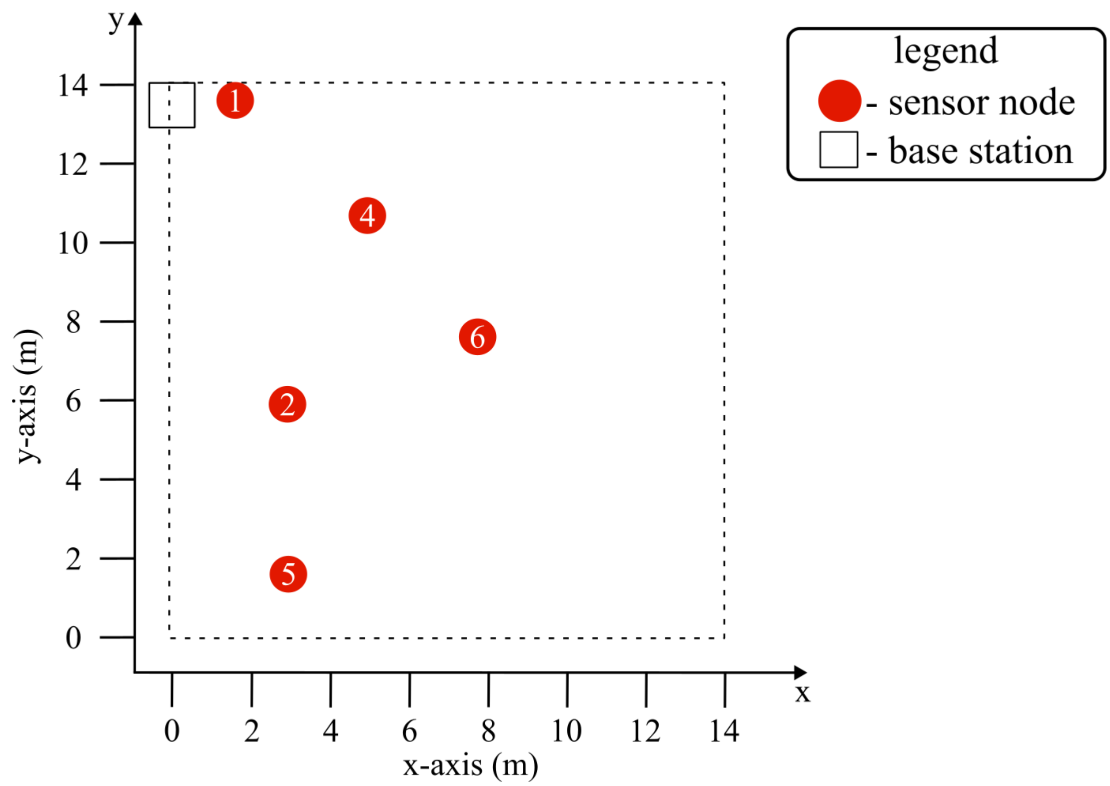


Figure 4. 2-D representation depicting experiment setup on Cartesian coordinate system.

positioned in areas that experienced less exposure to sunlight during periods of the day due to shade from nearby trees and structures. The remaining sensors and the base station were placed in areas where minimum shading occurred. This setup tested the impact the solar charging system had on the longevity of the sensors' battery life.

The sensor nodes were programmed to transmit a data packet to the base station approximately every ten seconds. Since the sensors do not transmit data at the exact same time, the average of all data values collected within the same minute is calculated for each sensor. This allows for spatial mapping at a given time. To model spatial patterns and predict values at unmeasured locations, the interpolation-based method, ordinary kriging with a Gaussian variogram model, was utilized [11]. The ordinary kriging estimator is

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i), \tag{1}$$

where $\hat{Z}(x_0)$ is the estimated value at location x_0, $Z(x_i)$ are known values at locations x_i, and λ_i are the kriging weights that satisfy the unbiasedness constraint, such that

$$\sum_{i=1}^{n} \lambda_i = 1. \tag{2}$$

The Gaussian variogram model used to compute spatial dependence is

$$\gamma(h) = c_0 + c\left[1 - \exp\left(-\left(\frac{h}{a}\right)^2\right)\right], \tag{3}$$

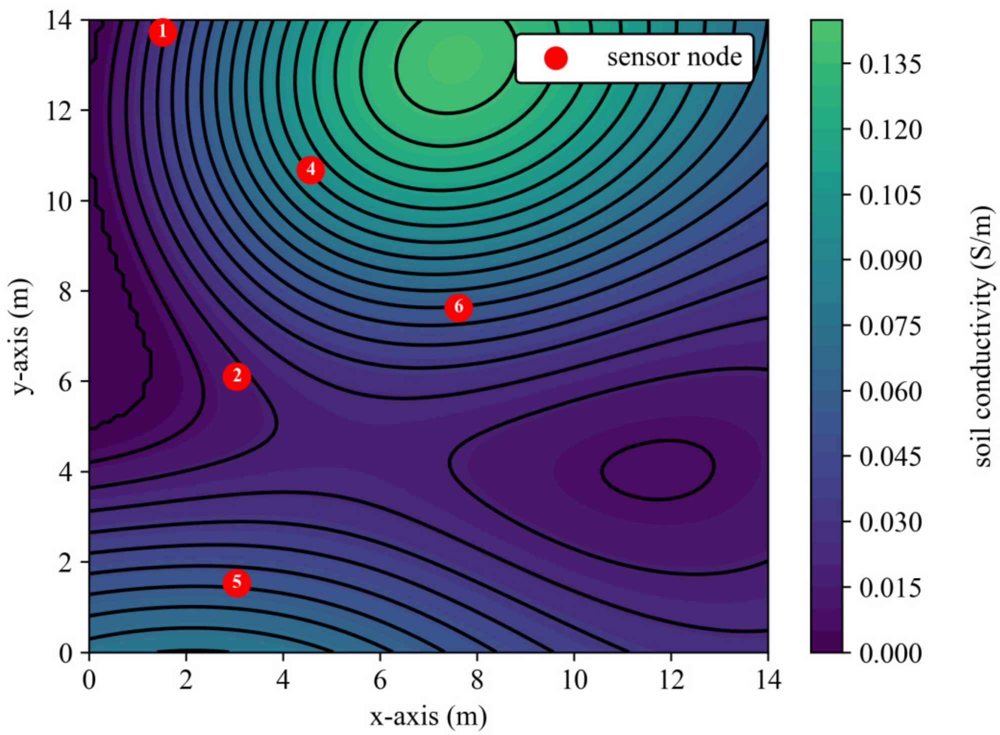


Figure 5. Spatial map generated from five spike nodes using Gaussian distribution model.

where $\gamma(h)$ is the variogram value at separation distance h, c_0 is the nugget, c is the sill minus the nugget (i.e., the partial sill), and a is the range parameter controlling the spatial correlation scale. Since the purpose of this paper is to demonstrate the capability of the sensor network, no test was conducted to determine if this spatial method was the best choice for accurate prediction of unknown values. However, ordinary kriging is an intuitive choice since it assumes the true mean value is unknown [9].

RESULTS AND DISCUSSION

After seven days of testing, three of the five spike sensors remained continuously operational or resumed operation after successfully recharging. Of the two sensors that stopped functioning during the test, one was found to have a loose wire between the solar cells and the solar charger, which prevented the battery from recharging. It is assumed that the other non-functional sensor shut down due to insufficient sunlight exposure, leading to battery depletion. No sensor lost communication with the base station while powered; however, the number of missing or corrupted data packets increased when sensor power levels dropped too low. The sensors withstood heavy rain with no damage occurring. The base station never lost connection to the internet, and the data could always be accessed from the synced cloud folder. Once the known data was processed, spatial maps were plotted to visualize the predicted spatial soil moisture data. Figure 5 shows one such spatial map.

CONCLUSION

Conductivity sensors have shown to be an effective tool for SHM of earthen embankments by monitoring soil moisture levels. However, real-time monitoring can be expensive, inconvenient, and limited due to the lack of custom sensors that provide the power, connectivity, and ease of use required. The objective of this study was to demonstrate a potential system that would address these issues by presenting a low-cost conductivity sensor network that utilizes wireless communication to a cloud server and solar charging. The experiment yielded promising results by successfully collecting and wirelessly transmitting soil conductivity data to a cloud server, and continuously recharging sensor batteries during the seven-day period. The software and hardware developed for this study are open-sourced and can be found in the ARTS-Lab's Github repository [7]. Future studies could involve improving the internal wire connections of the sensors to eliminate failures due to disconnected wires, software updates that address lost and corrupt data issues, reincorporating the geophone sensor, and testing UAV deployability. This research contributes to advancing structural health monitoring techniques and enhancing the safety and longevity of infrastructure.

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