Decision support system for prediction of earthworks failures

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Abstract: Asset monitoring of canal structures, embankments, bridges and a number of other critical assets will deliver sustainability through the reduction of needless human activities and promote enhanced data quality and accessibility for best practice in environmental management as required by environmental regulators and other government departments. This paper presents a prototyped low-cost platform with an appropriate mix of sensors located on one sensor node for gathering real-time data of resistivity, ground movement and in order to monitor earthworks failure.

Keywords: Soil Resistivity, asset monitoring, prototype sensor

Introduction

A key component of management of water resources lies in asset monitoring of the structures that contain water, e.g., dams and embankments. Earthworks failures can lead to disastrous consequences, including flooding, and can be very expensive to remediate. Early intervention and prevention requires identification of the incremental development of internal conditions that ultimately trigger failure. Spatially continuous data can achieve a level of sub-surface resolution significantly closer to the scale of true heterogeneity than currently achieved using conventional intrusive point sensing approaches alone.

While current automated procedures, sensors and SCADA systems provide information regarding the health of the assets, they have a number of limitations: (1) the cost of deploying/maintaining these solutions; (2) the level of intrusiveness; (3) the need for engineers validating measurements by visual inspection; (4) low temporal resolution with limited scope for predictive approaches to asset failure; (5) limited support for strategic decision-making. For this purpose there are currently available different solutions in order to monitor the health of an earthwork. According to Sellers *et al* one of the most commonly used methods is soil resistivity surveys and a 3D mapping of the ground using these results, as it can provide information about the moisture content of the earthwork in an non intrusively. An example of this method is the ALERTme system, which maps 3D the resistivity of a railway embankment using a kit designed for this purpose (specifications of 500V/up to 500mA), as it can be seen in Gunn *et al (2010)*. Similarly, there are available many ready to use solutions, but similarly with the ALERTme project, they use high voltage and current, which requires expensive voltage transformers, and cabling in order to mitigate health and safety risks during the experiments.

Together with the resistivity and moisture content, which can be also measured using dedicated pore pressure sensors, the field experts suggested that the movement of the ground (vibration, acceleration) can be a very informative measurand, as this could provide early notification about the possibility of earthworks failure. With the available solutions, a survey like that will require a high budget and additionally the usage of many different sensors, that generally do not allow the measurements using one and only interface.

This paper presents a solution to assess the physical integrity of vulnerable earth structures (dams, embankments and cuttings) - thereby facilitating the shift from more costly responsive remediation of earthwork failures to early intervention. We propose a unique, customized and cost-effective platform for automated monitoring of earthworks through prototyping a novel hardware/firmware solution in consultation with various stakeholders: (i) integration of analogue and digital sensors for measuring pressure and motion, (ii) resistivity sensor (board) that is controlled by main hardware (board) and requires low voltage compared to the off-the-shelf resistivity solutions, (iii) variable and on-demand sampling rates that can be dynamically controlled, (iv) a prototype mechanical waterproof design for housing main hardware, resistivity sensor-board and relevant sensors. We show initial results for ground movement, pressure and resistivity. Resistivity results are as expected based on the literature for clay-type soil. We show noticeable ground movement variation with artificially induced disturbance.

System Set-up

Our proposed monitoring platform that could integrate a range of sensors for monitoring the condition of earthworks assets (embankments, canal infrastructures etc) with minimized cost and high accuracy. This project has delivered proof-of-concept by deployment of a 12V network of five integrated-sensor nodes, appropriately cased and connected for power and communications under the ground surface. Measurements of resistivity, ground movement and pressure from the sensor network are communicated periodically and autonomously to a gateway and then onto a data collection hub. The outcome of this research is a underpins deployment of a network of these sensor nodes, application of monitoring techniques, intelligent data mining and data analytics to derive models concerning the condition of the assets and will assist in assessing infrastructures and informing management decisions.

Sensor Network

The deployment of the sensor network has been mainly affected by the measurement of soil resistivity, where a grid network of electrical resistivity electrode arrays is formed over the area of interest. The distance between the sensors is a direct function of the accuracy of the 3D mapping of the earthwork. For the above purposes, the sensors were deployed in a line of subsurface sensors, which could be extended in the future to multiple lines, in order to create the array that is usually used for resistivity measurements (Figure 1). In relation to Figure 1, we have deployed the top row of sensor nodes for proof-of-concept.

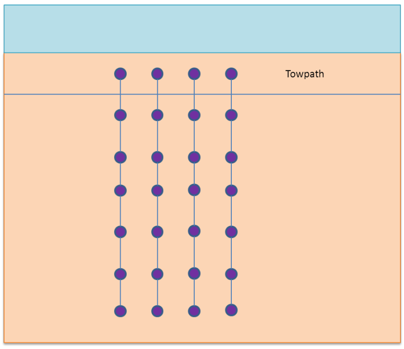

Figure 1*:* Embankment Deployment (Lateral View)

The deployed sensor network comprises the following:

- *Sensor Nodes* deployed in arrays: each node is a customised reprogrammable board that was designed and prototyped and is connected with three sensors and resistivity circuitry, and can be enabled for the usage of more sensors.
- *Sensor Communication Module*: Interfacing the sensor nodes to the gateway node using a *Controlled Area Network* (CAN)
- *CAN network*: The CAN cable has 6 pins. One pin used to power sensor node from the power supply, another is ground and the other two are used for CAN high and CAN low. The fifth pin is used as a ground sense, in order to have a reference for the resistivity measurement.
- *Hub for data collection:* Interfacing the Gateway with the Cloud through near near white space communication (~433 MHz)

Prototype Sensor

The prototype sensor consists of a main platform PCB board, a separate PCB board for the resistivity sensor and all the relevant cabling. All the hardware has been integrated in a 32.5 cm tall PVC tube with diameter of 14.5cm and thickness of 80mm, that provides both endurance and waterproof protection, as seen in Figure 2.

Figure 2: *Prototype Sensor Casing*

There is a special boardholder that enables us to pull out the main board for reprogramming or debugging should the need arise at this prototype stage. Holes were kept to the minimum to ensure waterproofing. At the bottom, there is a short copper probe sticking out of the node for resistivity measurements. The node has a special lid that can be sealed and cut open multiple times.

The main PCB board (Figure 3) has dimensions 110mm by 37.5 mm and can offer a wide range of serial, digital, analogue connectors for communication and integration of both on and off board sensors. The board also comprises switch mode regulators so that it could give different outputs stepped down from 12 V from the battery, as the majority of the sensors cannot operate at that voltage.

The prototype board consists of the following on and off- board sensors:

1. Resistivity board for injecting current, sensing voltage, sinking current, sensing voltage.
2. A *Digital Accelerometer*. This on-board sensor will be able to sense acceleration or vibrations (±2g/±4g/±8g dynamically selectable full-scale) in the soil.
3. An *Analog Pressure Sensor* that can measure absolute pressure (0 – 200kPa) using a single port, which was in contact with the soil (off board). Through a future calibration, the absolute pressure measurements can potentially translated in terms of pore pressure. Currently, for measuring pore pressure, specialised and expensive sensors are required.

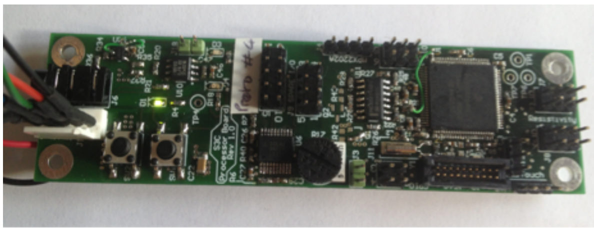

Figure 3: Prototype Sensor Board

A summary of the sensors and their sampling rates can be found in Table 1. These sampling rates can be adapted easily depending the circumstances and the defined requirements.

Table 1: Sensors Summary and Sampling Rates

Sensor Types	**Sampling Rate**
Accelerometer	12.5 Hz
Analog Pressure	1 sec
Resistivity Injection for measurement (Resistivity Board)	5 sec

Power Supply, Resistivity Sensor Board and Measurements specifications

The voltage supply used for both main and resistivity boards is an enclosed 12 VDC, 1.3A Switch Mode Power Supply (SMPS). The specific type of power supply was selected because of the availability of mains power at the best site in Falkirk Wheel and also due to its output isolation from mains ground, which could affect the measured data.

Power is distributed to all nodes using the CAN cable with one lead for power, one for ground compensation, in order to compensate the losses due to the length of the cable and ensure the accuracy of the results for resistivity measurements.

Resistivity board is also powered directly from the power CAN lead, and not as initially planned, through the regulated 10V from the main board. The main reason for this choice was to reduce the risk of damaging the main board and also to ensure that the maximum voltage available from the SMPS is used for better accuracy.

Resistivity Sensor Board

Resistivity sensor was built on a separate PCB board for safety reasons, as it will have to inject and sink current, which might negatively impair the other hardware parts on the main PCB board. The prototype of the resistivity sensor can be found in Figure 4.

Figure 4: Resistivity Sensor Node

Due to the voltage limitations, the global resistivity measurements will have to be redefined, as the maximum distance between the nodes will not exceed 1m. It is important to mention here that commercial resistivity kits can use voltages up to 800V and inject currents up to 2.5A. Our resistivity circuit will be able to inject much lower currents, which was set for the deployed nodes up to 119mA, and was selected by taking into consideration the common values of resistivity (1-10000 Ωm) and an average spacing of 1 m. Every sensor board is connected to a solid copper probe, similar to commercial resistivity kits and can work using both injection, sensing, or sinking mode. The most common material for these rods is stainless steel, but solid copper rods are also widely used and also due to the voltage limitations of the specific project a solid copper rod would offer higher conductivity compared to stainless steel.

Resistivity Measurements Specifications

According to Wenner(1916) and IEEE(2012), soil resistivity is measured using the 4-pin Wenner method. The first probe as seen in Figure 5, injects current according to our systems specifications, the two intermediate probes, sense the voltage in relation to a common ground and the last probe sinks the current.

The voltage measured at each probe will provide the voltage drop required to calculate the Wenner resistance and consequently the apparent resistivity using the formulas found in equations (1) or (2). These calculations can be executed at the data collection hub, which will receive all the relevant measurements.

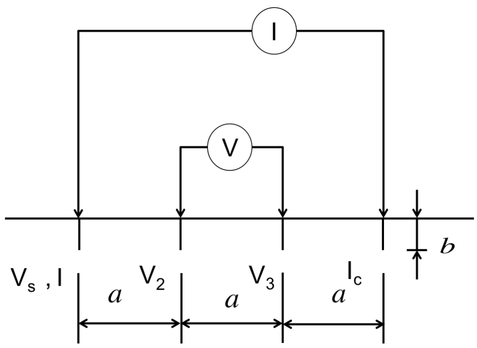

Figure 5: 4-pin Wenner Method

The spacing a between the probes for the deployment was selected to be 1m, and the depth of the probes b is 44.5cm, the height of the casing is 32.5 cm and the length of the rod that is placed at the bottom of the tube is 12 cm.

$$\rho_w = \frac{4\pi a R_w}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \tag{1}$$

where

ρ_w is the apparent resistivity (Ωm)

a is the spacing between the probes (m)

b is the depth of the probes (m)

$R_w = V/I$ is the Wenner Resistance (Ω)

If b is small compared to a, as is the case of probes penetrating the ground only for a short distance (as normally happens), the previous equation can be reduced to:

$$\rho_w = 2\pi a R_w \tag{2}$$

The resistivity sensor node was built and programmed in order to measure the voltage that is sensed at the two intermediate nodes, namely V_2 and V_3, the current injected I, the Voltage supply V_s and the sink current at the last node I_c. These measurements are critical for both calculating Wenner Resistance R_w and respectively soil resistivity ρ_w, but also in order to validate the measurements. For this purpose an additional measurement called ground compensation is acquired by using one of the extra leads of the CAN cable. Using ground compensation, we can compensate for power losses that occur due to the length of the CAN cable.

In order to determine soil resistivity from the above measurements, the voltage drop between the two nodes ($V = V_2 - V_1$) is calculated and followed by $R_w = V/I$, where I

is the injected current. Finally, using equation (1), we can determine the soil resistivity measured values.

Deployment

Deployment was carried out in Falkirk Wheel at Falkirk, Scotland at an embankment that is maintained by Scottish Canals during late February-beginning of March 2014. During the test period the weather at area was close to the average temperatures of the area with no extreme below zero temperatures.

Figure 6: Test site in Falkirk Wheel after the deployment of all subsurface sensor nodes and housing for power supply, getaway and hub.

Data Communications from Data Collection Hub to the Cloud

Since earthworks structures tend to be located remotely, a suitable communication technique was needed to automatically grab the data from the hub, transmit it to the nearest Wi-Fi hub for uploading to the cloud. Note that Scottish Canals plan to install Wi-Fi hotspots on their footpath structures.

There is a substantial amount of wireless communication technologies available such as mobile satellite, Wireless WAN (2G, 3G and 4G), IEEE802.11 Wireless LAN (Wi-Fi), infrared, IEEE 802.15 Wireless PAN (Bluetooth), radio transmission (IEEE 802.15 based and IEEE 802.11 based with different bands), Cellular Networks and IEEE 802.15.5 based Wireless Mesh Networks (WMN) but they all have different benefits and down falls. The technology used in this project had to be low cost, high accuracy and very effective in harsh conditions over a minimal range of 100 m.

Mobile satellite communication works very well over long ranges and should not have any issues with any harsh environments but can be extremely expensive to setup and maintain. In addition to the cost, launching another satellite will also contribute the increasing problem of "space junk" in space.

We therefore opted to explore near white space RF at 433 MHz. Our communications requirements are as follows:

- Feasibility to operate both indoors and outdoors in different weather conditions
- The ability to operate in high voltage environments (which is a case in the embankment at Falkirk Wheel, where high voltage electricity can found around the whole establishment)
- Effective operation in workshop environments with concrete walls, gas mains, sewer mains, heavy machinery, high voltage generators and other signals.
- Good system performance (as it can be found in Figure 7)

- Figure 7 shows reliability of the transmission as the distance between data collection hub and gateway to the cloud. While a distance of 80m seems a reasonable trade-off between accuracy and distance.

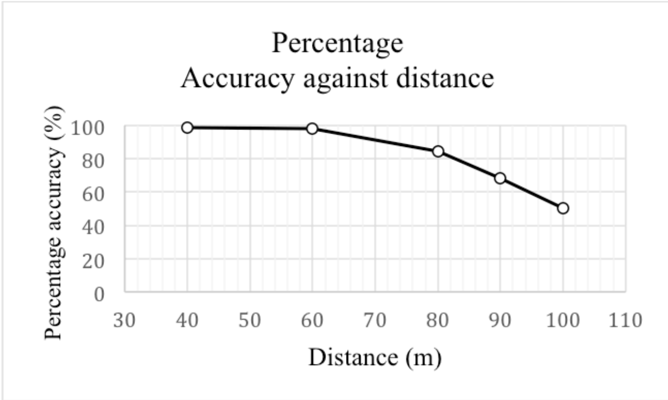

Figure 7: Outdoors range test, single core antenna, 15ms and 1500bps.

Better aerials such as directional Yagi-Uda and increased module voltages (up to 12V) could increase rate.

Results and Conclusions

All the collected data from each resistivity sensor were further processed in order to get the resistivity, ground movement and pressure. Due to the current setup the sensors are sending directly their measurements to the gateway, where they are receive a timestamp. Due to the amount of the data and each sensor's sampling rates , there have been cases of dropped or wrong order packages. This synchronization is more important for the resistivity analysis, as in order to define one resistivity value, measurements from all sensors are required.

During the pre-processing of the data, all resistivity data has been partitioned into windows, with each window starting from the message that the source is open (current will be injected), and finishing when closing message was receive. All remaining windows were discarded as not useful.

We have used two different approaches to calculate resistivity. (1) Assuming that the data arrive at the gateway with the same order the each sensor receives its measurements, and (2) assuming that the data can arrive with a different order but still can be grouped per sensor.

Figure 8 shows the results from the first scenario and Figure 9 from the second scenario. We can say that for both cases the average resistivity varies between 40-60 Ωm. In both cases, there are some higher resistivity values that reach around 90 Ωm, which can be either the result of missed data at the specific measuring window, though as we will discuss further this could be a normal resistivity value.

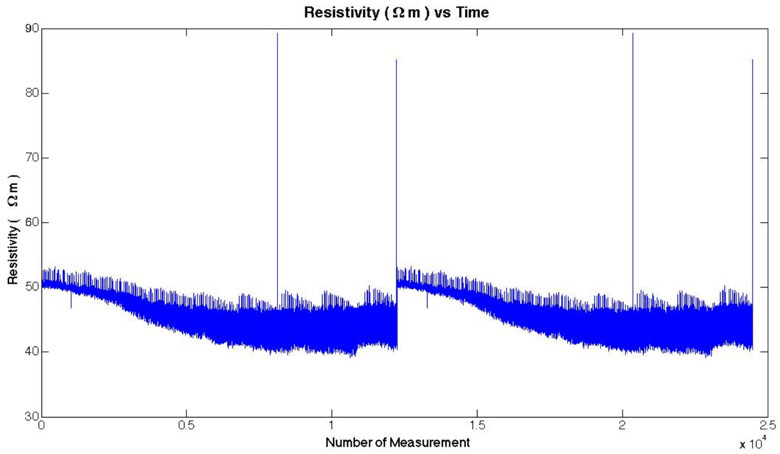

Figure 8: Resistivity using sensor network order to arrive at the gateway

Figure 9, is clearly more settled, as all the data that do not follow the initial assumption are discarded, thus the different number of measurements. This does not affect marginally the average resistivity, due to the high sampling rate.

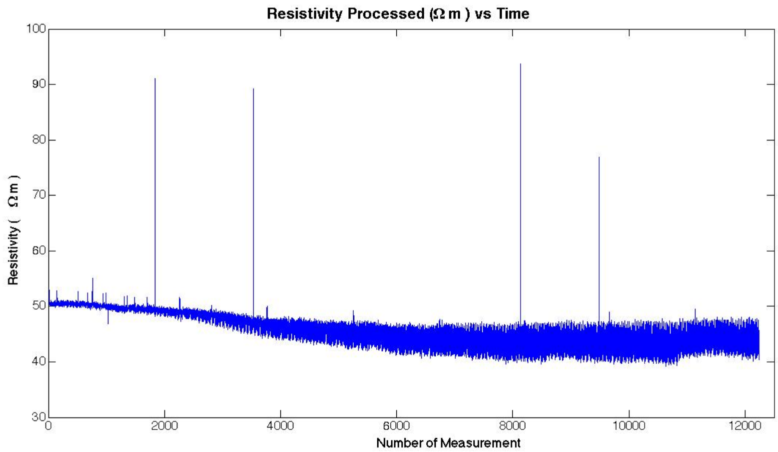

Figure 9: Resistivity when different arrival occurs.

According to Nwankwo *et al(2013)* and Pangonilo, the resistivity measurements that we represent above can be categorised as clay, which is one the most common soil types in Scotland. During the set up period, there were no extreme temperatures that would affect severely the measurements (extreme cold/dryness). Pangonilo claims that clay resistivity can be between 2-100 Ωm.

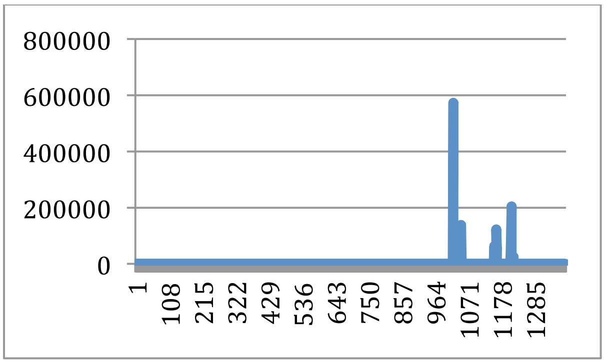

Figure 10: *$X^2+Y^2+Z^2$ vs number of samples*

Figure 10 shows the accelerometer sensor readings. While readings do not exceed a sum of squares of 200 to 250, there is a clear peak at 300. This occurred we jumped in the vicinity of the sensor node, which resulted in noticeable ground movement. This indicates the need for destructive testing, further data analytics and the potential to detect clear patterns of embankment failure.

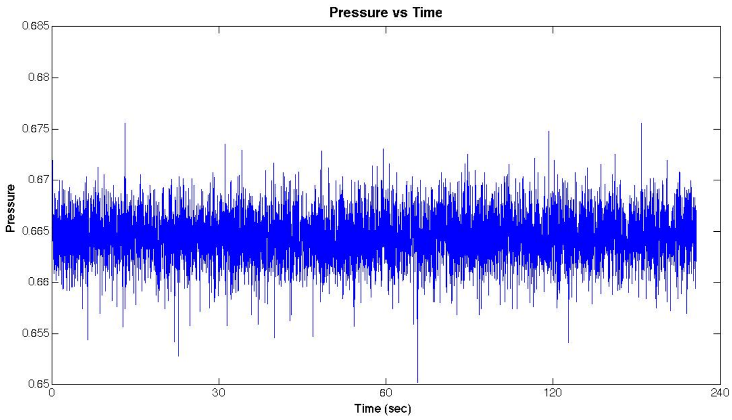

Figure 11: Pressure variations versus time

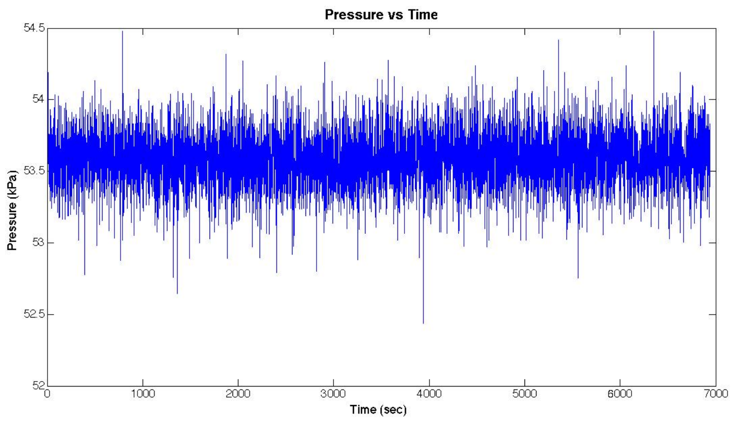

Figure 12: Pressure variations (kPa) versus time

Figure 12 shows the pressure readings and the conversion to kPa units. The deployed pressure sensor is a differential pressure sensor and it provides as an output the differential voltage, which is proportional to the differential pressure applied. This voltage output can be found in Fig. 11 and it has been amplified by a gain of 62. Fig. 12 shows the converted voltage output to pressure units by using the sensitivity of the sensor (according to the specific application) S=0.2 mV/kPa and by attenuating for the output gain. According to the figure, we can notice a variation of around 2 kPa during the 2 hours sample timespan and the above results translate to almost 0.5 atm.

Conclusions

In this paper, we have proposed a cost-effective prototype sensor solution for monitoring earthworks. Our current setup can measure soil resistivity, ground movement and pressure, but allows the incorporation of other sensors. The obtained results show expected resistivity values for the weather condition and soil material at the deployment site. Ground movement sensor sensitivity was proven and can be use in a future non-destructive test that could provide the profile of a healthy and failing earthwork. Finally, a further calibration of the absolute pressure with a pore pressure sensor would provide a cost-effecting alternative of the current methods of measuring pore pressure.

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