Stand-alone Geophone Monitoring System for Earthen Levees

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ABSTRACT

The potential of levee failures poses significant risks to populations living behind them. Levee monitoring using ground velocity measurements obtained from geophones has been demonstrated with the simultaneous deployment of wired geophone arrays. However, the scale of levees makes their monitoring with wired sensors a challenging task. This work reports on the development of a stand-alone geophone monitoring system for levees constructed of earthen embankments. The newly developed open-source sensor package can simultaneously measure ground velocity, conductivity, and temperature in addition to ambient atmospheric pressure and humidity. The system is fully independent of processing, power management, sensors, and data storage all contained within a single instrument. This work reports the initial experimental validation of the proposed system using a granular earthen levee in a flume under controlled erosion conditions. Data is collected and post-processed for anomaly detection; sensing capabilities, and the effect of sensor noise are discussed. To the knowledge of the authors, this is the first open-source stand-alone geophone system developed and tested for the monitoring of earthen levees.

Keywords: sensing, levee monitoring, geophone sensor, smart penetrometer, earthen embankment

1. INTRODUCTION

Extreme weather conditions and natural disasters are contributing factors to infrastructure deterioration and failure. Water-holding structures including dams and levees are shown to be the most impacted by conditions such as heavy rain and earthquakes.[1] Hard-wired systems are put in place to monitor these structures and issue early warnings to evacuate civilians and take preventive measures.[2,3] The advent of compact, drone-deployable sensors has paved the way for rapid evaluation of such infrastructure which was previously costly and slow due to the need for dedicated equipment and qualified personnel.[4,5]

Geophones are highly sensitive acoustic instruments composed of a spring-suspended mass wrapped with a coiled wire and positioned over a permanent magnet. Vibrations acting upon the geophone cause displacement of the mass which produces a voltage. This property makes geophones favorable sensors for their low-frequency sensitivity, optimal for ground vibration detection.[6] In seismology, geophone arrays are used to detect subsurface waves by measuring the time response of passive or active excitation signals using interferometry.[7] Therefore, in applications involving monitoring seismic activity, levee or dam structural deterioration, and landslide detection, geophones often prove useful.[8–10]

Levee failure occurs when the structural integrity is compromised due to flooding, seepage, earthquakes, or other causes.[11–13] Levee failure due to flooding is called overtopping and happens when the levee's waterside rises higher than the levee's crest causing external erosion.[14] When seepage occurs in a levee, the water flushes out soil particles developing channels internally. This phenomenon is known as piping or internal erosion which

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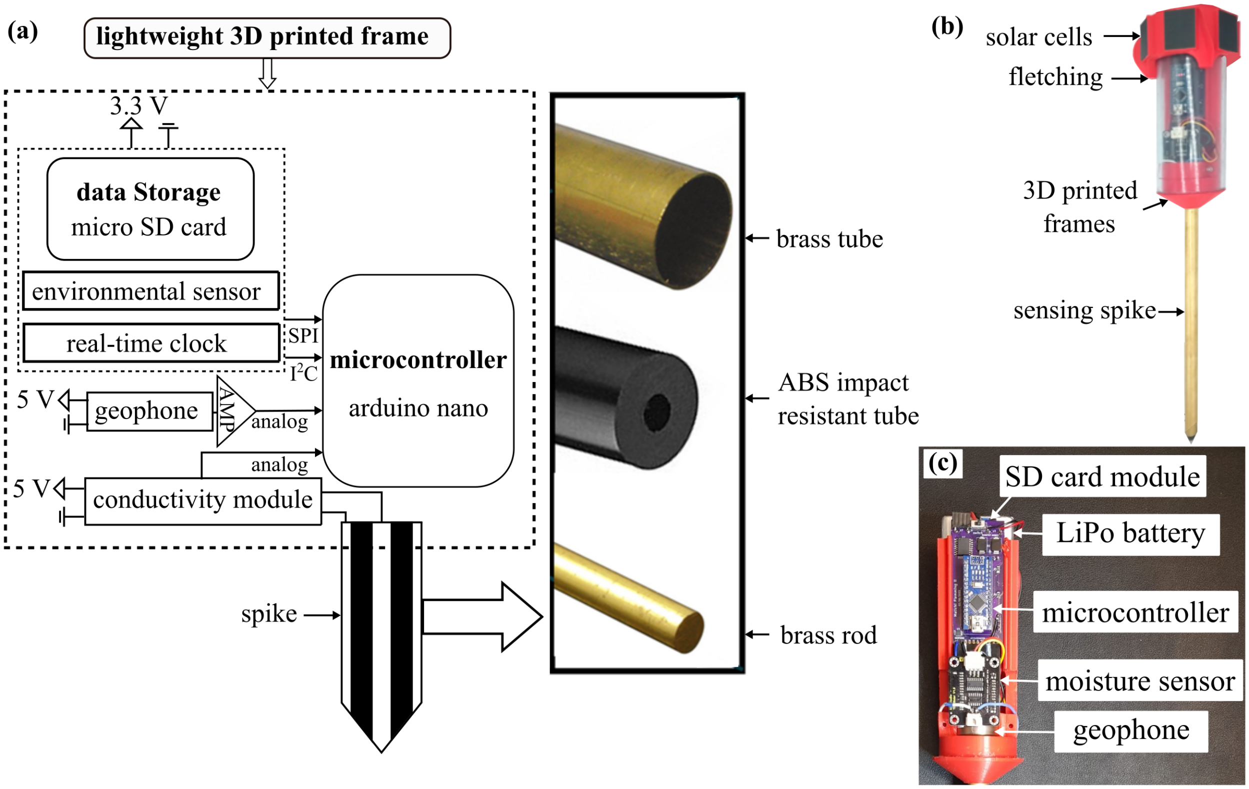

Figure 1: Detailed layout of the open source sensor package displaying (a) the sensor package's block diagram;(b) the sensor package construction; and (c) a breakdown of the various systems on board the sensor package.

is a major contributor to the diminishing structural integrity of levees over time. This phenomenon is usually caused by dead roots underground or wild animals that initiate seepage by burrowing into the levee creating openings for the water to travel through.[12]

Previous studies have utilized geophone sensors to monitor earthen levee erosion. Planes et al. used geophone sensors to monitor the ambient seismic noise[15] while Fisher et al. used geophone sensors to measure the velocity[16] to observe the internal erosion. However, none of these works have incorporated a completely self-contained geophone system for this purpose. To elaborate, in this context, self-contained denotes a system that contains its CPU, power management, sensors, and data storage in a single stand-alone instrument. Generally, wired geophone arrays are deployed for experimentation involving earthen levee fault detection. While large-scale geophone arrays have a greater signal-to-noise ratio and can acquire larger amounts of data than a single geophone,[17] this work presents an investigation into the capabilities of a single sensing node.

This paper focuses on the application of a standalone geophone-based smart penetrometer to monitor and analyze the integrity and failure of earthen embankment levees. In addition to the geophone, the sensor package measures soil conductivity and temperature along with ambient air temperature, pressure, and humidity; all information that can be correlated to assess changes in the levee's structural conditions. With computing, power management, sensors, and data storage all housed in a single instrument, the system is completely autonomous. This study presents the results of the initial experimental validation of the suggested system utilizing a granular earthen levee in a flume with controlled erosion. The designs for the smart penetrometer are available through a public repository released under the creative commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licenses.[18] This work will focus on studying the advantages and limitations of the designed sensor package as a single node of detection rather than a network. This effort aims to set a framework for future sensing networks utilizing this sensor as a building block. The contributions of this work are twofold: 1) presents the first development of an open-source standalone geophone system, and 2) provides a discussion on the sensor's performance during laboratory-scale earthen levee failure experiments.

2. HARDWARE DEVELOPMENT

Figure 1 depicts a block diagram of the sensor package, including, the various onboard modules, their voltage supplies, and communication protocols. The spike is designed to have two conducting surfaces, an outer tube and an inner rod separated by an insulating ABS plastic tube. The configuration allowed for the integration of a conductivity module allowing the spike to also function as an underground moisture probe. The frame of the package was also 3D printed with varying degrees of PLA density to ensure a strong yet lightweight frame. The mostly metal spike is robust, allowing it to survive the forces of being dropped from a drone into a levee. The package is designed to withstand appropriate environmental conditions over long deployment periods while collecting data through various sensors.

The sensor package, shown in figure 1(b), is fitted with a 3D-printed PLA attachment that has a dual purpose. The first is to secure six solar cells configured to aid in load sharing during sunny conditions, thereby extending battery life. Second, the attachment incorporates a helical fletching design to induce rotational stability during free fall, ensuring that the spike always points downwards. The frame is also designed to reduce the impact loading on delicate electronics by diverting the impact loads around electronics and damping the loads through low-density pockets within the frame itself.

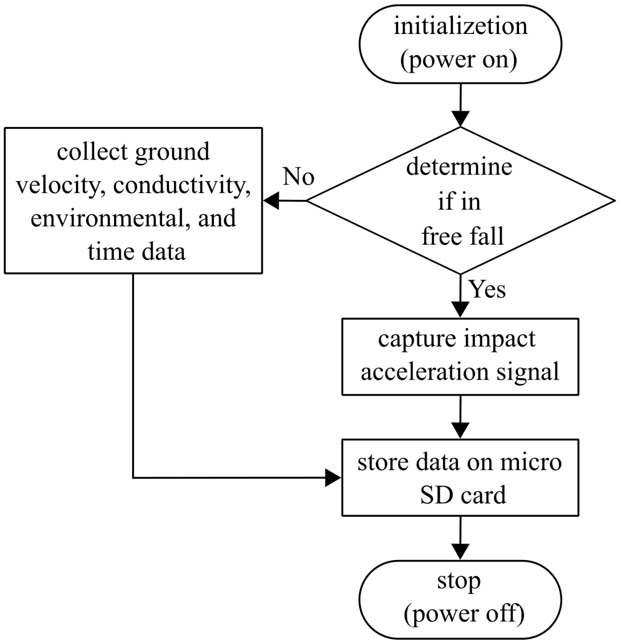

Figure 2: Sensor node data acquisition algorithm flowchart.

Figure 1(c) shows the internal electronics of the sensor package. Lithium polymer batteries are chosen for this application for their high power density and desirable recharging properties. The Lithium polymer battery chosen is a 3.7V 2500 mAh single-cell unit. Furthermore, an Arduino nano microcontroller was utilized as the core processor of the package for its desirable footprint. A Micro SD card module was also included to save data on device, this method of storage was chosen as it required no power to hold the state of the memory so that no data is lost in case of power system failure. The sensor package relies on multiple protocols such as Serial Peripheral Interface (SPI), I^2C serial communication, along with analog voltage readings to communicate with the various subsystems onboard. As for onboard sensors, an environmental sensing module was utilized to measure air pressure, humidity, and ambient temperature, all important parameters for early failure detection. Combined with a total dissolved solids (TDS) module, the spike measures changes in the electrical conductivity of the medium in which it is embedded. These changes can be attributed to the water seepage occurring before a breach. The package is also fitted with a sensitive geophone to detect ground velocity during the deployment period. Monitoring ground velocity can provide useful information about material shifting underground that is not visible on the surface, an indicator of a breach or water seepage. The geophone was daisy-chained to an amplifier to increase the low-energy vibration detection capability of the sensor package. A printed circuit board was designed to connect all the various subsystems onboard the package which was then fitted into an PVC outer tube to shield the package from the elements during deployment.

The data-collecting process is displayed in a flow chart in Figure 2. With the intended deployment method being a drop via a drone, the package is designed to detect once it is in free fall so that the initial impact with the ground is recorded using the accelerometer on board. Capturing the impact can provide information about the density and the type of ground the sensor is embedded in. Once the package is secured on the ground, the various sensors on board are initialized where environmental parameters, ground velocity, and moisture are recorded periodically. During operation, the power system utilizes both the solar panels along with the LiPo battery to extend operational time. Data is stored on board the package until retrieval on an SD card to prevent any loss.

3. METHODOLOGY

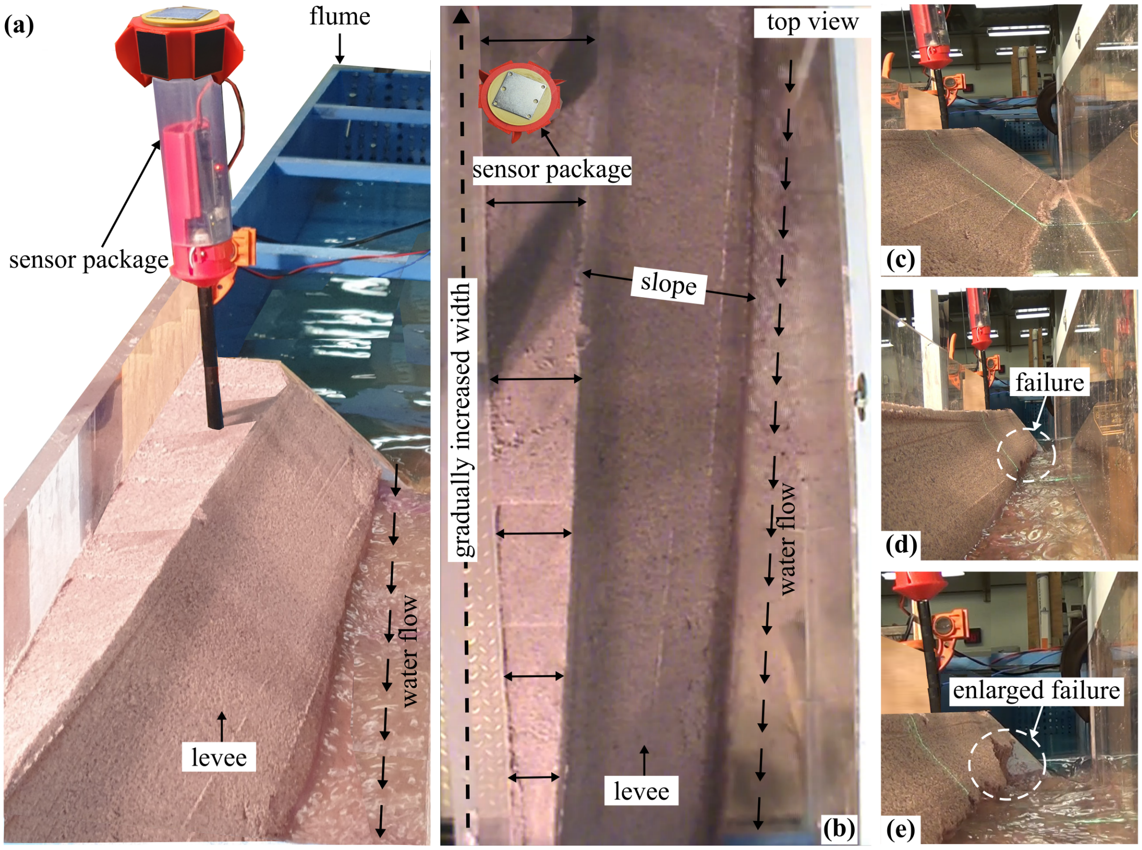

Figure 3: Laboratory-induced levee failure by overtopping experiment setup, showing: (a) experimental setup; (b) top view; (c) no water flow; (d) limited water flow, and; (e) high water flow.

The experimental study, shown in figure 3, is developed to investigate the use of smart penetrometers to identify early cracks in earthen embankments caused by internal erosion. During the experiment, the sensor package is mounted into the body of the levee via the sensing spike. Environmental parameters along with

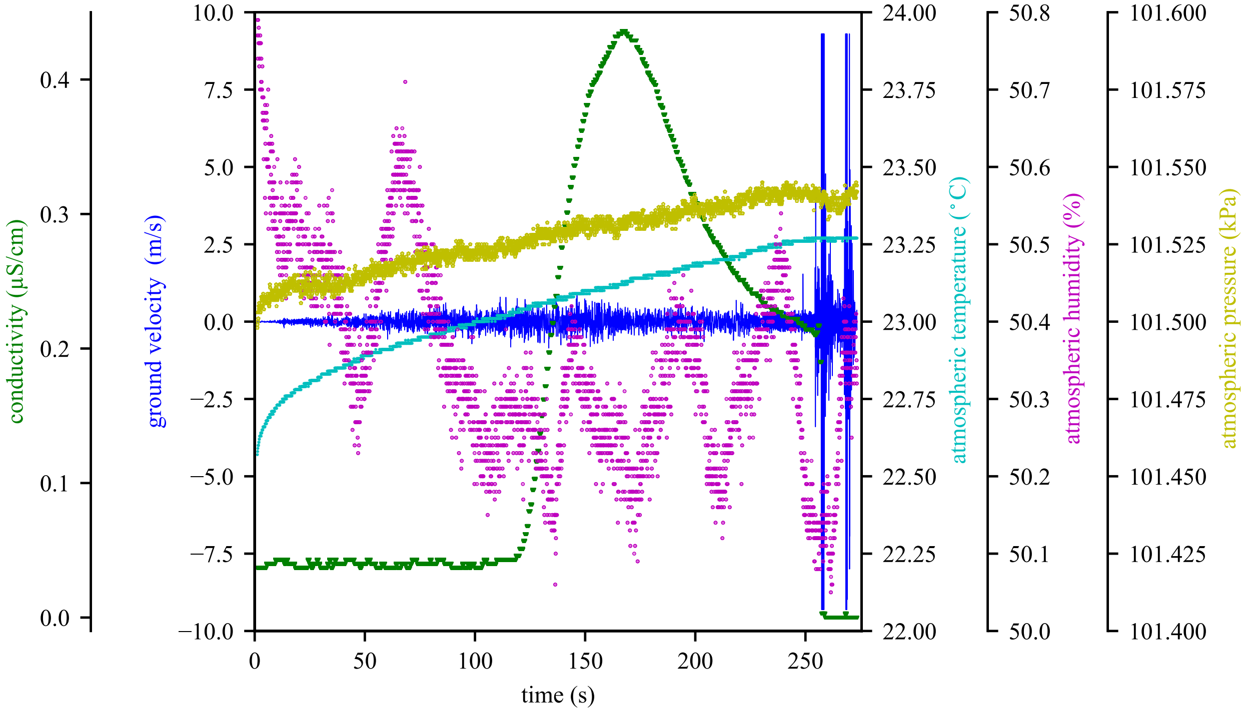

Figure 4: Data obtained from the sensor package obtained from the earthen levee experiment.

ground vibration and moisture levels are recorded as the water flow eroded the levee body until failure occurred. Figure 3 (a) shows the experimental setup used in testing. The top view, in figure 3 (b) provides a detailed description of the levee's form in addition to the direction of water flow. Figures 3 (c), (d), and (e) show how the levee failure gradually evolves. The main events detected during this experimental phase are the erosion and cracking induced by water flow, indicated in 3 (d) and (e). Cameras are positioned in the front, side, top, and back of the experimental setup to capture the evolution of the levee failure to then be used as a reference to validate the sensor package performance. A laser beam is also projected on the levee's side slope to provide another metric of levee damage for future comparison.

4. RESULTS AND DISCUSSION

The test results obtained from the sensor package are shown in figure 4. The two parameters that have the most variations during the test are ground velocity and conductivity, as those two measurements are directly proportional to the cracking and moisture seepage phenomena that typically occur before a large structural failure. Results show that the use of ground velocity from geophone and conductivity from the sensing spike data can be beneficial in detecting the events leading up to the levee's structural failure.

When moisture levels are observed during the experiment, a significant change of conductivity around 0.4 µS/cm is noticed at approximately 140 s which is due to the increased level of water flow. A sudden drop in conductivity is observed at 260 seconds which may be attributed to the formation of large failure and air pockets underneath the surface; however the exact mechanism that caused this sensor reading is unknown.

Geophone measurements of ground velocity reveal that until a significant failure occurs at roughly 240 seconds, the geophone returns steady results that are ±2.5 m/s. In contrast, a velocity of close to ±9 m/s is measured at the large levee failure around 250 s. The full structural failure of the levee's body is speculated to be caused by the water rushing into the corroded cracks and pockets. The the moisture measurement was cross-referenced with the ground velocity readings and multiple cameras used during the test. The formation of the cracks and their enlargement was shown to cause shifts in the surrounding sand which is detected first in this case by the conductivity reading and later by the geophone. However, the linkage between conductivity and ground velocity observed here are not representative of a full-scale levee.

Environmental parameters show the least connection to the deterioration of the structure, however, measuring atmospheric temperature, humidity, and pressure offers valuable information about the weather conditions surrounding the area of interest. For instance, high humidity levels along with a drop in atmospheric pressure can be an indicator of heavy rain which will increase the possibility of levee failure. Ambient temperature during the test was shown to range from 22 to 23.5 °C. The atmospheric humidity and pressure were approximately 50% and 101.325 kPa, respectively. As this experiment was run indoors, those parameters were recorded for system validation purposes and were not of importance to the levee failure analysis.

5. CONCLUSION

The introduction of a stand-alone sensor package for structural health monitoring of earthen levees is presented in this work. Considering the future aerial deployment, these sensors can be delivered at a lower cost to remote and inhospitable locations when compared to their hardwired counterparts. This sensor package is designed to measure environmental and ground parameters for monitoring of levees with the design made available to the public as an open-source project. Several tests are carried out to optimize the design and assess the reliability of all onboard sensors. The package was capable of detecting the slight variations in ground velocity and moisture levels before structural failure as indicated by the experimental results. The deployment period of such systems can be one of their limitations, as these sensors are expected to operate for extended periods without interference. This will be addressed in the future by considering larger batteries and implementing a power-saver mode. Future work will also concentrate on the deployment of a network of these sensors, as well as the possibility of using a wireless communication system to send data directly to the user.

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