ASME SMASIS 2023

The ASME 2023 Conference on Smart Materials, Adaptive Structures and Intelligent Systems

CONFERENCE SEPT 11–13, 2023
DOUBLETREE BY HILTON AUSTIN
AUSTIN, TX

CLASSIFYING SOIL SATURATION LEVELS USING A NETWORK OF UAV-DEPLOYED SMART PENETROMETERS

Puja Chowdhury[1], Joud N. Satme[1], Ryan Yount[1], and Austin R.J. Downey[1,2], Sadik Khan[3], Jasim Imran[2], Laura Micheli[2]

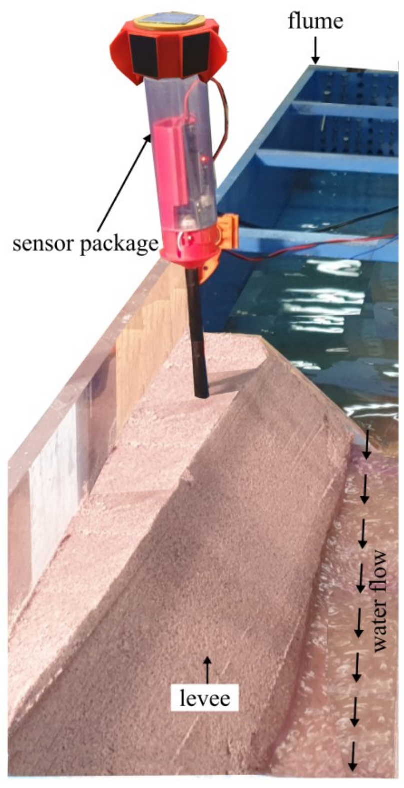
[1]Department of Mechanical Engineering, University of South Carolina, Columbia, SC

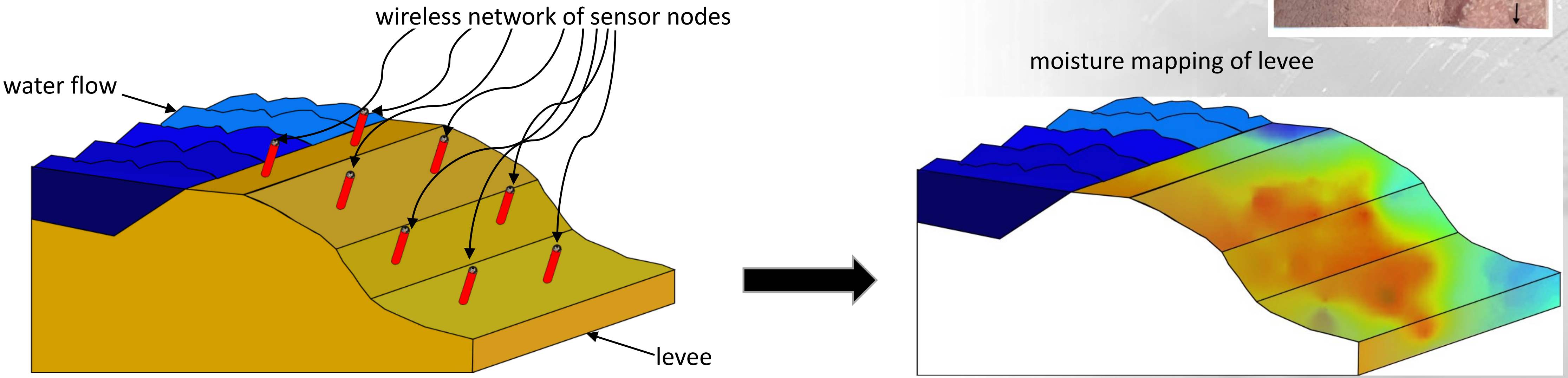
[2]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC

[3]Department of Civil and Environmental Engineering, Jackson state University, Jackson, Mississippi

❑ TABLE OF CONTENTS:

- Introduction
- Methodology
- Experimental Setup
- Results and discussion
- Conclusion

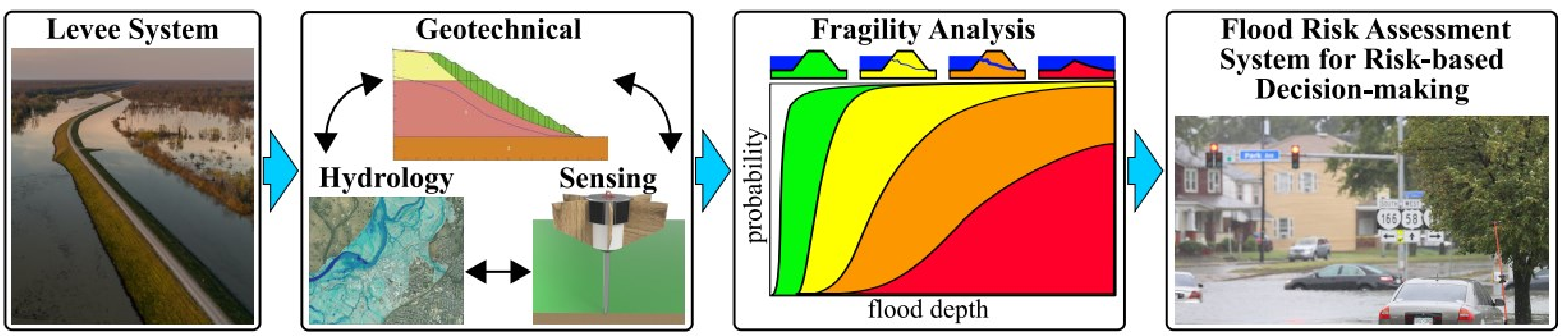




Introduction

❑ RISK ASSESSMENT OF LEVEE BREACH

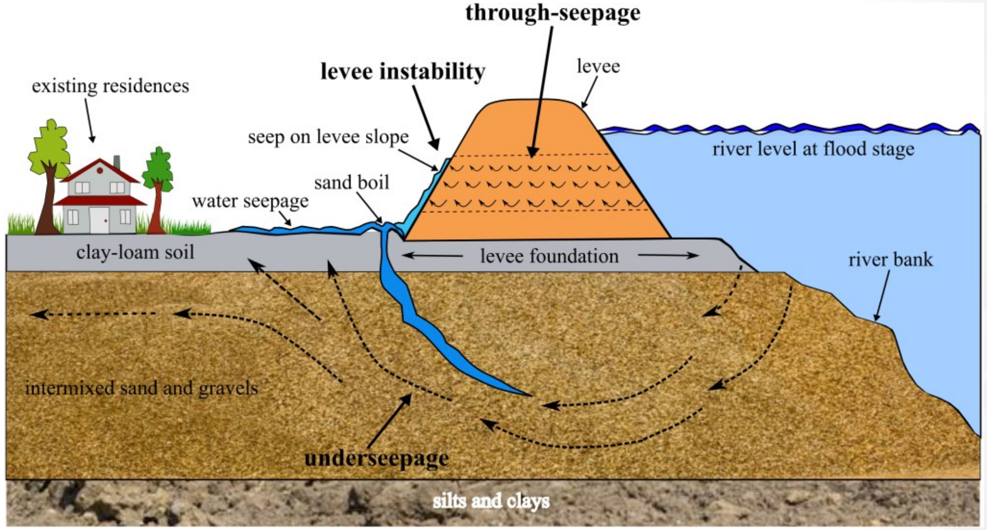
- This work is part of a larger effort to develop a data-driven fragility framework for risk assessment of levee breach.
- This presentation will focus on preliminary experiment on the development and validation of UAV-deployable smart sensing spikes for soil conductivity levels in levees.
- This work is being done in close collaboration with experts in data-driven risk assessment, geo-technical, and hydrology.



ASME 2023 SMASIS
The ASME 2023 Conference on Smart Materials, Adaptive Structures and Intelligent Systems

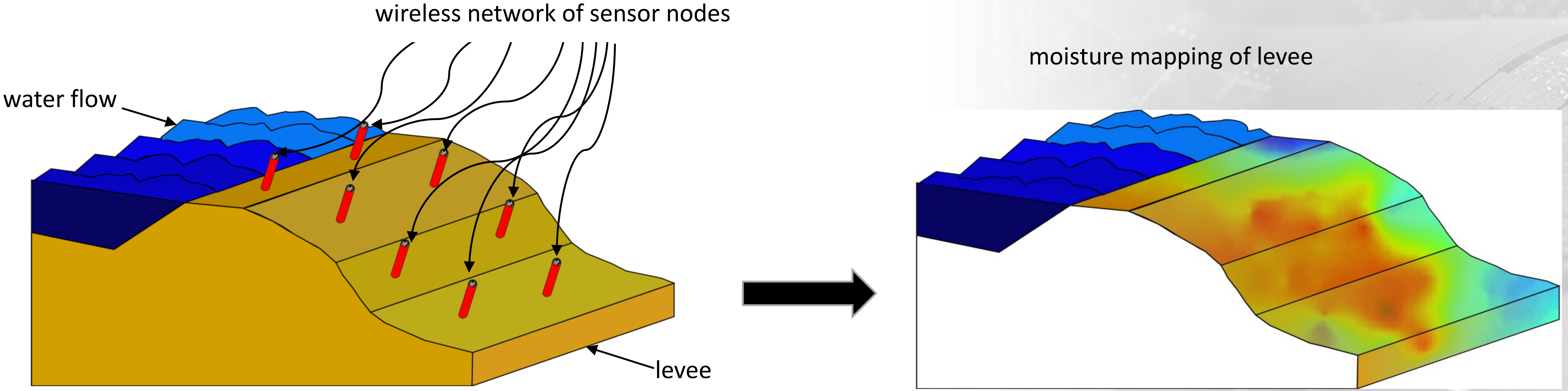
❑ LEVEE

- A dry levee works by absorbing and slowing down the water until river level drops.
- Levees are made mostly of
  - compacted dirt,
  - not concrete or metal,
  - are permeable.
- Water will seep through or under a levee given enough time.



❑ CONDUCTIVITY-BASED MONITORING

- A network of sensors, as well as the possibility of using a wireless communication system to send data directly to the user.



❑ Kriging

- **Kriging** is a spatial interpolation method with a few key types or models.
- **Simple kriging** assumes the model : $Z(x) = \mu + \epsilon(x)$
  - where Z is the kriging predicted value at x
  - where μ is a known constant
  - where ϵ is error (small scale variation) at x
  - simple and not really used in practice
- **Ordinary kriging** assumes the model: $\mathrm{Z(x) = \mu + \epsilon(x)}$
  - where $\mathrm{\mu}$ is an unknown constant
  - assumption of a constant mean is unreasonable for this case
- **Universal kriging** assumes the model: $\mathrm{Z(x) = \mu(x) + \epsilon(x)}$
  - where $\mathrm{\mu(x)}$is a deterministic function.
  - also called kriging with external drift or regression kriging

Methodology

❑ CONTRIBUTIONS

- The expandment of experimental data using kriging.
- The categorization of soil saturation using a network of smart sensing spikes.

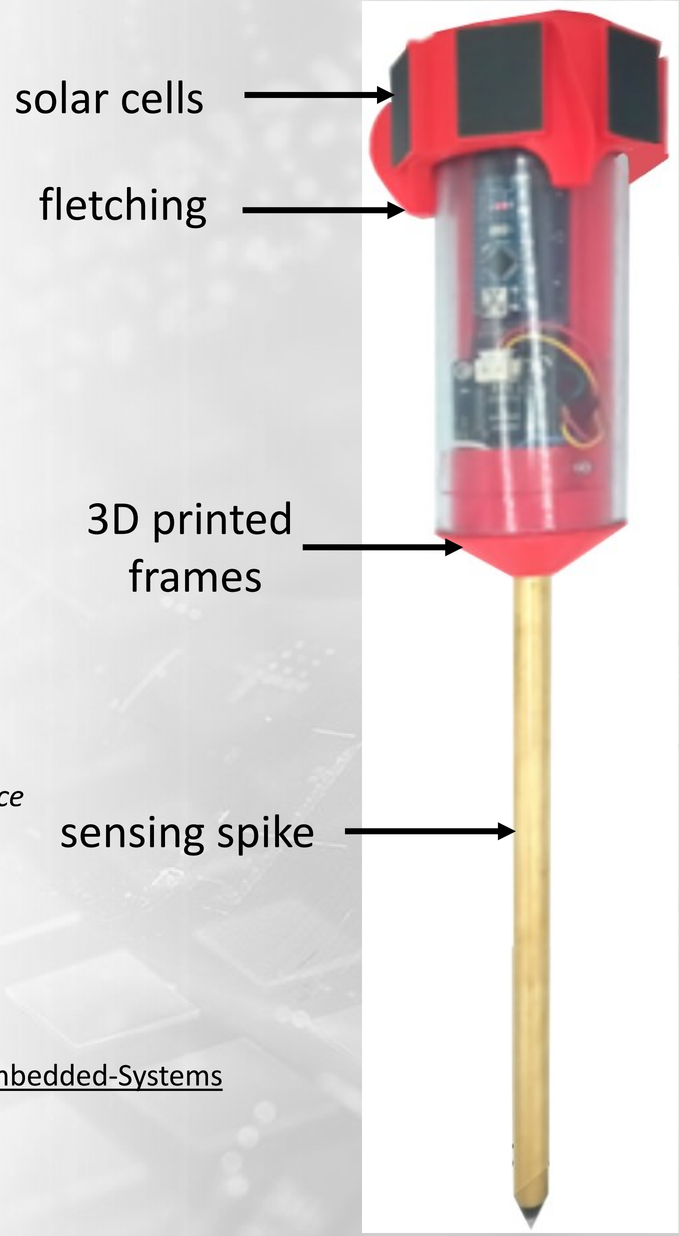
❑ HARDWARE DEVELOPMENT

- Developing the sensing spikes.
- Experimental setup.

❑ Sensor package

❑ **Initial work:**

- The first open-source stand-alone geophone-based sensor package developed and a published paper on this. [1]
- 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.[2]

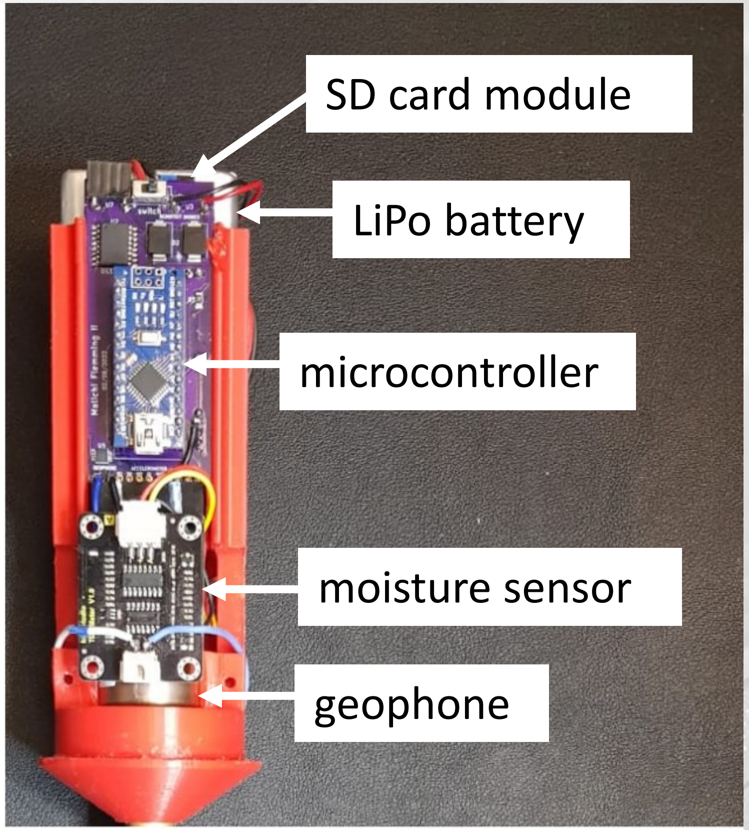


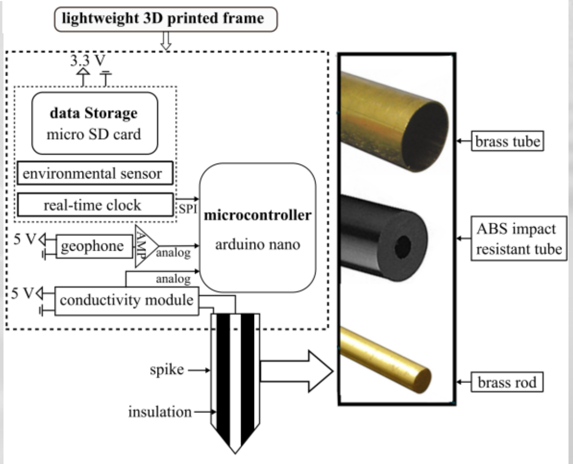
[1] Puja Chowdhury, Joud N. Satme, Malichi Flemming, Austin R. J. Downey, Mohamed Elkholy, Jasim Imran, and Mohammad S. Khan. Stand-alone geophone monitoring system for earthen levees. In Zhongqing Su, Maria Pina Limongelli, and Branko Glisic, editors, *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023*. SPIE, apr 2023. doi:10.1117/12.2658552

[2] https://github.com/ARTS-Laboratory/Smart-Penetrometers-with-Edge-Computing-and-Intelligent-Embedded-Systems

❑ Sensor package(Electronics)

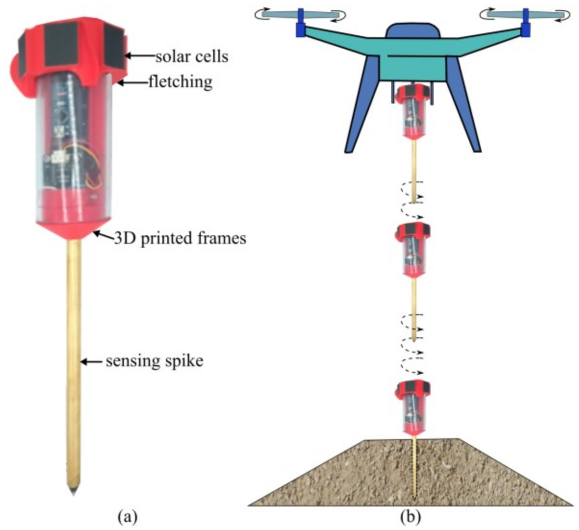
- Lithium polymer batteries are for their high-power density and desirable recharging properties.
- An Arduino nano microcontroller is utilized as the core processor of the package for its desirable footprint.
- An environmental sensing module is utilized to measure air pressure, humidity, and ambient temperature.
- A sensitive geophone to detect ground velocity during the deployment period.
- A Micro SD card module is to save data on device.



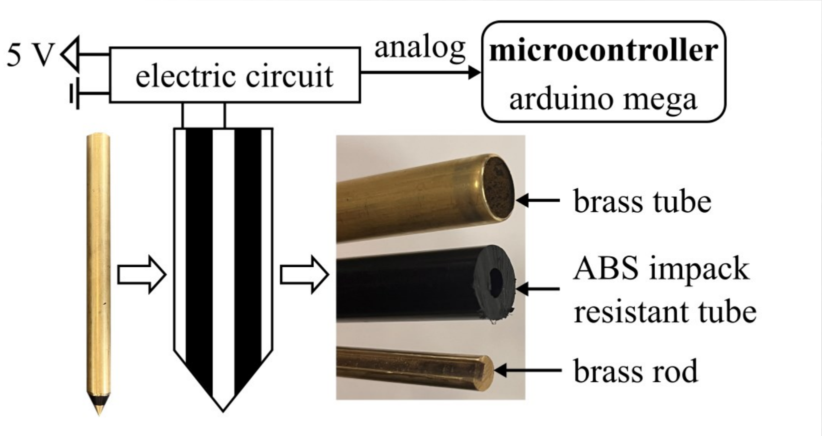


❑ SENSING NODE

- ❑ Initial work starts with the development of UAV deployable sensor package
- ❑ The spike is designed to have two conducting surfaces
  - an outer tube
  - an inner rod
  - separated by an insulating ABS plastic tube.



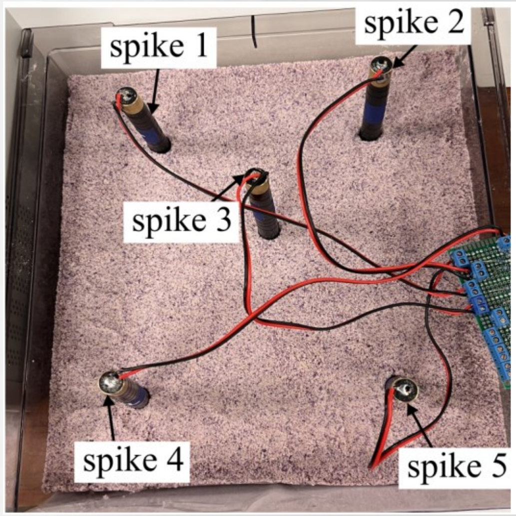
(a) The UAV deployable sensor package , and (b) a 2D view of the UAV sensor deployable process via the drone

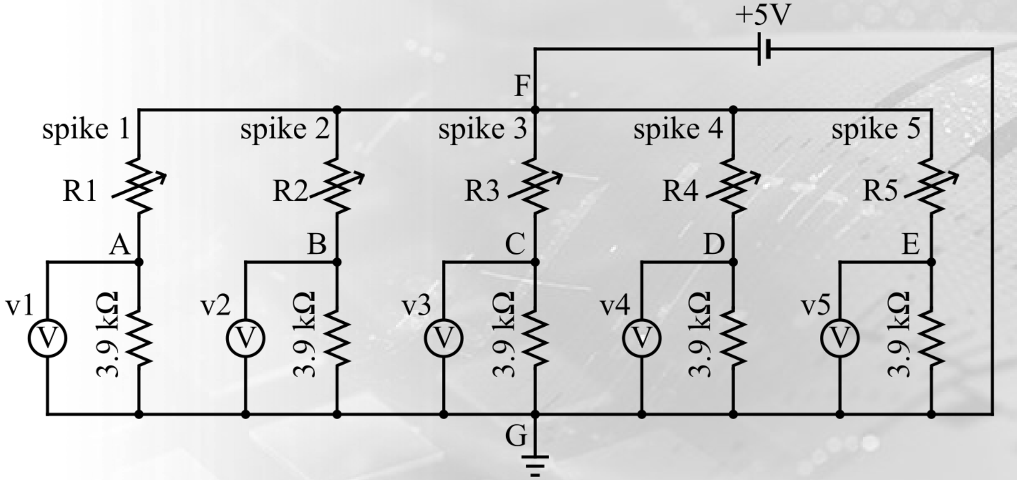


The sensing spike construction

❑ ELECTRONICS

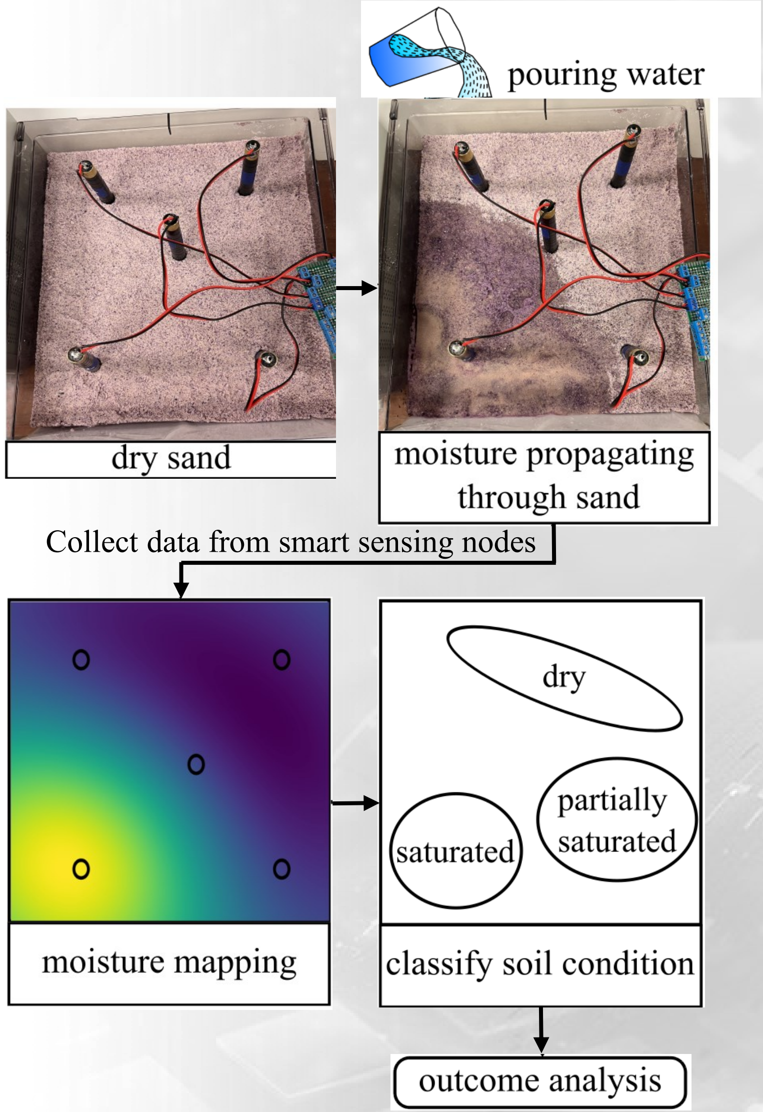
- A potential difference of 5 V was provided by a DC power supply to the spikes.
- The spikes of the moisture-sensing network are set in parallel concerning power and ground (shown as F and G respectively).
- Each spike (R1-R5), modeled as a variable and voltage divider using a constant 3.9 kΩ resistor.
- Potential points A-E are then measured using an analog to digital converter onboard a microcontroller as $V = [v_1, v_2, \cdots v_5]$
- The voltage drop measured and point A for instance will be directly proportional to the moisture level measured by the spike (R1).





❑ FLOW CHART

- Five sensor spikes are inserted in the sand-filled box during the experiment.
- Water is added to the corner of the container, and moisture spreads throughout the sand.
- Collect the data from sensor spikes.
- Moisture mapping of the entire area by using kriging model.
- Classifying soil condition by applying k-mean clustering.

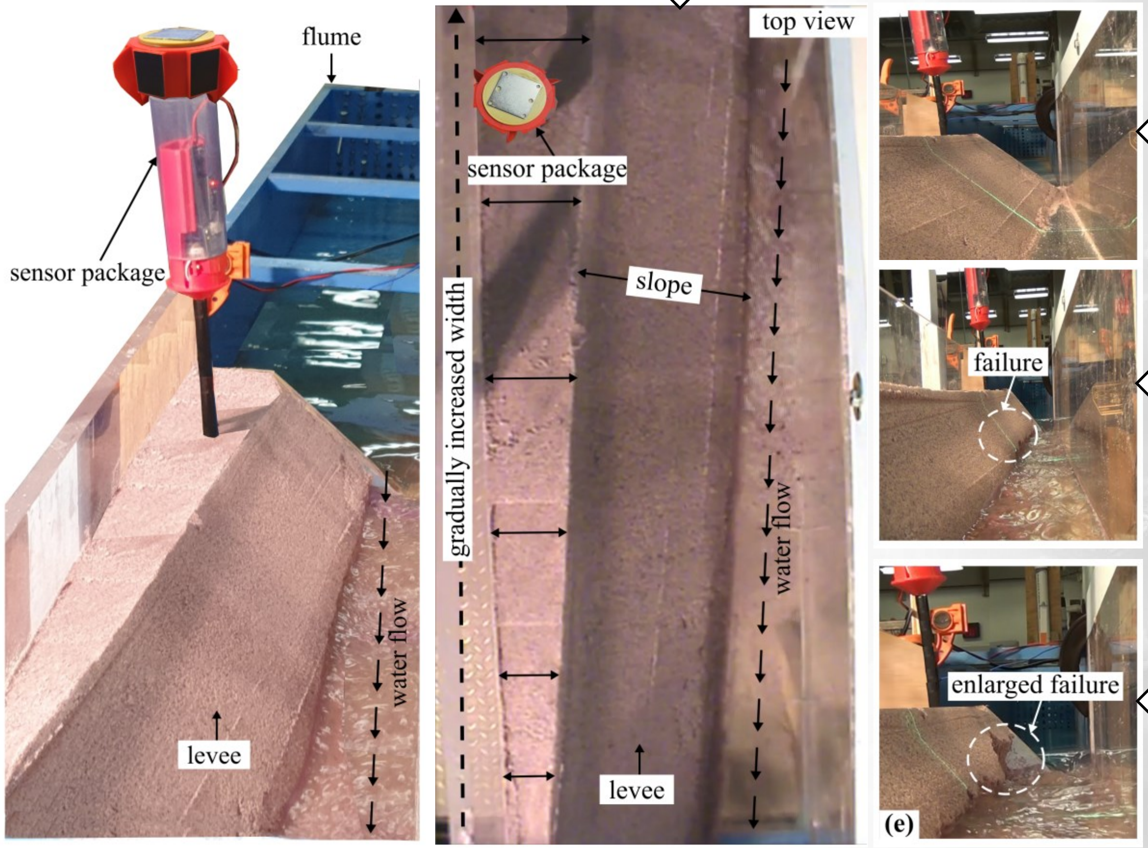


Experimental Setup

❑ SENSOR PACKAGE LEVEE FAILURE TEST

top view

experimental setup



no water flow

limited water flow

high water flow

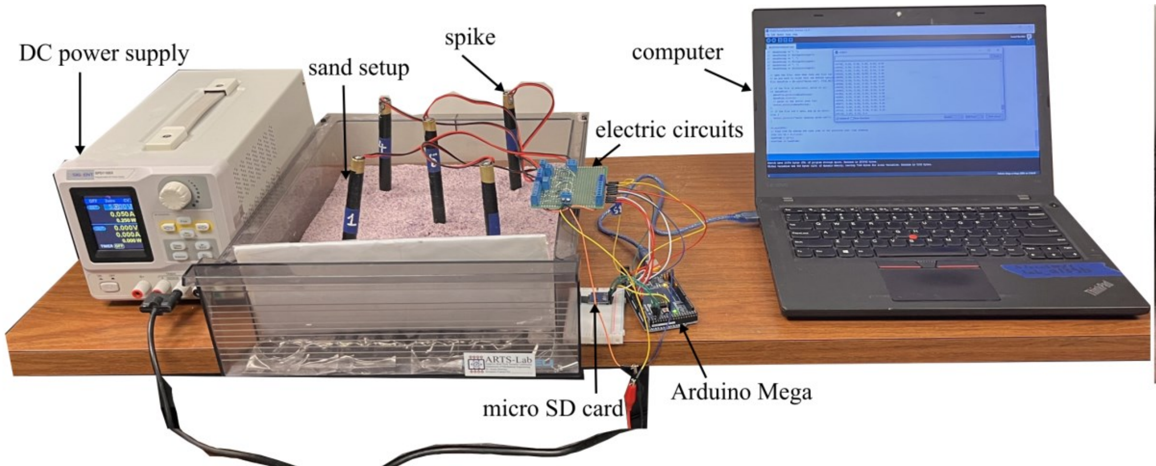
❑ SENSOR PACKAGE LEVEE TEST

MOISTURE TEST WITH SENSING NODES

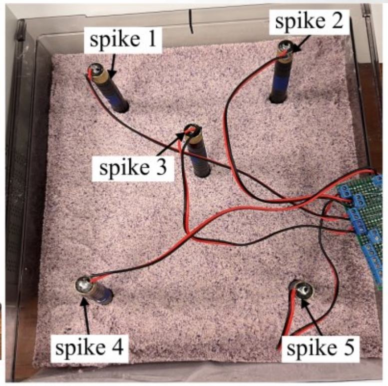
- A container of 10.8 x 12.4 inches is used.
- Sand is then filled to a height of 1.5 inches.

TABLE 1. Five-spike moisture test position coordinates.

spikes	notation of fixed resistor with respect to the spike	x-coordinate (inch)	y-coordinate (inch)	z-coordinate (inch)
1	v_1	2.5	9.3	1.69
2	v_2	8.3	9.3	1.69
3	v_3	5.4	6.4	1.69
4	v_4	2.5	2.5	1.69
5	v_5	8.3	2.5	1.69



(a)



(b)

❑ Data interpolation

- Ordinary kriging is used to interpolate the data for all the spatial points.
- The spikes' locations are $S = [s_1, s_2, \cdots s_5]$
- The coordinates of the spikes are $[X, Y] = [(x_1, y_1), (x_2, y_2), \ldots, (x_5, y_5)]$
- The voltage measurements are $V = [v_1, v_2, \cdots v_5]$
- The desired prediction from kriging model is $v_k = \mu + \varepsilon(s_k)$

where,

v_k is continuous accurately map at all possible $s_k = (x_k, y_k)$

μ= the true mean of the entire dataset, the desired estimation is performed by ordinary kriging

$\varepsilon(\cdot)$ = the error caused by small scale variation at s.

- The estimation $\hat{v}_k = \sum_{i=1}^{n} \lambda_i v_i$
- The loss function $L_{\mathrm{krging}} = E(v_k - \sum_{i=1}^{n} \lambda_i v_i) - 2m(\sum_{i=l}^{n} \lambda_i - 1)$
- The [X, Y, V] is used to train the Gaussian variogram models.

❑ Clustering

- This work classifies moisture levels in earthen levees into three clusters
  - dry
  - partially saturated
  - saturated
- K-means clustering algorithm is used.
- The squared Euclidean distance is used with Voltage (v) being the sole feature considered as like

$$\left\| s_p - s_q \right\|_2^2 = \left(v_p - v_q \right)^2$$

- The iterative approach is followed to minimize the within-cluster sum of squared error (SSE) or cluster inertia.

$$L_{SSE} = \sum_{i=1}^{n} \sum_{j=1}^{m} \omega_{(i,j)} \left\| v_i - c_j \right\|_2^2$$

where,

c_j is the centroid for cluster j

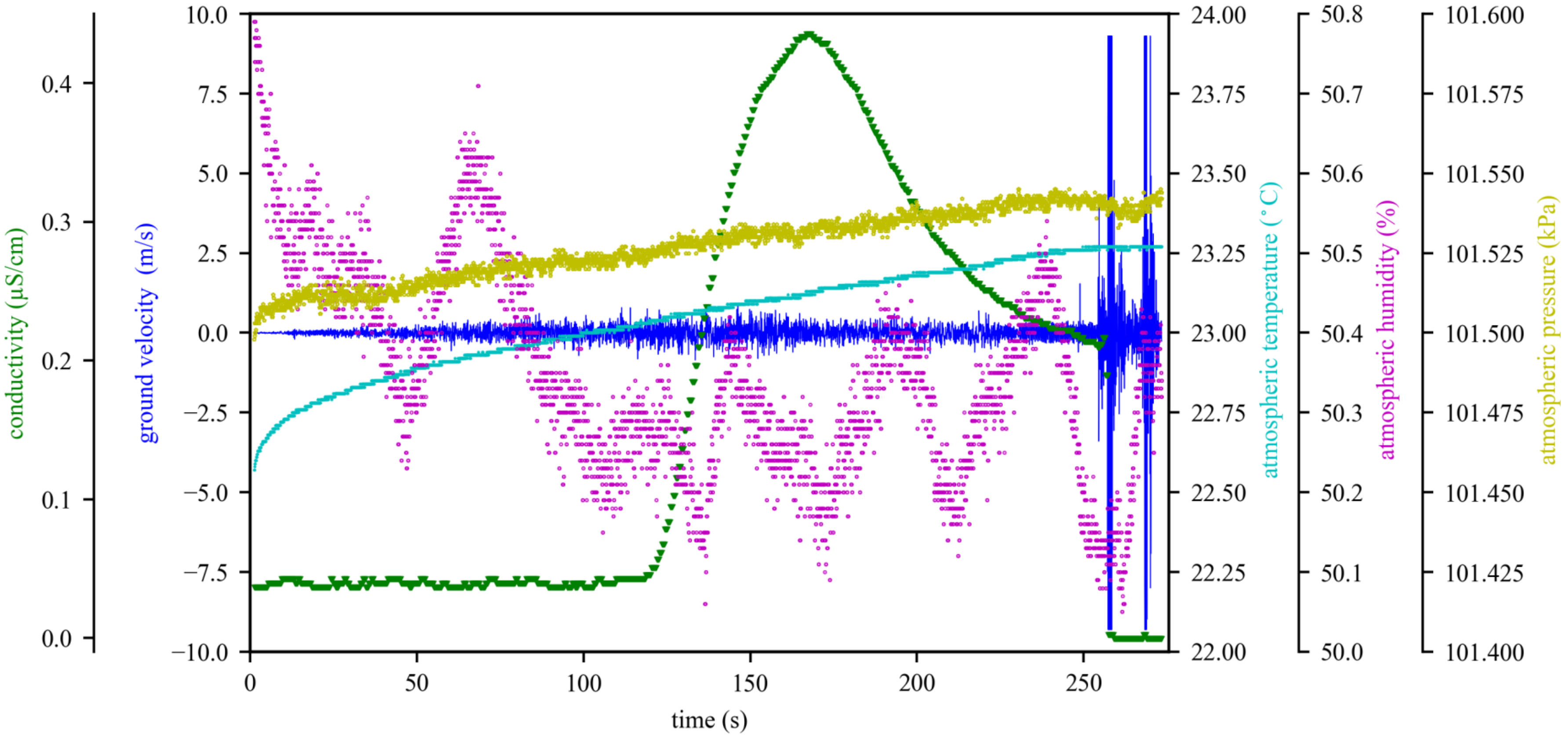
$\omega_{(i,j)}$ = 1 if the sample v_i is in cluster j or *0* otherwise.

m = 3 for three clusters.

Results and discussion

SENSOR PACKAGE LEVEE FAILURE TEST

- Experimental results from sensor package.
- 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.



❑ MOISTURE TEST OF A NETWORK OF SENSING SPIKES

- During kriging, only a single timestamp of measurements is considered for moisture mapping of the whole experimental area.
- Spike 4 voltage measurement is shown to be higher compared to the other four spikes
- Spikes 1 and 2 show the lowest voltage reading.
- The area surrounding spike 4 is considered to have the highest level of moisture
- The bottom left corner has the largest voltage meaning more moisture compared to the top right corner of the mapping which is around 1.5 V.

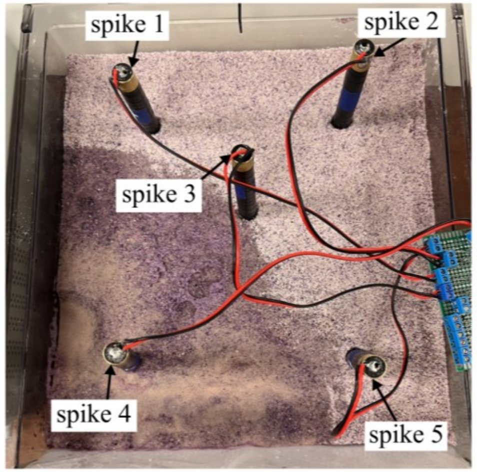
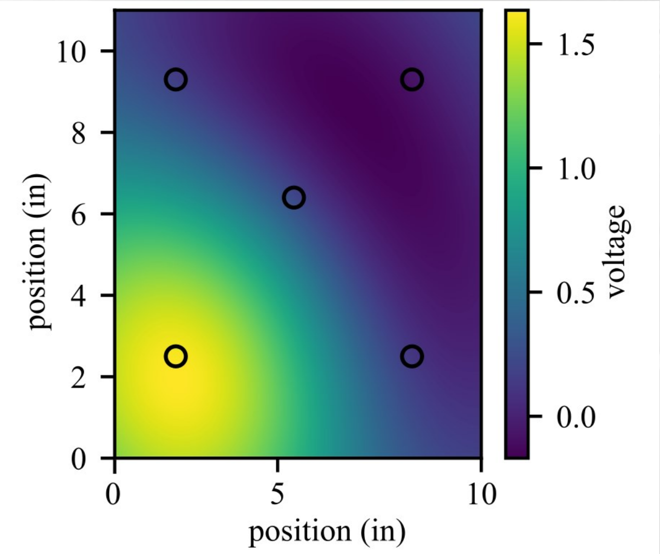


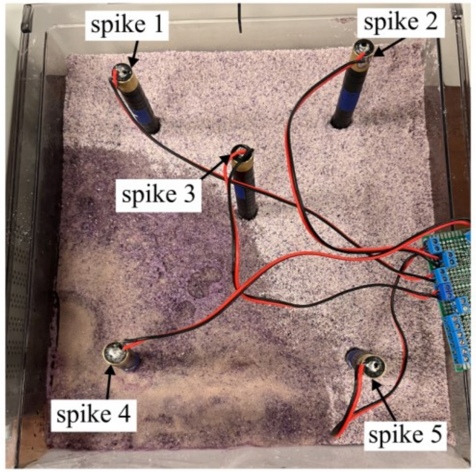
TABLE 2. Five spikes voltages for a single time stamp.

spikes	spike 1	spike 2	spike 3	spikes 4	spike 5
voltage (V)	0.014	0.014	0.024	1.549	0.078



MOISTURE TEST OF A NETWORK OF SENSING SPIKES

- The highest voltage of the centroid is 1.372 V at the threshold between 1.0 to 1.635 V.
- This centroid value is close to the spike 4 value 1.549 V values and considered this cluster as a saturated one.
- The centroid value of 0.629 V is considered partially saturated as this threshold 0.324 to 1.000 V is close to spike 5, 3 values.
- The lowest value of the centroid is 0.019 V and ranges between -0.168 to 0.324 V and categorized as dry is close to spike 1, 2.



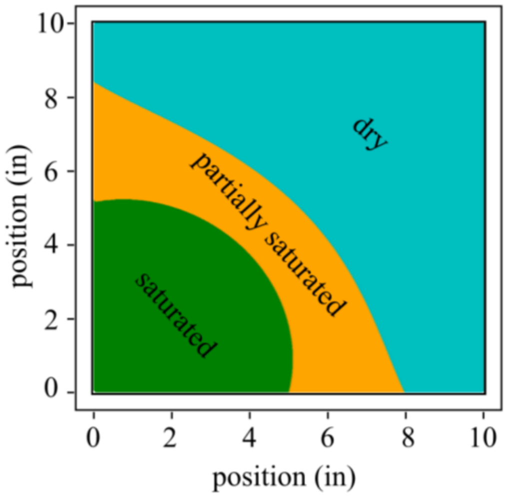


TABLE 3. Threshold and centroid values for *k*-mean clustering.

minimum v (V)	maximum v (V)	centroid v (V)	categories
-0.168	0.324	0.019	dry
0.324	1.000	0.629	partially saturated
1.000	1.635	1.372	saturated

Conclusion

Conclusion

- A preliminary experiment on the development and validation of UAV-deployable smart sensing spikes for soil conductivity levels in levees
- A measurement method for estimating soil saturation levels.
- Demonstrated the sensing platform in lab-scale testing.
- To identify possible levee failure concerns and maintenance needs, this work evaluates soil conditions utilizing a network of smart sensing sensor spikes.

Open-Source Hardware Designs

https://github.com/ARTS-Laboratory/Smart-Penetrometers-with-Edge-Computing-and-Intelligent-Embedded-Systems

❑ Acknowledgement

The National Science Foundation provided support for this work through Grants 2152896 under the title of **LEAP-HI: A Data-Driven Fragility Framework for Risk Assessment of Levee Breach.** The National Science Foundation's support is sincerely thanked. The authors' opinions, results, conclusions, and recommendations in this material are their own and do not necessarily reflect the views of the National Science Foundation.

NSF

UNIVERSITY OF SOUTH CAROLINA

ASME 2023 SMASIS
The ASME 2023 Conference on Smart Materials, Adaptive Structures and Intelligent Systems

Thanks!

Contact information:
Email: pujac@email.sc.edu
Website: https://www.chowdhurypuja.com