

A preliminary study of environmental monitoring using embedded sensors in the soil

Kazuhiro Mukai ⁱ⁾, Yunshun Zhang ⁱⁱ⁾, Peter Hubbard ⁱⁱⁱ⁾ and Kenichi Soga ⁱⁱⁱ⁾

i) Researcher, Takenaka Research and Development Institute, Takanaka Corporation, 1-5-1 Ootsuka, Inzai, Chiba 270-1395, Japan.

ii) Ph.D. Student, Department of Civil Engineering, University of California at Berkeley, 760, Davis Hall, Berkeley 94720-1710, USA.

iii) Professor, Department of Civil Engineering, University of California at Berkeley, 760, Davis Hall, Berkeley 94720-1710, USA

ABSTRACT

Green infrastructure is a stormwater management technique that can be used to mitigate urban floods and heat islands. However, proactive monitoring and control is required to ensure its smooth operation. In particular, determining evapotranspiration, an essential process in biosphere–atmosphere interactions in cities that maintain cultivated and irrigated landscapes, is challenging. Understanding activities that govern evapotranspiration in a wide range of shallow soils is useful for planning and operation of green spaces. Recently, distributed fiber-optic sensors for monitoring civil structures and infrastructure have opened up new possibilities compared with conventional sensor systems. They operate based on the principle that strain variation in the soil is linked to environmental factors such as temperature and soil moisture changes. In this research, we examined the relationship between strain and temperature/soil moisture changes. By embedding fiber-optic strain sensors and other sensors in the soil tank, we investigated the feasibility of the sensors in a simulated soil environment.

Keywords: Green Infrastructure, Fiber-Optic Sensing, In-ground Wireless Sensor Networks

1 BACKGROUND

According to the United Nations, 70% of the world's population will live in urban areas by 2050. Therefore, the population density is expected to increase due to rapid urbanization in these areas (United Nations, 2017). Green infrastructure is an alternative stormwater measure that can help to provide safe water circulation in big cities. Recently, climate change has caused severe problems in urban areas, such as urban flooding and heat islands. Ensuring proper water circulation is essential to maintain sustainable living in future cities. On the other hand, some countries such as Japan are facing problems related to aging and population decrease. Green infrastructure is expected to offer solutions in alternative ways. For example, multifunctional and distributed infrastructure can play a crucial role by performing various tasks in future cities, such as capturing rainfall in urban green spaces for evapotranspiration. Thus, green infrastructure is one of the measures to contribute to maintaining natural water circulation in metropolitan areas. However, detecting evapotranspiration in these regions for quantitative evaluation of green infrastructure is a challenge.

Wireless sensor networks (WSNs) can collect a large volume of data from a wide range of areas. On the other hand, the use of distributed fiber-optic sensors for monitoring civil structures and infrastructure opens up exciting new possibilities compared to the use of conventional sensor systems (Soga and Luo, 2018).

Strain/temperature monitoring using fiber-optic sensors has been widely used recently. Furthermore, applications of fiber-optic sensors in environmental monitoring have been increasing (Joe et al., 2018). Thermal monitoring cables have been commonly used in environmental monitoring, but they have not been deployed for strain change detection in the soil.

In terms of monitoring stability, due to the considerable risk that sensor nodes can get destroyed by human actions in urban areas, we established an in-ground buried sensor system for soil moisture detection. Soil moisture is one of the critical parameters to determine evapotranspiration from the soil surface. Figure 1 shows the schematic of sensor deployment. As shown in the figure, the sensing region of the sensor was buried in the soil. Only the general gateway of the WSNs and fiber-optic sensor analyzer were deployed in a secure place on the ground.

The purpose of this study was to demonstrate proof of concept advanced sensing systems for environmental monitoring. As a preliminary test, signal propagation of the WSN units in the soil was tested in the laboratory. In addition, strain changes of the soil was monitored daily in a semi-outdoor environment.

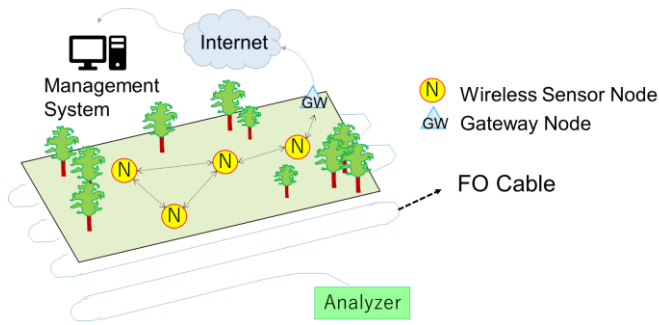


Fig. 1. In-ground buried sensors for soil moisture detection.

2 SENSING TECHNIQUES

2.1 Wireless sensor network units

The WSN units, which have been used for infrastructure health monitoring, was applied. The wavelength for signal propagation was 433 MHz, which is shorter than the conventional telecommunication wavelength. By shortening the wavelength, the arrival range of the signal becomes shorter. However, the signal becomes to propagate through the soil.

2.2 Fiber-optic sensor

A fiber-optic strain sensor was applied to measure strain changes in the soil. There are several methods of fiber-optic sensing. The optical frequency domain reflectometry (OFDR) technique was adopted in this experiment. To transmit in-ground strain changes to the fiber-optic sensor, 3D printing anchors made of plastic were attached to the strain-sensing cable. The 3D printing anchor and a picture of fiber-optic sensor deployment in the soil tank are shown in Fig. 2.

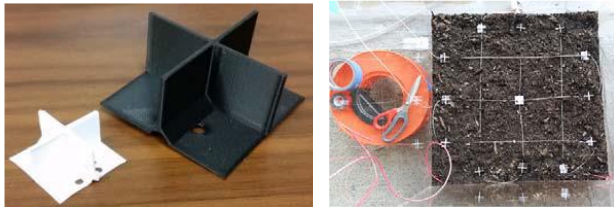


Fig. 2. 3D printing anchor (left) and fiber-optic sensor deployment (right).

3 EXPERIMENTAL METHOD

Two types of plastic tanks were prepared for small-scale testing. The soil was poured in these tanks to simulate the ground condition.

3.1 In-ground testing of WSNs

We confirmed signal propagation in the soil. To begin with, the calibration test for soil moisture sensors was used in this experiment. The test image is presented in Fig. 3. Soil moisture sensors connected to the WSNs system is used in this study. A soil sample from each category of soil was compacted using the same energy specified in the standard Proctor test (ASTM D 698). The volumetric water contents of samples ranged from 5% to 30%. Nevada sand was used for this experiment.

Original volumetric water content was measured by the method based on the JGS standard test method.



Fig. 3. Calibration test for soil moisture sensors.

Water has a higher density than the sand, so the signal propagation in the saturated soil rapidly decreased compared to that in unsaturated soil (Lin et al., 2019). To test the effect of saturation on signal propagation in the soil, water was poured into the tank in which 6 WSN units were buried. The water was poured from the bottom of the tank until the tank was fully saturated. After the sand was fully saturated, the water was drained from the bottom of the tank. The experimental equipment and cross-sectional image of the tank are shown in Fig. 4. The WSN nodes are centered in the horizontal position in the box.

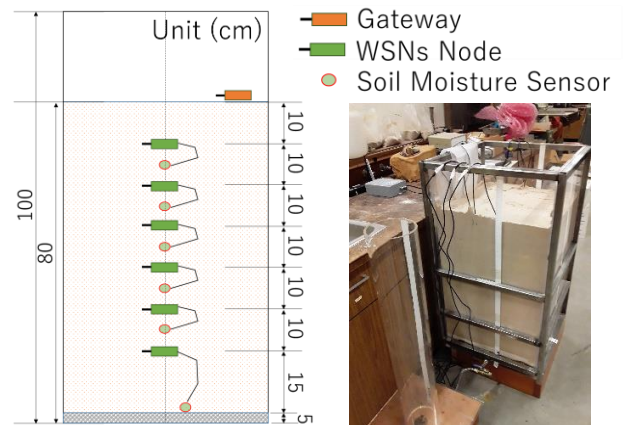


Fig. 4. WSNs' unit installation (left) and sand tank (right).

3.2 Monitoring strain in the soil under daily thermal changes

To test the strain change under the simulated environment, the soil box was established using a plastic tank (Fig. 5). The tank was 50 cm in width and depth 60 cm in height. 25-cm soil layer was placed in the tank. The tank was placed in a balcony on the 4th floor of Davis Hall at the University of California Berkeley campus. Although the container could receive sunlight, it did not get wet by rainfalls. To simulate the real environment, a plant, Fern, was put in the box. The measurement was conducted for the entire day to see the strain change caused by natural temperature change. The anchors were attached to the fiber-optic sensor every 40 cm and set it horizontally in the soil tank. The sensor part was arranged orthogonally. The soil tank was placed in a

semi-outdoor space. As the tank received sun heat, the temperature both inside and outside of the tank increased. The thermal change caused the expansion of the soil and water in the tank and expansion of the container itself. To see the plastic tank volume change caused by solar heat, the fiber-optic sensor was placed outside the tank. The laser distance was measured from the top of the plastic tank to observe the expansion of the soil.

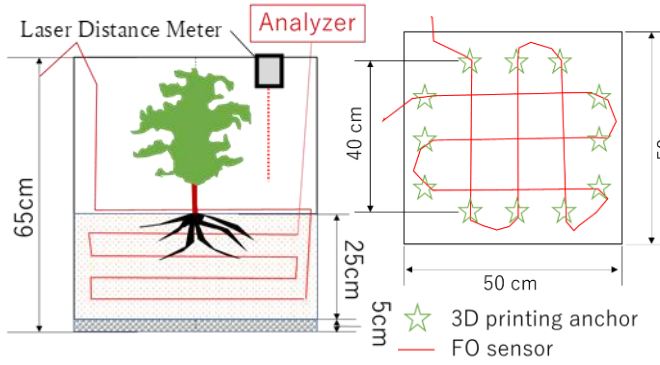


Fig. 5. Simulated soil environment for fiber-optic sensor-based monitoring.

4 SIGNAL PROPAGATION IN THE SOIL

4.1 Soil moisture sensor calibration

Figure 6 shows the calibration test results for the soil moisture sensor. The calibration curves were created for all soil moisture sensors for this test. The calibration curves were linear. However, the sensor output values were slightly smaller than the actual soil moisture measured using a furnace. As all the curves showed the same tendency, it is possible to correct the output value using a correction factor.

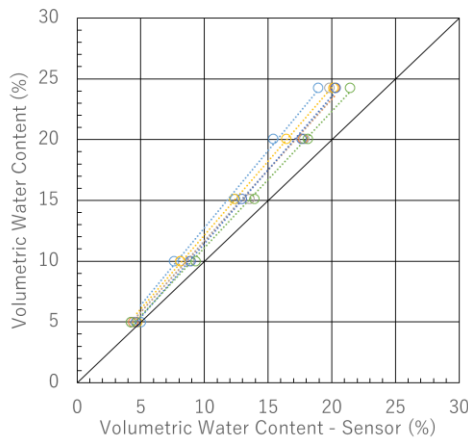


Fig. 6. Calibration of soil moisture sensors.

4.2 Signal strength change

Signal strengths and soil moisture changes during the test are shown in Fig. 7. The chart shows only the node at the top of the box. Other results are shown in Table 1. The signals from the buried WSN nodes were received by the general gateway directly in this test. The signal strength received at the general gateway is represented

as the received signal strength index (RSSI). RSSI was almost the same before and after water injection, and even the tank was filled with water completely. Generally, if RSSI is in the range from 0 dBm to -30 dBm, the signal transmission is good (Pamukcu et al., 2011). Although a slight decrease in RSSI was confirmed after starting the water injection, the change was small, and the system kept showing good signal transmission. This result shows that the signal propagation is stable even the water content of the soil around the units has been increased. However, this test was conducted in a small plastic box in the laboratory. The signal might have gone through the side of the plastic box. In the real underground situation, the signal can pass through the ground surface only. Although more experiment is necessary for the implementation of a real-world condition, the WSN system performed well in our simulated underground situation and showed robust signal transmission.

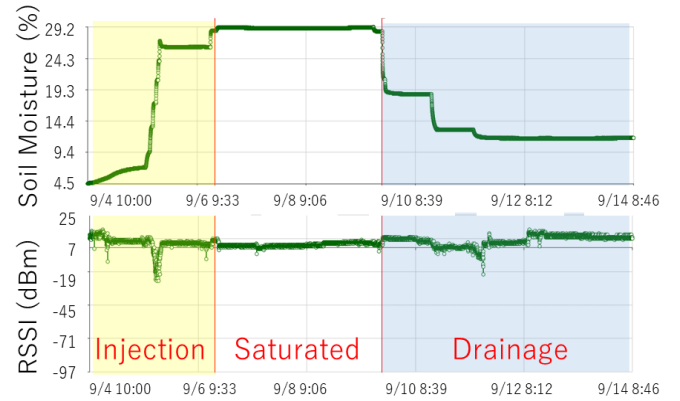


Fig. 7. Soil moisture and received signal strength index (RSSI) at Node F.

Table 1. Signal strength in various soil moisture conditions.

Node Name	Measurement	Before	⇒	After Saturated	⇒	After Drainage
		2019/8/21 10:00:00		2019/9/8 10:00:00		2019/9/14 10:00:00
A	Soil Moisture(%)	0.5	⇒	36.3	⇒	36.2
	RSSI(dBm)	1	⇒	-5	⇒	1
B	Soil Moisture(%)	0.0	⇒	31.8	⇒	31.5
	RSSI(dBm)	0	⇒	-4	⇒	2
C	Soil Moisture(%)	0.6	⇒	32.0	⇒	29.3
	RSSI(dBm)	4	⇒	-4	⇒	-5
D	Soil Moisture(%)	0.1	⇒	28.3	⇒	25.8
	RSSI(dBm)	5	⇒	-5	⇒	-3
E	Soil Moisture(%)	0.0	⇒	No Data	⇒	No Data
	RSSI(dBm)	5	⇒	No Data	⇒	No Data
F	Soil Moisture(%)	0.1	⇒	29.0	⇒	11.9
	RSSI(dBm)	5	⇒	1	⇒	4

5 STRAIN CHANGE OF THE SOIL

5.1 External factors and soil condition

The daylong temperature changes on the experiment day are shown in Fig. 8. Both air and soil temperatures are shown in the graph. By placing it on the south side of the tank that received sunlight directly all day long, the maximum difference in the air temperature measured with a thermometer was nearly 20 °C. The soil temperature started to increase later than the air temperature. In addition, the peak value of the temperature (the southeast corner) had appeared earlier than that of the northwest corner. This result indicates that the soil exposed to direct sunlight was warmed. The maximum difference in the soil temperature was nearly 10 °C. The soil used in this test was the one commercially available for gardening; it contained silty soil and humic substances. Before starting the test, water was poured into the soil tank. The volumetric water content of the soil was constant at ~31% during the trial. For the measurement of volumetric moisture content, a soil moisture sensor having a calibration curve was used.

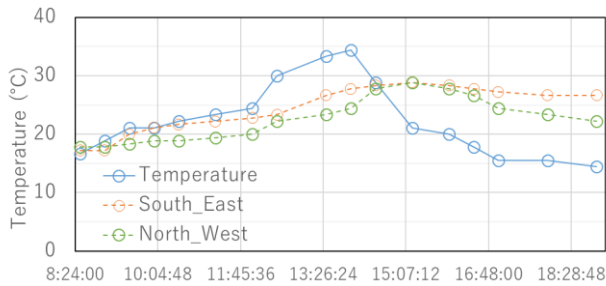


Fig. 8. Air and soil temperature changes on the test day.

5.2 Daily strain changes of the soil in the tank

Strain changes throughout the entire length of the fiber-optic sensor is presented in Fig. 9. Several peaks were observed, and the peak shapes changed with time. The positions where the strain peaks appeared are matched with the sensing region, which is the section separated by the two anchors in the soil. This result indicated that the 3D printing anchor can transmit the strain change of the soil to the fiber-optic sensor.

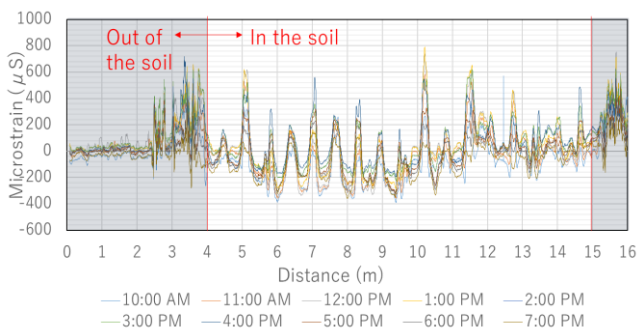


Fig. 9. Strain in the soil measured by fiber-optic sensor

Figure 10 shows the displacements obtained from the changes in strain during the day for two sensors arranged perpendicular to the north-south and east-west directions. To figure out the effect of the air temperature on the strain sensor, the displacement of the part that was not affected by the strain outside the soil is presented in the same figure. The peak of the displacement of the north-south direction appeared earlier than the east-west direction. Although this difference was assumed to be caused by the sun position, the peak value appeared earlier than the soil temperature peak. There is a possibility that the strain change in the soil would be due to other factors such as vapor pressure in the soil; therefore, additional studies are necessary to determine factors affecting the strain change. The result from the east-west direction has a similar tendency with the soil temperature change in the day. On the other hand, the displacement observed for the sensor outside the soil was smaller than the value in the soil, suggesting that the strain measured with the fiber-optic sensor in the soil was caused by factors other than the air temperature change itself.

Although the factors affecting the strain need to be clarified, the results demonstrated that the strain change in the soil reflects the atmospheric condition of the place. Therefore, soil environment monitoring using fiber-optic strain sensing can help to understand interaction between soil and atmosphere.

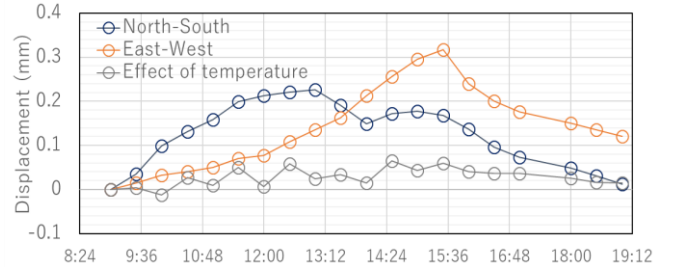


Fig. 10. Displacement calculated from strain changes.

To figure out whether the soil was expanding during the test, the surface position was observed by the laser distance, and the expansion of the tank itself was monitored using fiber-optic strain sensors. The results are shown in Fig. 11. As a result, the plastic container was expanded with a maximum of 0.27 mm throughout the day. The value was close to the measurement value of the fiber-optic sensor in the soil, as shown in Fig. 10. Otherwise, the expansion monitored by the laser distance was more prominent than these measurements. The vertical expansion calculated from the results was 1.63 mm maximum. However, as the data obtained from one point of the soil tank, we need to do more experiments to confirm this phenomenon. From the results, the horizontal strain found in the soil seems to be caused by the tank volume change. These results showed that small strain changes in the soil can be monitored using fiber-optic sensors with 3D printing

anchor and OFDR analyzer.

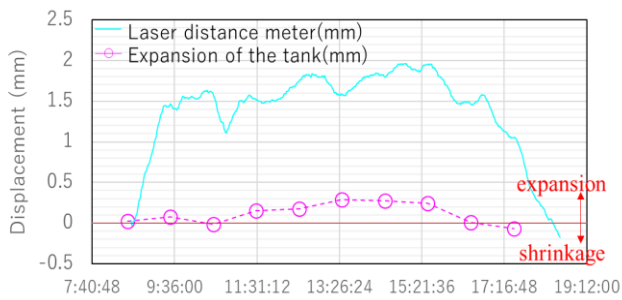


Fig. 11. Volume changes of the soil and plastic tank.

6 CONCLUSIONS

A small-scale testing of advanced soil environment monitoring technique was conducted as a preliminary study in the laboratory. In-ground WSNs performed well under high water content. The 3D printing anchor transmitted the strain change of the soil to the fiber-optic sensor. By using the OFDR analyzer, we monitored small strain changes in the soil. In future work, we will investigate environmental factors that cause strain

changes in the soil. For understanding the practicality of the monitoring system, further work must be performed using larger equipment in the real-world environment.

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