Implementing fiber sensors to monitor humidity and moisture

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ABSTRACT

In a quest for fiber optic sensors that could monitor soil moisture, Blue Road Research implemented fiber Bragg grating sensors in such a way that they could detect humidity, soil moisture evaporation rates, and pressure changes from soil weight. These were then used to monitor soil in controlled flood tests to determine the moisture levels in a soil test bed. Fiber optic sensors seem well suited for humidity and soil moisture monitoring since they can easily be multiplexed with many sensors on one fiber line, and they have distinct longevity advantages that enable their use in applications involving wet environments, remote locations or long distances, electromagnetic interference, flammability, or other harsh environmental conditions that may degrade ordinary electronic sensors or their measurements. This paper describes the workings of a highly accurate optical humidity sensor that can be multiplexed on a fiber optic strand to monitor humidity that may lead to corrosion, soil moisture levels and changes, weather conditions, etc. as well as means to record such data.

Keywords: soil moisture, relative humidity, pressure, weight, temperature, grating, fiber optic sensor, FBG, corrosion, evaporation

1. BACKGROUND AND INTRODUCTION

Humidity and moisture sensors are currently employed to monitor soil moisture levels for crop production, livestock feed temperature levels, road conditions, erosion monitoring, and water seepage. The United States Department of Energy (DOE) funded a major portion of research into such sensors for Blue Road Research to develop a groundwater monitoring sensor for levels between 2% and 18% gravimetric soil moisture (2-18% of the total weight of a soil sample is due to water) that could monitor moisture above hazardous waste sites.

Current technology used to measure soil moisture uses many methods, the best known are the neutron probe, time-domain reflectometry, and gypsum blocks, each with highly varying costs and accuracy; the DOE uses as a standard of measurement the neutron probe in the flood test depicted in Figure 1. Unfortunately, these probes only take one data point at a time and use radioactive materials to perform their function. For other types, multiplexing the sensor over hundreds of meters was cost prohibitive and often inaccurate. Fiber optic sensors offer long sensor life without rusting or corroding, which is important for sensors that must be buried in hundreds of locations.

Fiber Bragg gratings have been used to sense strain and temperature for several years. They are created on a fiber strand with a laser that permanently changes the index of refraction of the fiber several times in a periodic fashion over a short distance (over a few millimeters to several centimeters). The combination of these lines form a grating that causes only a specific wavelength of light to be reflected, called the Bragg wavelength; the rest passes through.

As the grating properties are changed (such as when the fiber is strained), the Bragg wavelength shifts, which can be detected by spectrometers at high frequency with very high resolution (allowing sub-microstrain measurements of megahertz vibrations). Because of this capability, fiber Bragg gratings (FBGs) have been attached to bridges, cantilever beams, and many other places previously reserved for piezo strain gages. Temperature also elongates the fiber, causing a change in the Bragg wavelength; so unstrained FBGs are often used to measure temperature in places where electrical sensors may not work well.

Figure 1. Neutron Probe Monitoring Soil Moisture

2. HOW CAN LIGHT IN GLASS FIBER MONITOR HUMIDITY?

Blue Road Research's focus on extracting environmental information from fiber gratings has led the company's researchers to investigate the response of many materials to environmental stimuli. Capitalizing on the response of certain fiber optic coatings to humidity, Blue Road Research investigated the repeatability of several techniques and found that certain optical fiber coatings respond linearly over wide humidity ranges, as seen in Figure 2, and that thicker coatings increased the response magnitude, in agreement with previous studies[1] and previous research by other scientists at Blue Road Research[2].

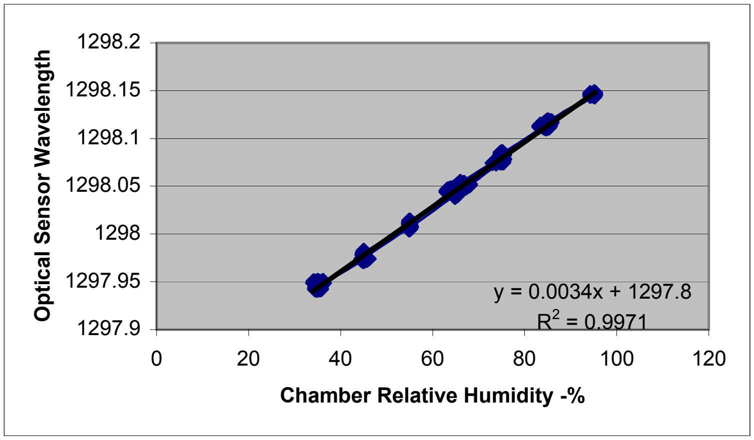

Figure 2. Linearity of Response for Fiber Optic Humidity Sensor

Humidity changes can be detected when the coating over a fiber grating sensor shrinks or swells in response to the humidity in its environment, causing changes in the strain state of the fiber at the grating. In the case of the fiber sensors currently employed by Blue Road Research, the coating swells in the presence of moisture up to saturation of the coating (near 100% relative humidity). Figure 3 shows that this swelling induces an axial strain on the grating, increasing the spacing between the lines of the grating, which causes a wavelength shift. It should be noted again that temperature also lengthens the grating, linearly changing its wavelength.

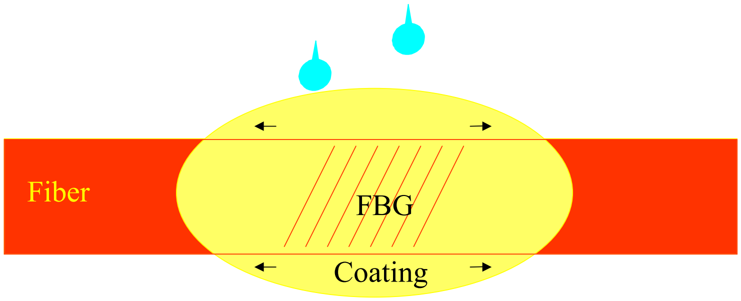

Figure 3. Fiber Sensor Coated for Humidity Response

3. HIGH RESOLUTION MEASUREMENT METHODS

Several techniques can be used to evaluate the wavelength shift (and thus the environmental effects acting on the grating). The most popular may be to illuminate the grating with a broadband light source and view the light reflected by the wavelength-selective grating on an optical spectrum analyzer (OSA). This yields detailed data in a very turnkey package, with many sensors viewable at once.

Blue Road Research also measures this sensor wavelength using a patented configuration[3], which measures sensor wavelength by masking it behind another fiber grating of similar wavelength. Any wavelength change is then detected as an intensity change as more or less light is allowed to transmit through the filtering grating – like a passing rain cloud would veil the sunshine. This provides an unnecessarily high bandwidth for moisture sensors (up to 2 megahertz) but has the distinct advantage of using inexpensive photodetectors to measure the resulting unfiltered light. Some humidity cycles measured by this system are shown in Figure 4; note the consistency of the fiber humidity sensor with the humidity measured by the RTD sensor in the environmental chamber.

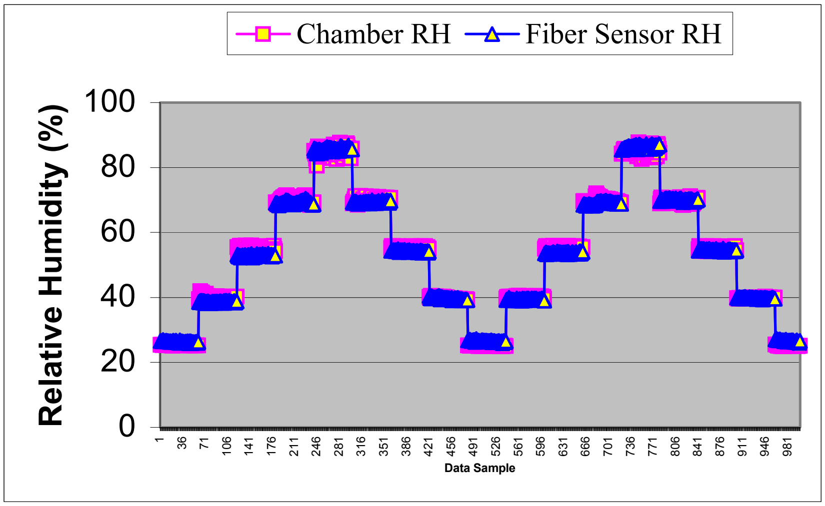

Figure 4. Comparison Graph Showing Fiber Sensor Performance with Industrial RTD Sensor in a Humidity Controlled Chamber

An added bonus to this procedure is that temperature effects on the humidity sensor can be minimized if the filter grating is selected with only a response to temperature and is collocated with the sensor. In this combination, the filter wavelength and the sensor wavelength shift almost simultaneously with temperature, yielding no net intensity change, leaving only the humidity effects (except for slight mismatches in temperature response between the gratings). Figure 5 shows one of the demodulation systems Blue Road Research produces to monitor fiber sensors by this method.

Figure 5. Flight Test Sensor System

4. FIBER SENSORS CAN RESPOND TO MOISTURE VIA EVAPORATION RATE

When Blue Road Research tested the humidity sensors in soil test beds (preparing to meet the needs of the Department of Energy), the difference between humidity and soil moisture was clarified. As shown in Figure 6, soil measurements saturated the fiber sensor near 4% gravimetric soil moisture (4% percent moist soil created by weighing the desiccated soil, weighing a known amount of water, then mixing the two and leaving it to equilibrate). The fiber sensor did not respond above the reading of 100% relative humidity, even if more moisture was added to the soil. Therefore, the basic humidity sensor range, when applied as a soil moisture sensor, fell far short of the 2-18% soil moisture range hoped for by the Department of Energy.

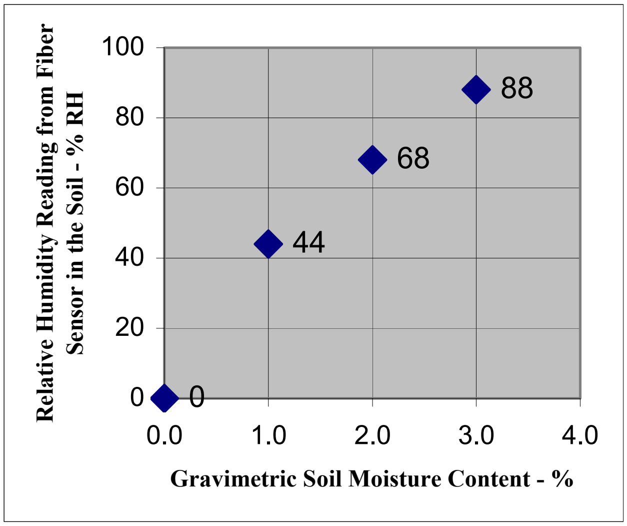

Figure 6. Relative Humidity in the Soil vs. Moisture Content of the Soil

Since the fiber grating sensor was able to measure humidity, but ineffective within soil greater than 4% moisture, Blue Road Research engineers experimented with using the sensor outside the soil to infer the moisture level by monitoring evaporation rates.

To measure this, two fiber sensors were placed in a tube, each on a optical fiber strand: one that responded to relative humidity (RH) and temperature, referred to as the humidity sensor, and one that responded to temperature only. The tube was perforated near the location of the two sensors and buried so that the perforated area was covered with sandy loam soil at a known moisture level. In this configuration, moisture was free to evaporate from the soil into the tube through the perforations, where the fiber sensors monitored the humidity and temperature. The temperature variations were then subtracted from the system using the temperature sensor. Figure 7 shows a variation of this setup where both sensors are on one fiber strand. Also shown in the diagram are the spacing tabs that prevent the sensors from touching the insides of the tube, should it become wet.

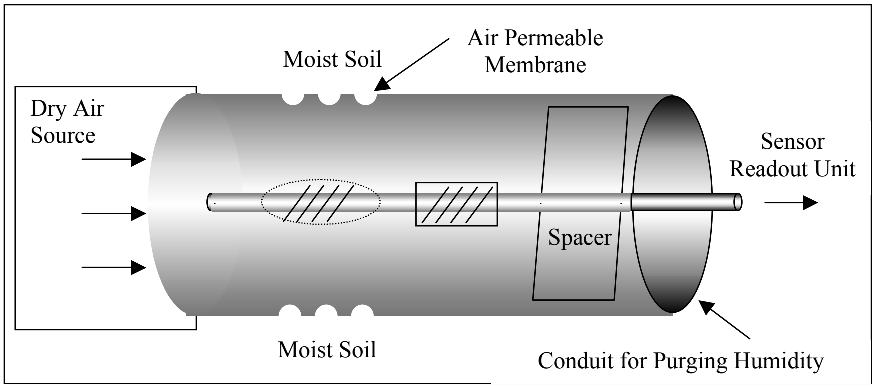

Figure 7. Diagram of Sensing Moisture System for Fiber Sensors

Because the air in the tube would approach saturation as moisture evaporated from the soil (assuming soil above 4% moisture gravimetrically), the moist air needed to be evacuated from the tube, allowing the soil moisture to evaporate uninhibited. This was done by blowing a dry gas through the tube, allowing the moisture-swollen coating of the fiber sensor to dry out. The moisture evaporation tube for the fiber sensor is shown in Figure 8.

Figure 8. The Moisture Evaporation Tube for the Fiber Sensor, soon to be Buried

Blue Road Research chose to use nitrogen as the dry air source and purged the tube at controlled flow rates for various amounts of time, watching the sensor response to both the purge and recovery after purging ceased. Those responses are plotted in Figure 9. The highest line represents the humidity in the tube when the soil was near 18% soil moisture. From its initial equilibrium humidity state, the humidity level in the tube shows a continuous drop for the duration of the approximate two-minute nitrogen purge, then a characteristic recovery as the humidity of the air in the tube climbed back to saturation (due to the moist soil).

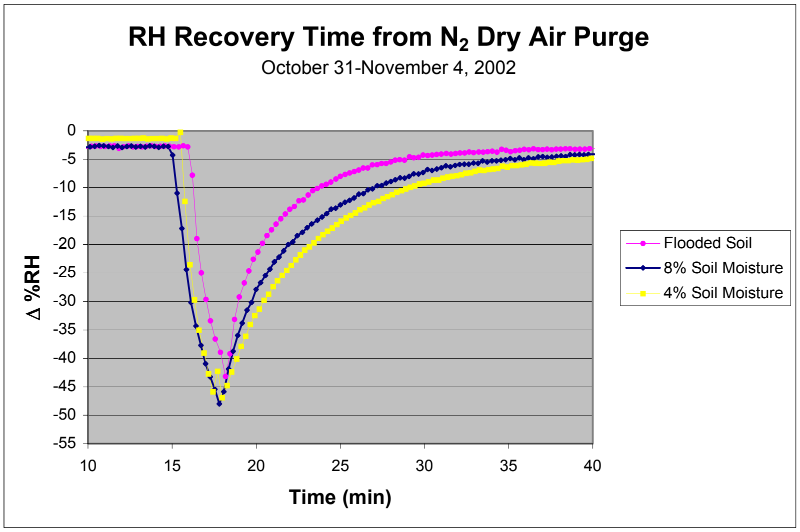

Figure 9. Graph Showing Fiber Sensor Tracking of the Evaporation Rates for Three Soil Moisture Levels

The soil moisture level can be determined from this method by recording the time elapsed between two humidity levels as the humidity recovers, or by noting the humidity regained by a certain time limit from a common starting humidity (both of which are proportional to soil moisture levels, since the rate of RH recovery is the evaporation rate into the tube). The data in Table 1 is taken from the graph in Figure 9. It shows the recovery time to various humidity levels within the tube, relative to saturation. Note how the differences in recovery time for each soil moisture level become easier to distinguish as the sensors return closer and closer to saturation, though a difference is obvious in less than a minute. Resolution increases with data collection time, until saturation.

	Humidity Recovery Time (min)			
Soil Moisture	**-35%**	**-25%**	**-15%**	**-5%**
4%	1.45	3.65	7.45	20.37
8%	1.17	2.8	5.9	15.3
Flooded	0.56	1.4	3.57	10.1

Table 1. Minutes Required for Humidity Recovery for Three Soil Moisture Levels after Purging Tube to –45% of Saturation

Although sixty seconds does seem like a long time required to take a data point (not to mention recovery time before a successive data point can be measured), dozens or perhaps hundreds of these sensors can be monitored simultaneously with proper optical equipment, and further experimentation will likely reveal that the recovery slope (rate of change) or the integral of recovery curve can yield data even more quickly. Other untested options include carefully measuring the purge with a known and controlled quantity of gas, or comparing the sensor response to very short purges.

Of course, the laundry list of other factors that will effect the evaporation rate include the temperature of the soil, the temperature of the air at the soil interface, the humidity of the air in the tube, the vapor pressure, the granularity, and area of the exposed soil (or holes in the tube). However, fiber grating sensors seem ideally suited to this configuration, since they can be easily multiplexed by inscribing several gratings on each fiber line at most any desired spacing, and monitored simultaneously. These fiber lines will easily fit into a protective tube over long distances, and many of the conditions that cause uncertainty in traditional evaporation measurement experiments may be controlled over the short duration required for each humidity reading.

5. FIELD TESTS: FLOODING A TEST BED MONITORED WITH FIBER SENSORS

Blue Road Research constructed a soil moisture test bed and instrumented it with fiber moisture sensors to determine responsiveness of the sensors in the event of soil flooding. Not only was tube for monitoring evaporation rate buried in the soil, but scientist also chose to bury two pressure sensors, one above the other, in the test bed to measure the weight difference of the moistened soil.

Note the evaporation channel running into the side of the test bed in the photograph in figure 10. The black cord running from a tube in the top is from an electrical moisture sensor called a Thetaprobe that estimates moisture from changes to a high frequency electrical signal it has sent through the soil[3]. It has been reviewed as one of the best standards for comparison among moisture sensors[4]. The sensors to monitor evaporation and pressure are ported out the other side of the box and to the readout equipment elsewhere.


Tube for evaporation channeling

Figure 10: Soil test bed at Blue Road Research's Fairview facilities

The soil was placed into the test bed leaving 6 inches of packed soil between the two pressure sensors and more than that above and below the sensors. All the soil was sandy loam, and was packed after every few additional inches were shoveled into the box.

The first flooding was performed in January of 2003 and the second was in August of 2003. All the results of the evaporation sensor were plotted together in the following figure (11). This data is the result of subtracting the temperature sensor data from the humidity sensor (to remove the temperature effects). Notice that the purge phase (the down swing) was very noisy; it is thought that this is because of the aliasing of rapidly changing sensors being scanned by an optical spectrum analyzer (OSA) that did not have sufficient bandwidth to monitor the sensors. The OSA was used to allow for multiple sensors and sensor types to be monitored simultaneously (evaporation and pressure sensors). Focusing only on the recovery rate of each series of the dataset, notice that the "recovery slope" (immediately to the right of the lowest point) varies for each moisture level; each correlated to the electrical moisture sensor voltage level (faster evaporation rates were found in wetter soil).

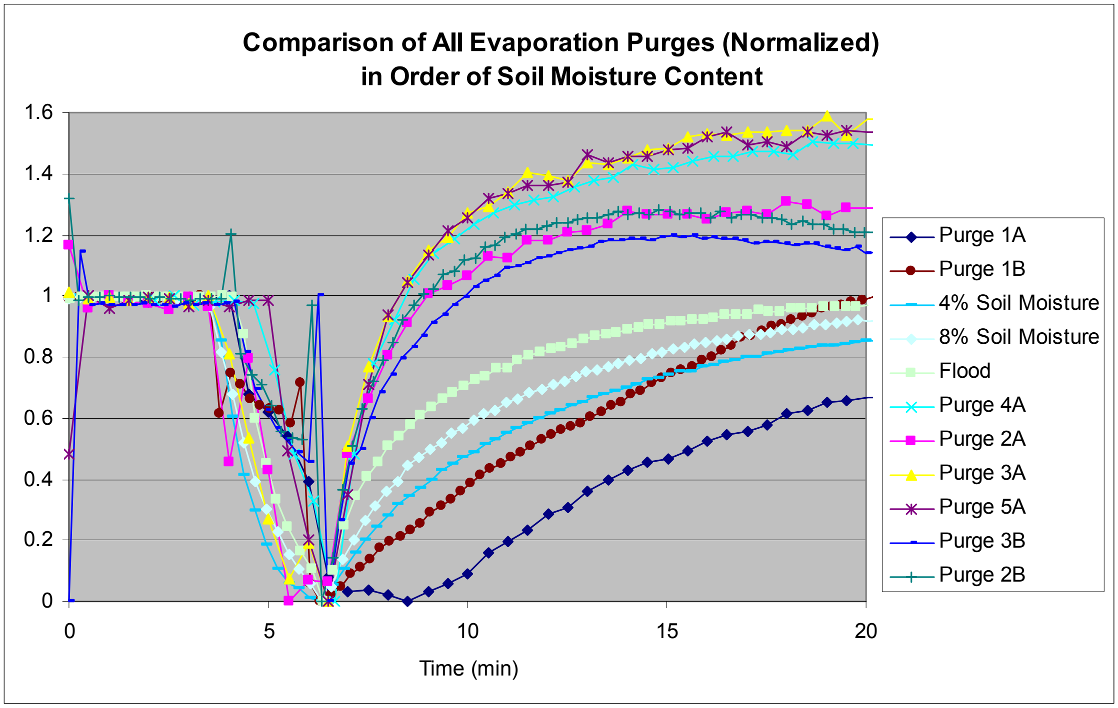

Figure 11: Humidity levels during and after purges. The recovery slopes correlate with moisture levels.

Each purge labeled A was taken from the January dataset; B corresponds with the August flood test; 4%, 8%, and Flood were the lab tests, where flood was estimated to be about 18% soil moisture. Another interesting detail seen in the recovery data is that the "dry" data set for January is distinctly different that the same for the August test; likely because the dry soil dynamics change when soil first becomes wet.

This data confirmed that soil moisture levels can be inferred from evaporation rates, even though compaction was likely different between the lab tests and the outdoor field tests. More calibration would be necessary for high accuracy if soil types change or compaction levels – since these would likely affect evaporation rates. Temperature levels of the soil might also cause a change, but if the sensors are buried deeply enough, this might not vary much. Temperature variations of the dry air would still need to be compensated for or controlled.

6. INFERRING MOISTURE FROM SOIL WEIGHT

The fiber optic pressure sensors were monitored almost continuously with an OSA as the soil was flooded. Using a pressure sensor above and below the area of soil in being interrogated, changes in the moisture content of that soil level were tracked. Ideally, this would minimize errors cause by weight added to the surface of the soil (although certainly the lower sensor would respond less than the upper sensor, losing some of the cancellation effect). Notice the correspondence of this data in figure 12.

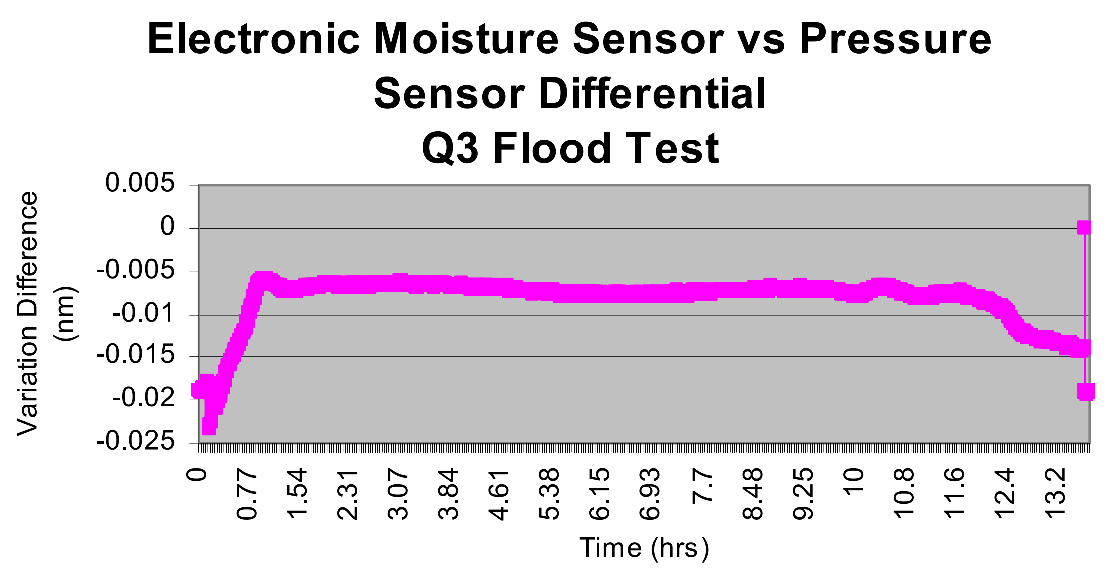

Figure 12: Difference between Upper & Lower Pressure Sensors in Soil Test Bed During Flooding

The major events of interest in this data set are the addition of water at 0.1 hours, the seepage of water into the soil layer of interest, causing the lower sensor to increase its pressure reading, the leveling out of pressure change as the quantity of water in the soil layer ceased increasing (about 1 hour), then the decrease of pressure on the lower sensor as the water slowly passed through the soil layer toward the soil below, beginning at ~12 hours. A third pressure sensor placed in the next soil level below this one would have allowed a view of the water moving from one level to another.

7. CONCLUSION

Fiber optic sensors can monitor humidity and moisture content in air and soil through moisture absorption, evaporation, and pressure. By using fiber optic pressure sensors in soil or fiber optic humidity sensors to monitor evaporation rates, soil moisture levels and moisture in organic materials can be inferred. These sensors could potentially be useful to monitor humidity for numerous applications, including corrosion, material erosion near foundations, highway conditions, agricultural studies, living conditions, as well as in laboratory research applications such as environmental chambers. These experiments have proved beneficial, allowing Blue Road Research to introduce new sensors that can be monitored in high quantities of 50 or more per fiber strand to improve knowledge of structural health.

8. ACKNOWLEDGEMENTS

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Some of the concepts and configurations described in this paper are protected by patents owned or licensed by Blue Road Research[5].

9. REFERENCES

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