Distributed Monitoring of Soil and Groundwater during In-Situ Thermal Remediation Using Fiber Optic Sensors

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ABSTRACT

This paper is focused on the implementation of fiber optic sensors for monitoring of soil and groundwater during in-situ thermal remediation of contaminated sites. A network of distributed fiber optic sensors has been implemented to monitor the distribution of soil and groundwater temperature and the level of groundwater in several in-situ thermal remediation projects.

Keywords: in-situ thermal remediation, soil temperature, groundwater level, fiber optics, distributed sensing, multi-parameter sensing

1 INTRODUCTION

In-Situ Thermal Remediation (ISTR) is an efficient contamination removal process using localized heat sources inserted deep into the soil to to heat up the soil to a target temperature (i.e., 100 ºC to 700 ºC) [1][2]. Elevated temperature causes the vaporization of hazardous substances and pollutants which are then extracted by the Soil Vapor Extraction (SVE) system. The success of the ISTR process is highly dependent on the accurate measurement of soil temperature distribution and water table at multiple locations. Environmental remediation is a process which occurs deep in the soil saturated with highly corrosive chemicals such as chlorinated solvents and volatile organic compounds (i.e., tetrachloroethylene, polychlorinated biphenyls, and methylene chloride) known as VOC [3]. However, due to the severe conditions (high temperature, harsh chemicals, and the electromagnetic interference generated by electric heaters), the state-of-the-art electronic based sensors fail or lose performance in such environments [4].

In this study, a distributed fiber optic pressure and temperature sensor, based on fiber Bragg gratings (FBG), has been developed for the accurate and high-fidelity measurement of soil temperature and the level of groundwater through hydrostatic pressure sensing (Figure 1). The prototypes have been successfully field-tested in brownfields and federal Superfund remediation sites and the results have been compared with electronic transducers. In this research, several key challenges related to material compatibility of transducers, high-resolution and low-pressure sensing, and temperature compensation for pressure monitoring have been addressed by capitalizing on AOMS core innovation on multi-parameter sensing using metal embedded fiber optic sensors [5].

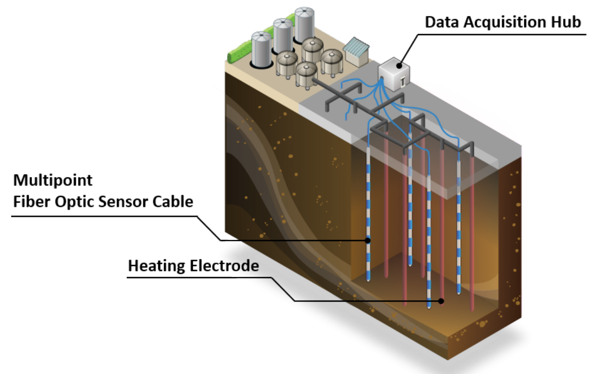

Figure 1: Fiber optic sensors in in-situ thermal remediation

2 SENSOR IMPLEMENTATION

Optical fibers are widely used for the monitoring of physical parameters such as strain, stress, force, pressure, temperature, and chemical concentration. Fiber grating, which is a periodic modulation of the index of refraction, is widely utilized for sensing parameters such as strain and temperature. The gratings are inscribed in optical fibers by UV or femtosecond laser radiation using phase mask or direct writing techniques. When FBG is exposed to a broadband spectrum of light, due to the coupling of the contra-directional core modes, the light at a specific wavelength, called the Bragg wavelength, with a specific bandwidth is reflected back. The sensing characteristics of FBGs arise from photo-elastic and thermo-optic properties of optical fibers [6][7].

In this research, we have used AOMS fiber optic sensing system (Figure 2). The monitoring system is an end-to-end hardware/software platform with the capability to monitor over 120 sensor cables each accommodating over 100 sensing points. This enables collecting sensor data from over 12,000 points simultaneously. AOMS core technology is based on metal embedded fiber optic sensors for harsh environment sensing [5]. Two types of fiber optic sensor cables have been used in this research:

I) Multi-point temperature sensors (Figure 3)
II) Single-point pressure sensors (Figure 3)

Both types of sensors are ruggedized in metal structures and special types of metal alloys have been used to make the transducer bodies resistant to corrosive chemicals.

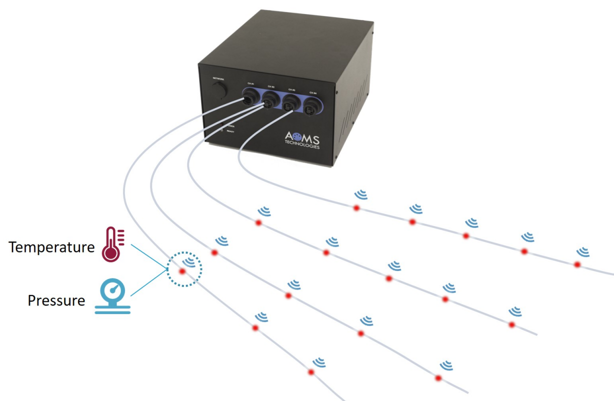

Figure 2: AOMS distributed fiber optic sensing platform

Figure 3: Fiber optic pressure and temperature sensor cables

The technical specification of the sensors are listed in Table 1.

Table 1: Fiber optic sensor specifications

Parameter	Value
Temperature range	-55 ºC to 350 ºC
Temperature accuracy	±0.1 ºC
Pressure range	0 to 170 kPa (0 to 17.3 mH2O)
Pressure accuracy	±0.25% F.S.

3 RESULTS

Figure 4 shows the distribution of temperature in a Superfund remediation site at 8.5 meter below the ground surface (BGS) [8].

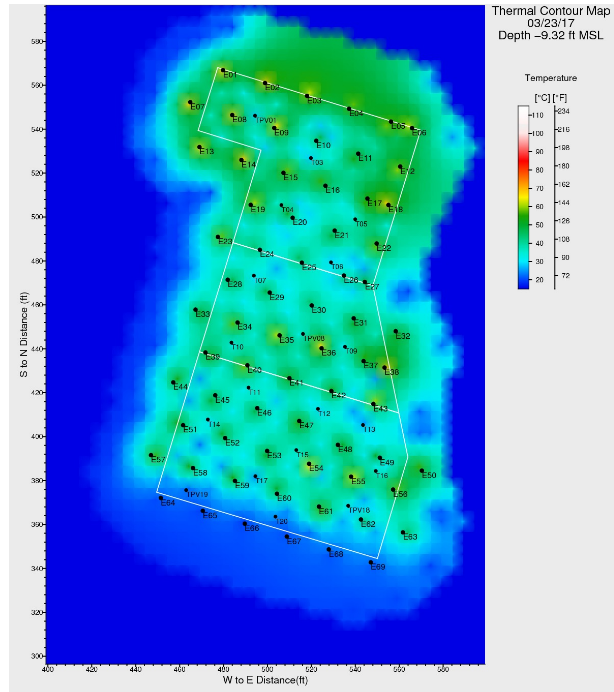

Figure 4: Distributed temperature data in a Superfund remediation site [8] (“T”: temperature monitoring wells, “TPV”: groundwater level monitoring well, “E”: heating electrodes)

Figure 5 shows the groundwater level in 5 wells over a period of 6 days. The changes in the level of groundwater are due to the tidal effects as wells as the injection of water in the heating electrodes to harmonize temperature [2].

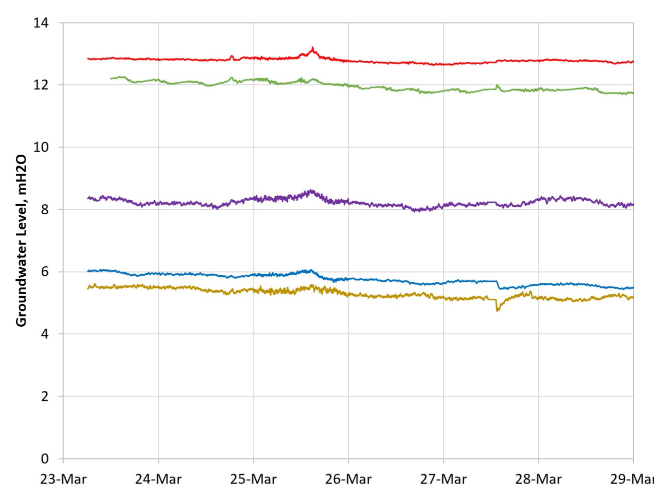

Figure 5: Groundwater level measurement in 5 wells over a 6-day period

The performance of the temperature sensors has been benchmarked against standard thermocouple sensors by co-locating arrays of both types of sensors in a thermal well in a remediation project using Electric Conductive Heating (ECH). The results are shown in Figure 6. As shown in the graphs, fiber optic temperature sensors outperform existing temperature sensors especially in remediation projects in which electric heating generates electromagnetic interference. One of the distinguishing features of fiber optic sensors is their premium performance unaffected by the deployment depth, i.e., sensors located near the ground surface and the ones placed at the bottom of the wells have the same accuracy and transient response.

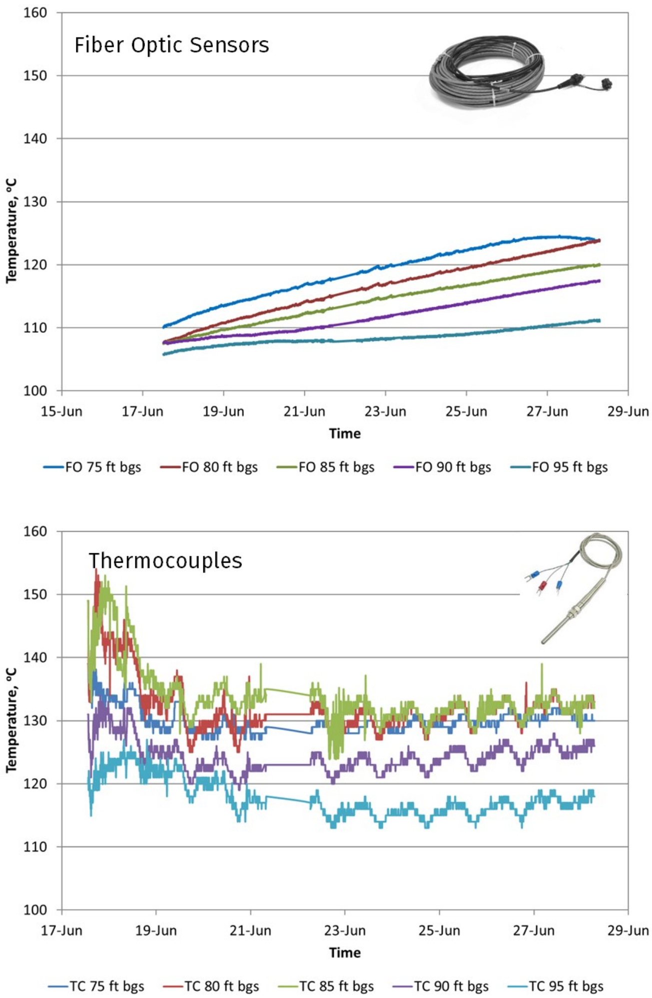

Figure 5: Comparison between fiber optic sensors and thermocouples in an in-situ thermal remediation project

4 CONCLUSIONS

We have deployed multi-point pressure and temperature sensors for the first time in in-situ thermal remediation for monitoring of soil and groundwater. Some of the deployments have taken place in highly corrosive environments contaminated with chlorinated solvents where electronic sensors have reportedly been failed. The data from the sensors are used by ISTR operators for real-time optimization of the heating process and monitoring the progress of the contamination cleanup process. The fiber optic sensors provide ISTR operators with 3D maps of actionable data to improve efficiency and reduce downtime. The sensors not only provide high fidelity data isolated from electromagnetic interferences and corrosive chemicals but also respond to small changes in temperature and grounndwater level.

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