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HYDRAULIC TOMOGRAPHY USING FIBER BRAGG GRATING MULTILEVEL WELL

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Understanding the spatiotemporal distributions of groundwater pressure and temperature is essential to evaluating groundwater resources, flow, shallow geothermal resources, etc. A conventional groundwater monitoring well measures aquifer status (i.e., groundwater pressure, temperature, pH, electrical conductivity, etc.) by opening a screening interval on the casing at a specific depth in a single borehole. The sensors (e.g., piezometer and thermometer) can measure the aquifer status at a depth of the well screen. The measurements of aquifer status from these conventional wells represent an average value within the screen interval. The method of constructing this type of monitoring well is well-developed and broadly used in subsurface environmental investigations, such as groundwater resource monitoring, contaminated site remediation, seawater intrusion, etc. Developing a well monitoring system for some complicated groundwater systems to observe the depth-discrete aquifer status and collect water samples is essential. Moreover, a depth-discrete monitoring system allows monitoring the fracture flow in bedrock for single or multiple fracture systems at the depths of interest, including sampling, level measurements, and hydraulic tests. Accordingly, a depth-discrete monitoring system provides a more complete and detailed groundwater delineation than the traditional full-screened well system. There are two conventional approaches to monitoring the depth-discrete aquifer status: (1) a monitoring well cluster, which consists of several traditional monitoring wells spaced alongside; the screens of these wells must be placed at the depth interval corresponding to their target aquifers; (2) a nested well, which assembles multiple well casings in a single borehole; the screen of each well casing is placed at its target aquifer. Also, the vertical hydraulic connection between any of the two well casings is interrupted by a grout seal. These two types of well groups can successfully observe the depth-discrete aquifer status of the multi-aquifer system. However, constructing a well cluster is costly and time-consuming. Developing a nested well risks failure in interrupting the vertical hydraulic connection as the number of monitoring zones increases. Accordingly, a more economical and efficient monitoring method, the multilevel monitoring system (MLMS), has been developed to satisfy the requirement of monitoring the multi-depth discrete aquifer status for complicated aquifer systems. Currently, optical fiber sensing technology is mature and has been used to develop a variety of environmental sensors. Compared to the electronic sensors, optical fiber sensors have several attractive advantages, such as small size, a lower weight, the possibility of spectral measurements, high acid and alkali resistance, a waterproof nature, immunity to electromagnetic interference, a common voltage requirement, no explosion risk, a serial multiplexing capability, and minimal signal loss over a long distance. So far, three types of optical fiber technologies have been used for environmental sensor development. The first type is the optical fiber sensors developed based on Fabry-Pérot Interferometry (FP). Several studies employed FP sensors to establish a piezometer. However, the FP piezometer's primary drawback is that the measurement accuracy is sensitive to the temperature and stability of the light source. Accordingly, a good temperature

compensation method and a stable light source for FP sensors are necessary for stable and long-term measurement. The second optical fiber technique is Bragg grating (FBG) technology. FBG sensors have been used in various fields, such as landslide monitoring, ground settlement monitoring, instant pollutant detection, etc. Moreover, several studies have employed FBG piezometers to measure groundwater pressure under various environments, such as marine sediment, soil slope, alluvial fan areas with subsidence, etc. For accurate field pressure measurement, the FBG pressure sensors are usually developed by packaging method (e.g., packaging and FBG in polymer or by elastic elements method or metal diaphragms. Moreover, these FBG pressure sensors require temperature compensation to improve measurement accuracy since they are sensitive to temperature and strain. In this study, we employed the metal diaphragms method to develop our FBG pressure sensor. The third technique is optical fiber-based technology such as distributed temperature sensing (DTS) and distributed acoustic sensing (DAS). The DTS interrogator is at least four times more expensive than the FBG unit, while the DAS interrogator is even more expensive than the DTS unit. Accordingly, an FBG MLMS developed by our team is used for hydraulic tomography. Conducting hydraulic tomography (HT) needs to collect the groundwater levels during the sequential pumping tests. Afterward, K and Ss fields are estimated by geostatistic inverse technique, successfully linear estimator (SLE, Yeh et al., 1996), through assimilating the observed groundwater levels. These hydraulic parameters describe the characteristics of aquifer heterogeneity. This study employed the new FBG MLMS to conduct HT at a contaminated site during several sequential remediation injection events. Since the water injection for conducting HT is replaced by the remediation agent injection, distributing plume in the aquifer is no longer an issue for conducting HT in a contaminated site. We also compare the images from the time-lapse cross-hole electrical resistivity tomography (time-lapse CHERT) to the derived K field to examine the capability of the new FBG MLMS. The results show that the newly designed multi-function and multi-depth fiber Bragg grating (FBG) sensing system is a viable tool to monitor depth-discrete groundwater pressure and temperature at different wells simultaneously and benefit HT. The groundwater pressures and temperature in response to the four injections are successfully monitored from the FBG system at discrete depths in the 2-inches wells. Afterward, these multi-depth aquifer responses are utilized to delineate the K and Ss fields through SLE. The ratio of electrical resistivity change from CHERT before and after the injections validates the reliability of estimated hydraulic parameter fields. The temperature measurements also support the derived K field. These analysis results support that the multi-depths FBG sensing system is a particle for conducting HT. Besides, this new system collects much more data than the traditional well with a single screen interval. In other words, these results demonstrate that the integration of HT and MLMS to delineate the hydraulic heterogeneity in the remediation site is a particle method, thus reducing the well construction cost and enhancing the data collection efficiency, and providing a more economical approach conduct HT.

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