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A distributed soil temperature measurement system with high spatial resolution based on BOTDR

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This paper presents a new, recently developed, distributed soil temperature measurement sensor system, with high spatial resolution, based on Brillouin optical time domain reflectometry (BOTDR). The process of developing the distributed soil temperature sensor is introduced in detail, including the principle, materials, installation, instrumentation and calibration. The new distributed soil temperature sensor improves the spatial resolution from 100 cm to 3.3 cm, and has some other unique advantages, including long distance measurement capability, a longer life cycle, galvanic isolation, EMI immunity, good stability and ease of integration. Finally, an *in situ* comparison test was carried out, where results from the new sensor were compared to data measured using a standard point-mode system. This test proves that the newly developed distributed sensor is both accurate and has the capability to measure continuously the distribution of the soil temperature along the whole borehole depth, indicating that this new measure technique has a wide and powerful application potential.

Keywords: distributed temperature measurement, Brillouin optical time domain reflectometry (BOTDR), high spatial resolution, soil temperature.

1. Introduction

Soil temperature is one of the main indicators of the soil physical field, and its variation reflects the energy exchange process between the soil and its surrounding environment [1, 2]. Soil temperature is one of the basic factors that govern soil moisture evaporation, seepage, soil–water interaction, and ultimately affects the soil strength, deformation, permeability, water retention and other engineering properties [3–5]. Changes in soil temperature may also cause foundation damage [6], ground instability, destruction of oil and gas pipes and other geotechnical engineering problems [7, 8]. Research on variation of soil temperature is therefore very important for understanding soil behavior. Currently, the primary methods of monitoring the variation of soil temperature are through a variety of temperature sensors that are buried in the soil. The temperature sensors commonly used include mainly thermocouple, thermistor, thermal resistance and other types, belonging to a point-mode sensor system. Functions such as the stability, durability, anti-interference and waterproofing of these systems, often do not meet the monitoring requirements of modern geotechnical engineering, which need a long time and distance, and a large area and depth of temperature monitoring.

Distributed optical fiber temperature sensing technology has rapidly developed as a new innovative tool over the past few decades. This technology is capable of monitoring the temperature of measured objects, with a distributed, long distance (currently up to 80 kilometers) and continuous measurement. As the optical fiber is made of quartz glass which is a non-metallic material, and the measurement principle is based on light spectrum changes, it has high stability, good durability, anti-interference, corrosion resistance and is waterproof. These properties make it especially suitable for geothermal field testing and monitoring in rigorous circumstances [9–11].

In recent years, the distributed optical fiber temperature sensing technology has been mainly based on Raman optical time domain reflectometry (ROTDR) and fiber Bragg grating (FBG) technology, which have been used in geotechnical engineering temperature monitoring [12–14]. The temperature measurement technology based on ROTDR can work on fully distributed soil temperature measurements, but cannot measure and monitor soil deformation. In addition, the Raman scattering efficiency is much lower than the intensity of Raman reflecting light and Brillouin scattering light, therefore, in practical engineering application, the length of ROTDR measurement is only 30 km shorter than that of Brillouin optical time domain reflectometry (BOTDR) technology. Besides, ROTDR spatial resolution is between 1 m and 2 m, which is often insufficient to meet the needs of geoengineering surveying. The FBG-based temperature measurement technology can accurately measure the soil temperature, but it belongs to quasi-distributed measurement, and its manufacturing process is very expensive.

The BOTDR-based measure technology belongs to fully distributed measure modes, and besides measuring the object's temperature, can also measure the strain. However, the current BOTDR products such as AQ8603 and NB8511 all have the restriction of a 1 m spatial resolution, which influences the measuring and locating accuracy for its temperature measurement. In this study, in order to overcome these problems, a BOTDR-based temperature measurement technology with a high spatial resolution was designed and developed, and its capability and accuracy in soil temperature measurement were verified through comparative *in-situ* testing.

2. The principle of BOTDR

The measurement principle of BOTDR is that an optical pulse is launched into an optical fiber, and some backscattered signals come back to the input end for measurement and interpretation. There are three main types of scattering, including Brillouin scattering. Brillouin scattered light is caused by non-linear interaction between the incident light and photons that are thermally excited within the light propagation medium [15, 16]. This scattered light is shifted in frequency by a Brillouin shift $\nu_B(\varepsilon, T)$ and propagates in the opposite direction relative to the incident light. It has been found that there is a relationship between Brillouin scattered frequency shift $\nu_B(\varepsilon, T)$ and temperature T or strain ε, which can be expressed as:

$$\nu_B(\varepsilon, T) = \nu_B(0, T_0) + \frac{\partial \nu_B(\varepsilon)}{\partial \varepsilon}\varepsilon + \frac{\partial \nu_B(T)}{\partial T}T \tag{1}$$

where $\nu_B(\varepsilon, T)$ is the Brillouin scattered frequency shift with strain at a certain temperature T, $\nu_B(0, T_0)$ the is Brillouin scattered frequency shift without strain at temperature T_0, $\partial \nu_B(\varepsilon)/\partial \varepsilon$ and $\partial \nu_B(T)/\partial T$ are respectively the strain coefficient and the temperature coefficient, T_0 is the initial temperature.

When the fiber is loose, that is to say there is no strain variation, there is a linear relationship between the Brillouin scattered frequency shift and the temperature:

$$\nu_B(T) = \nu_B(T_0) + \frac{\partial \nu_B(T)}{\partial T}(T - T_0) \tag{2}$$

The pulsed light is launched at one end of an optical fiber, and BOTDR receives the Brillouin backscattered light at the same end (see Fig. 1**a**), through the signal processing unit. After using time domain analysis, the Brillouin scattered power along the optical fiber is obtained (see Fig. 1**b**).The distance Z from the position where pulsed

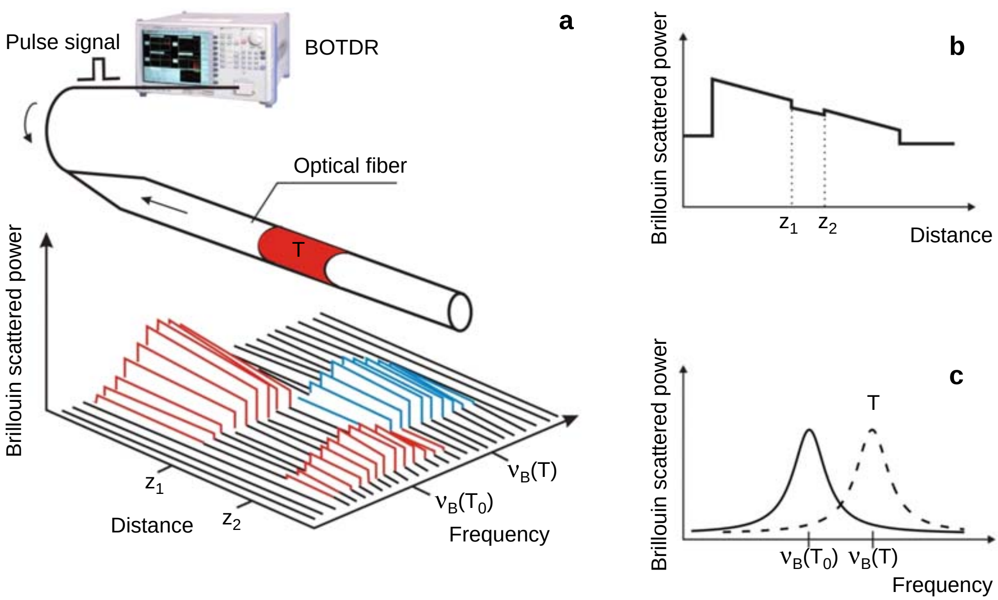

Fig. 1. The measurement principle of BOTDR.

light is launched to the position where the scattered light is generated can be determined using the following formula

$$Z = \frac{ct}{2k} \quad (3)$$

where c is the velocity of light in a vacuum, k is the refractive index of the optical fiber; and t is the time interval between launching the pulse light and receiving the scattered light at the end of the optical fiber.

In order to measure Brillouin frequency shift $\nu_B(\varepsilon, T)$, repeated measurement is made by slightly changing the frequency of the incident light and the Brillouin spectrum at any position along the optical fiber is obtained by means of heterodyne detection in the time domain (see Fig. 1**c**).

Therefore, by using formulas (2) and (3), the temperature distribution along the fiber sensor can be obtained, based on the analysis of BOTDR scattered light frequency shift. Using only one sensing optical fiber, the distributed measurement of temperature can be achieved.

However, the problem of limited spatial resolution needs to be overcome for application of BOTDR in distributed temperature measurement of soil. The spatial resolution restriction is that each measurement value along the fiber is based on Brillouin scattering frequency drift of the start measuring point forward within 1 m. The temperature measurement at a given point of fiber therefore actually reflects an integrated fiber-optic temperature within 1 m length. The 1 m spatial resolution makes it difficult to obtain a fine temperature measurement with BOTDR. To solve this problem, a high spatial resolution BOTDR-based temperature sensor was designed and developed in this study.

3. Research and development of the BOTDR-based distributed temperature sensor

3.1. Principle

The BOTDR technology has a characteristic that is sensitive to the fiber strain and temperature. When the sensing optical fiber is in a loose state, it can be used as a distributed temperature sensor. Due to the 1 m spatial resolution of BOTDR, measurement deviation occurs in the case where there are dramatic changes of temperature within 1 m length of the sensing fiber.

To solve this problem, the following scheme was designed. A sensing optical fiber is loosely installed in a small polyurethane tube (PU tube) which is coiled evenly around a rod whose diameter is d and the measure length is L_0. The coiled sensing fiber length L depends on coiling number per meter of the rod (n) and the rod diameter d, and this relationship can be expressed as:

$$L = n\pi d L_0 \quad (4)$$

T a b l e 1. Relationships between θ, n, d and d_0.

θ = 2 cm			θ = 5 cm			θ = 10 cm		
d [cm]	n	d_0 [mm]	d [cm]	n	d_0 [mm]	d [cm]	n	d_0 [mm]
4	398	2.5	4	159	6.3	4	80	12.6
5	318	3.1	5	127	7.9	5	64	15.7
6	265	3.8	6	106	9.4	6	53	18.8
7	227	4.4	7	91	11.0	7	45	22.0
8	199	5.0	8	80	12.6	8	40	25.1
9	177	5.7	9	71	14.1	9	35	28.3
10	159	6.3	10	64	15.7	10	32	31.4

The sensing fiber length is thus greatly increased within the 1 m measure length, and as a result, the spatial resolution is improved. According to formula (4), it can be deduced that the spatial resolution of the coiled sensing fiber is raised $n\pi d$ times as that of the linear measure length L_0. In formula (4), n and d are design parameters which are determined by the spatial resolution requirement; the larger the n or/and d, the higher the spatial resolution. Table 1 lists the relationships between spatial resolution θ, n, d and d_0. Here, d_0 denotes the interval of the coiled sensing fibers, which is equal to the diameter of the protection tube. It can be seen from Tab. 1 that θ of BOTDR can be promoted from 1 m up to centimeter level, and the target value θ can be easily obtained simply by adjusting n and d values.

3.2. Installation

The installation process of the distributed temperature sensor with high spatial resolution is as follows. Firstly, the sensing fiber is put into a PU tube with the diameter d_0. According to the target θ value, n, d and d_0 can be determined from Tab. 1 or

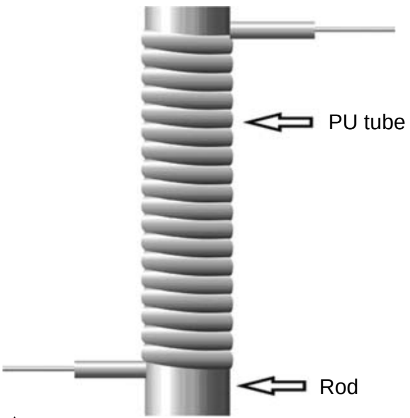

Fig. 2. The rod coiled by the PU tube with the sensing fiber.

Fig. 3. A temperature sensor.

formula (4). The PU tube with diameter d_0 controls the interval of the coiled sensing fibers as the PU tube with the sensing fiber is then coiled onto the rod, that can be wood, plastic or iron (see Fig. 2). A temperature sensor is shown in Fig. 3.

3.3. BOTDR instrument

The BOTDR instrument used in this research is AQ8603 optical fiber temperature/strain analyzer produced by Ando Company, the basic parameters of which are listed in Tab. 2. From this, it can be seen that the maximum spatial resolution is 1 m. The accuracy of AQ8603 measurement for temperature nylon sensing optic fiber is 0.2 °C.

3.4. Calibration

After the installation of the temperature fiber sensor is completed, calibration between BOTDR measured Brillouin scattered frequency shift and real temperature is necessary. This is undertaken as follows.

The temperature fiber sensor is put in an adjustable constant temperature laboratory to obtain the temperature coefficient. The laboratory temperature is set to start at –5 °C, and then increased at a 5 °C interval up to 50 °C. Each time, the laboratory temperature stabilizes, the BOTDR measurement is recorded. Thus, a calibration curve

Table 2. The basic parameters of AQ8603.

Distance range [km]	1, 2, 5, 10, 20, 40, 80				
Readout resolution [cm]	5				
Accuracy of distance measurement [m]	$\pm(2.0\times10^{-5}$ × distance measured [m] + 0.2 [m] + + 2×sampling resolution [m])				
Range of strain measurements	from –1.5% to 1.5%				
Pulse width [ns]	10	20	50	100	200
Distance resolution [m]	1	2	5	11	22
Accuracy of strain measurements	±0.004%	±0.004%	±0.003%	±0.003%	±0.003%
Repeatability	<0.04%	<0.02%	<0.02%	<0.02%	<0.02%

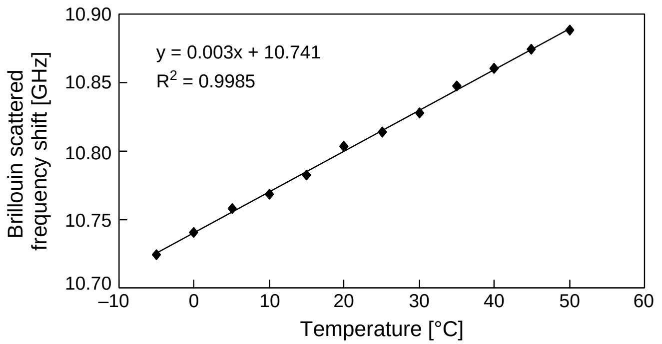

Fig. 4. The Brillouin scattered frequency shift of the sensor with temperature.

can be obtained as in Fig. 4. Here, the temperature coefficient is 3.0 MHz/°C, and the correlation coefficient between Brillouin scattered frequency shift and temperature is 0.9985.

4. Comparison test *in situ*

In order to verify the validity and feasibility of the distributed temperature sensor (DTS) developed for soil temperature measurement, a comparison test between the designed DTS and the traditional point-mode digital thermistor sensor (PMS) was carried out *in situ*. Two boreholes were drilled with a hand drill on a lawn in the campus of Nanjing University. The depth of both boreholes was 1 m, the diameter 5 cm, and the distance between the two 30 cm. As the two boreholes are very close and have the same depth, the soil temperature distribution inside two boreholes is assumed to be the same.

A DTS was inserted into one of the boreholes with the following specific parameters: coiled single-mode optical fiber with nylon sheath – 900 μm; the diameter of the polyurethane tube – 4.2 mm; the rod is polyvinyl tube; $L_0 = 1$ m, $d = 4.3$ cm, $n = 240$, $L = 32.42$ m, θ reaches 3.3 cm; the temperature coefficient of the fiber sensor is 3.0 MHz/°C, and the sensor accuracy is 0.2 °C.

The PMS was used as a reference temperature sensor, in the second hole, and had the following specific parameters: the temperature measure range is from –50 °C to 70 °C, the measure accuracy is ±0.1 °C; a polyvinyl tube of 1 meter in length whose material and size are the same as those of the DTS rod; five temperature sensors were fixed on the polyvinyl tube at 15 cm, 30 cm, 45 cm, 60 cm and 75 cm depth, respectively.

Using formula (4), the length L of the distributed sensor at the rod depths: 15 cm, 30 cm, 45 cm, 60 cm, 75 cm was calculated at 4.86 m, 9.73 m, 14.59 m, 19.45 m and 24.32 m, respectively. The soil temperatures inside the two holes at 15 cm, 30 cm, 45 cm, 60 cm, and 75 cm depth were then measured respectively using AQ8603 and the PMS data logger, (see Fig. 5).

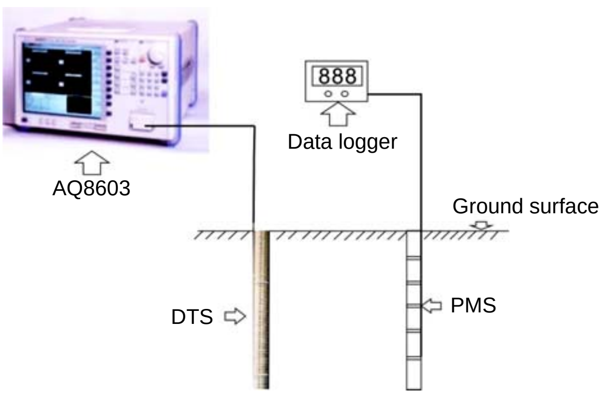

Fig. 5. A schematic diagram of comparison test.

The comparison test was carried out on June 25, 2009 and the soil temperature field data were recorded at 08:00, 10:00, 12:00, 14:00, 16:00 and 18:00 hours. The time required to perform a measurement was about 10 minutes. The maximum frequency of the temperature changes that can be monitored was 144 times a day. Figure 6 shows the variation curves of soil temperature with depth and time measured by the two methods.

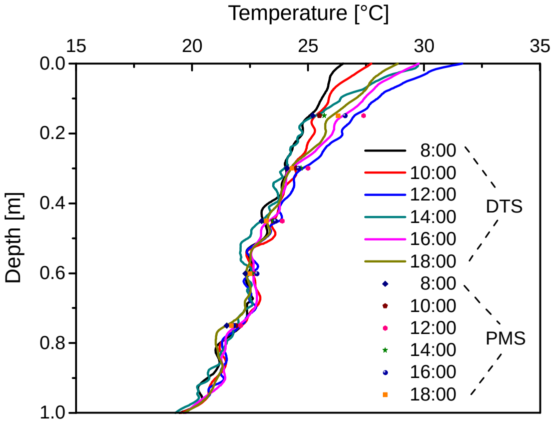

Fig. 6. The soil temperature distribution curves measured by the DTS and the PMS.

From Figure 6 and Table 3, the measurement results obtained using the DTS are shown to have a good match with those obtained with the use of the PMS, the correlation coefficient between the results being 0.982. This proves that the DTS is capable of accurately reflecting the continuous distribution of soil temperature along the whole borehole depth. The comparison results also indicate that the spatial resolution of the DTS has been greatly improved from 100 cm to 3.3 cm.

The DTS has the following advantages and application potentials:

– It can continuously measure the distribution of soil temperature at 5 cm sampling intervals with a centimeter-level high spatial resolution. The measure length of the sensor is up to kilometers.

T a b l e 3. The soil temperature results measured by the DTS and the PMS.

	15 cm		30 cm		45 cm		60 cm		75 cm	
Time	DTS [°C]	PMS [°C]	DTS [°C]	PMS [°C]	DTS [°C]	PMS [°C]	DTS [°C]	PMS [°C]	DTS [°C]	PMS [°C]
8:00	25.1	25.2	24.0	24.1	23.1	23.5	22.4	22.3	22.0	21.6
10:00	25.3	25.5	24.4	24.5	23.5	23.9	22.6	22.7	22.1	21.9
12:00	27.0	27.4	24.8	25.0	23.7	23.9	22.5	22.7	22.1	22.1
14:00	25.3	25.7	24.0	24.7	23.0	23.5	22.5	22.6	21.9	21.8
16:00	26.5	26.6	24.2	24.6	23.3	23.6	22.7	22.8	22.0	21.8
18:00	26.0	26.3	24.3	24.3	23.2	23.2	22.3	22.6	21.5	21.7

– The sensing optic fiber is made of silicon oxide, which is non-metal and will not to rust, giving it a longer product lifespan.

– The DTS is based on BOTDR, which has galvanic isolation, and thus EMI immunity and has good stability.

– It has a small size and is lightweight, and the fiber itself is not only a sensor, but also a data link, so it is very easily integrated in other measure systems

– It can be easily built into various temperature sensors according to the specific requirements, make it very flexible and suitable for the temperature monitoring in the soil, especially under the poor field conditions.

– The DTS can be easily connected in series, forming a large-scale temperature monitoring network.

5. Conclusions

We have described in this paper the development of a new distributed soil temperature sensor that improves spatial resolution from 100 cm to 3.3 cm, and which greatly increases the temperature measuring and locating accuracy of BOTDR.

A comparative *in situ* test was carried out, which proves that the distributed sensor developed is feasible and accurate to measure continuously the distribution of soil temperature along the full borehole depth.

The sensor has some unique advantages, including a long distance measurement capability, a longer life cycle, galvanic isolation, EMI immunity, good stability, and ease of integration, all of which indicate that this technique has wide application and a great potential market.

Although the system is very expensive now, the cost of this system will be lower and lower with the development of BOTDR demodulation technology in the future. Further work is underway to standardize and improve the scientific construction of the new distributed soil temperature sensor.

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