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A bored pile deficiency detection method based on optical fiber temperature measurement

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ABSTRACT

In this paper, a new deficiency detection method for bored piles is proposed based on the optical fiber temperature measurement. In this method, only one optical fiber cable is adopted for both measurement and transmission. By studying the heat transfer process between optical fiber and bored pile, the basic principle of the distributed optical fiber technique for bored pile integrity assessment is described. The detection equation is also derived. In addition, model tests are carried out at different heating powers, and the results show the temperature rise in the optical fiber cable is in direct proportion to the heating power. Deficiencies can be identified from analyzing the coefficients in the temperature rise – heating power expressions. Moreover, different values of temperature rise in air and in concrete are obtained when a same heating power is applied. The results imply that the proposed optical fiber temperature measurement can be considered as a possible way of detecting the bored pile deficiency and its mode by analyzing the values of temperature rise.

1. Introduction

Currently, rapid urbanization progress and development of large infrastructures are conducted worldwide, leading to a notable increase in pile foundation applications. Among different types of piles, bored piles are widely adopted due to their moderate cost and strong adaptability. However, the integrity of a bored pile is greatly influenced by site conditions during construction, such as fluctuation of water table and heterogeneity of soil. The deficiencies, including necking, broken piles, exposure of reinforcement, and segregation, could result in a significant reduction in the bearing capacity of a pile [1]. It is reported that up to 20% of bored piles have been found to have such integrity problems [2]. Hence, the detection of deficiencies through an efficient and convenient way can be of great benefit and has gained intensive investigations in recent years.

So far, various detection methods have been successfully employed for pile integrity assessment, including the low-strain and high-strain tests, the acoustic transmission method, core drilling, and the static load test [3]. However, these traditional methods have been found to have the following disadvantages: cumbersome, inefficient, expensive, low accuracy, stringent working conditions, inability of quantity analysis, as well as limited point-type detection [3–6]. Therefore, the requirement for a fast, online, and long-term monitoring scheme in the modern projects stimulates the development of new methods in pile deficiency detection.

In recent years, the optical fiber sensor technique is increasingly used in health monitoring of reinforced concrete structures, including buildings, bridges, tunnels, pipelines, and piles [7–11]. Among literatures, three types of optical fiber sensors are commonly used for civil structural health monitoring: the Fabry–Perot interferometer sensors, the fiber Bragg grating sensors, and the Brillouin Optical Time Domain Reflectometer (BOTDR) sensors. Schilder et al. [11,12] and Schallert et al. [13] integrated the Fabry–Perot interferometer sensors into reinforced concrete piles, and managed to obtain detailed strain information in both static and dynamic load tests. The fiber Bragg grating sensors were also adopted and acquisition of strain data is achieved, although their suitability for dynamic assessment has not been confirmed [11]. Moreover, Baldwin et al. [14] and Kister et al. [15] employed the fiber Bragg grating sensors to monitor both the temperature and strain in the processes of pile driving and bored pile casting. In spite of the successful applications of the Fabry–Perot interferometer sensors and the fiber Bragg grating sensors, they generally apply point measurements. In other words, a strain cannot be detected unless a sensor has been set up at that particular point. Hence, more than one optical fiber cables are often required to be embedded so as to allow more than one sensors being used.

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However, this may induce the inconvenience of construction. Other than the above two types of sensors, the BOTDR sensors have also been used for strain and temperature measurements. Nan and Gao [16] employed the BOTDR technique in a model test of backfill mining. Jiang [17] applied the PPP-BOTDA distributed optical fiber sensor technique to strain measurement of tube piles, and the test results suggested that the PPP-BOTDA technique can be considered as a promising method for pile detection. Piao et al. [18] employed the BOTDR to obtain the distributions of axial force and lateral friction as well as the tip resistance of a bored pile. In addition, Song et al. [19,20] applied the BOTDR to static load tests, and managed to monitor the strain distribution, lateral friction, and tip resistance of super-long piles. Although the BOTDR sensors are regarded to overcome the limitation of point measurement, they are usually of high expense. For instance, a good-quality BOTDR equipment costs around 2,000,000 RMB in China. In view of the above, a new detection method, which is more economical and simple for construction, is proposed in this paper.

In the proposed method, the distributed optical fiber temperature measurement is applied, and only one optical fiber cable is adopted for both measurement and transmission. A brief introduction to the detection system is given in Section 2. The detection equation is derived based on the detection principle, as presented in Section 3. In Section 4, a model bored pile is built for testing so as to study the relationship between temperature rise and the integrity of the pile, and the test results are analyzed and discussed. In the end, the preliminary findings are concluded in Section 5.

2. Detection system

The principle of an optical fiber temperature detection system is based on the strong dependence of thermal parameters of the pile on deficiencies. Abnormal temperature distribution due to a deficiency can be detected when the pile is heated. Hence, it is believed that the integrity of a pile can be assessed by quantitative analysis of the temperature obtained from the thermal sensors embedded in the pile.

2.1. System composition

The optical fiber temperature detection system mainly consists of three components: a distributed optical fiber temperature measuring apparatus (i.e. Distributed Optical Fiber Temperature Measurement Sensor, referred to as DTS hereinafter), a temperature sensor, and a heating system. A brief introduction to each of the components is given as follows.

(1) A DTS is composed of a laser emitter, an optical fiber wavelength division multiplexer, a photoelectric receiver and amplifier module, a signal processing system, and an optical fiber winding temperature sensor. Through the laser signal communication and analysis, the temperature in the optical fibers can be obtained.
(2) A temperature sensing optical fiber cable is used as the temperature sensor. The sensor receives the optical signals and transmits them to DTS. The metal clad fiber cable, in which the plastic coat is wrapped around by a stainless steel armor, is adopted as it can enhance the thermal stability and protect the cable against external physical hazards.
(3) A pressure regulator is included in the heating system to provide a proper and stable heating power. The power range is selected according to the length and electrical resistivity of the fiber cable.

The sensing fiber cable is bounded around the main reinforcing bars of the steel cage, forming U-shaped structures. The cable is connected with DTS and the pressure regulator in parallel, and the regulator in turn connects to an external power source so as to form a closed loop, as shown in Fig. 1.

2.2. Detection procedure

Firstly, the DTS emits laser light to the sensing fiber cable and the initial temperature is recorded. Afterwards, the power of the heating system is switched on and the sensing fiber cable starts to be heated. By setting the data point spacing, e.g. 0.2 m, and the time interval, e.g. 30 s, both the temporal and spatial distribution of the temperature field in the fiber can be acquired. Based on the thermal parameters in different parts of the pile, its integrity can be assessed with the aid of the theoretical analysis presented in the following section.

3. Principle of detection

3.1. Heat transfer process

Since the diameter of a sensing fiber cable is usually relatively small (around 5 mm or smaller), and the heating power applied is generally low, usually in the unit of W/m, the zone in the concrete influenced by heating is therefore limited around the cable, especially compared with the dimension of the cable length. For this reason, a one-dimensional heat transfer model is adopted in order to analyze the heat transfer process in the fiber cable and concrete. When the fiber cable and concrete reaches a steady thermal state, the temperature field is referred to as 'stable'. In the analysis, it is assumed that the thermal conductivity of concrete is constant. The cable radius is denoted as r_1, and the radius of the heating influencing zone is assigned as r_2.

Initially, the temperature of the sensing fiber cable T_0 is set equal to that of the surrounding concrete. After the heating process is conducted over a time period Δt, the stable thermal state is achieved, with the temperature of the cable denoted as T_1. In the one-dimensional heat transfer model of a single cylindrical wall, a circular thin wall with a radius of r and a thickness of dr is under consideration. Based on the Fourier's law of heat transfer, one can obtain

$$Q = -2\pi r L \lambda dT/dr \tag{1}$$

where T is the temperature at the point with distance r away from the center of the cable. L is the cable length, Q is the heat flow, and λ is the thermal conductivity of the pile.

By integration, it can be obtained,

$$\left(Q\int_{r_1}^{r} dr/r\right)/(2\pi L\lambda) = -\int_{T_1}^{T} dT \tag{2}$$

$$T = T_1 - Q\ln(r/r_1)/(2\pi L\lambda) \tag{3}$$

where T_1 is the temperature at the point with distance r_1 away from the center of the cable, which is also the temperature of the cable when the stable thermal state is reached.

Fig. 2 shows a logarithmic distribution of the temperature along the radial direction. When $r = r_2$, $T = T_2 = T_0$. Eq. (3) can be rewritten as:

$$Q = 2\pi\lambda L(T_1 - T_2)/\ln(r_2/r_1) \tag{4}$$

3.2. Derivation of detection equation

At the stable thermal state, the total heat quantity generated in the sensing fiber cable is assumed to be equal to that conducted to the surrounding concrete [21,22]. Hence, it gives