Applicability on optical fiber sensors for stress evaluation of piles

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ABSTRACT

Recently, sensors that use optical fiber have spread in the field of civil engineering. The BOTDR method, using an optical fiber sensor, has the characteristics of continuous measurement over long distances. The purpose of this study is to examine the method of stress distribution through piles by means of optical fiber sensor. This method could be effectively used for monitoring strain distribution during pile loading tests, in order not only to examine the quality of piles but also to clarify the mechanism of load bearing by the pile. In this study, the in-situ full scale vertical load test was carried out to obtain the fundamental characteristics of FBG (Fiber Bragg Grating) for estimating the stress distribution of the pile. The test pile was constructed by the steel pipe soil-cement pile method. The specifications of the test pile are a diameter of 800mm and a length of 24.0m. The sensors used in this study are the traditional measurement methods such as strain gauges and the new measurement methods such as FBG. The results of the in-situ full scale vertical load tests have a good correlation between the measured strain values by strain gauges and those by the optical fiber sensors.

Key words: *Pile, Optical Fiber Sensor, In-situ Vertical Load Test, Strain*

1. Introduction

Piles, which support buildings and structures in the architecture and the civil engineering, undergo pile load tests to examine the bearing capacity, tensile resistance and horizontal resistance. The strain which occurs during the pile load tests is measured by strain gauges and rebar gauges. The strain gauges and the rebar gauges in vertical load tests are installed at the soil stratum boundary and the pile tip, whereas the strain gauges and rebar gauges in horizontal load tests are installed at the dominant points of horizontal force such as the earthquake force and the earth pressure. However, it is difficult to obtain the continuous strain distribution because the lead wires of strain gauges which are installed in the pile body are confined.

There are some research studies on the measurement of strain in the civil engineering field. Kojima et al. (2003) carried out three types of experiments such as two loading tests, a tensile tests and a bending tests. The authors estimated the conditions for measurement of the deformation of soil structure due to external factors by using an obtained optical fiber sensor. Kusakabe et al. (2003) developed a method for measurement of the strain distribution through piles by means of optical fiber sensors. The method could be effectively used for monitoring strain distribution during loading tests, in order not only to examine the quality of piles, but also to clarify the mechanism of load bearing by pile. The efficiency of the method for reinforced concrete piles and steel piles was verified by comparing measurements with conventional methods using a set of strain gauges. De Battista et al. (2016) presented the use of distributed fibre optic sensor technology to measure the temperature and strain of reinforced concrete test piles during construction and during static load tests. They reported that the concrete curing temperature profiles of the piles were used to detect the presence of the significant defects in the piles. They also described that the load test strain profiles along the length of the piles were used to determine the load capacity of the piles and estimate the design parameters of the various soil strata. Pelecanos et al. (2017) et al. presented a case study of an Osterberg-cell test of a pile located at Isle of Dogs in London, which was heavily instrumented with distributed optical fiber sensors, strain gauges, displacement transducers and extensometers. Special emphasis is given on the data from optical fiber, which offers an advantage due to their spatially continuous nature.

The purpose of this study is to develop the newly measurement method using the optical fiber sensor of strain and the evaluation of stress for piles. The in-situ full scale load tests were carried out to examine the applicability of optical fiber sensors for the pile load test.

2. Measurement method for optical fiber sensors

An optical fiber sensor consists of optical fiber or glass at the sensor part. It can build an irrefrangible sensor system because there are no electronic components at the sensor part. Therefore, it can reduce costs and energy for the maintenance after introducing the monitoring system. Moreover, the remote sensor system is built at a low cost since it does not require an information transmission device. The sensor signal through the optical fiber is transmitted over a long distance.

There are two types of optical fiber sensors. Figure 1 indicates the optical fiber sensor itsellf. This sensor type uses a method in which the incident light from the optical source device travels refractionally between the center section of core with a higher refractive index and the outer part of the clad with a lower refractive index. The sensor, which is attached to the optical crystal at the tip of the optical fiber, is shown in Fig. 2. This sensor type meansures the reflected light from the tip of the optical fiber.

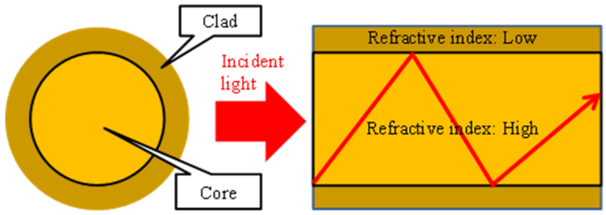


Fig. 1 Sensor of optical fiber sensor itself

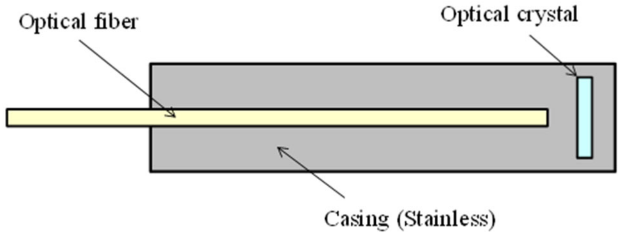


Fig. 2 Sensor with optical crystal at optical fiber tip

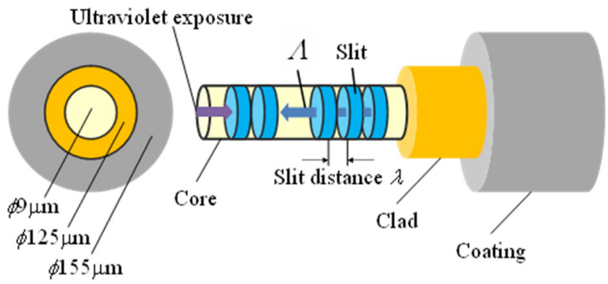


Fig. 3 FBG (Fiber Bragg Grating)

The used sensor in this study is the same type sensor as shown in Fig. 3, which is called FBG (Fiber Bragg Grating). The structure of FBG is shown in Fig. 3. The FBG sensor is equipped with a slit which reflects a specific wavelength Λ (i.e. Bragg wave-length) when exposed to ultraviolet light. The magnitude of Bragg wavelength bears a proportionate relationship to the strain. Thus, the distance of slit λ changes with the change of the Bragg wavelength when the strain occurs. The characteristics of FBG are described as follows;

1) It can measure compressive and tensile strain.

2) The high-speed measurement is possible without averaging the signal because the high level optical signal can can be imported to the measurement equipment due to the high reflection degree of FBG.

3) It provides a stable strain measurements because it is not affected by noise from electromagnitic fields.

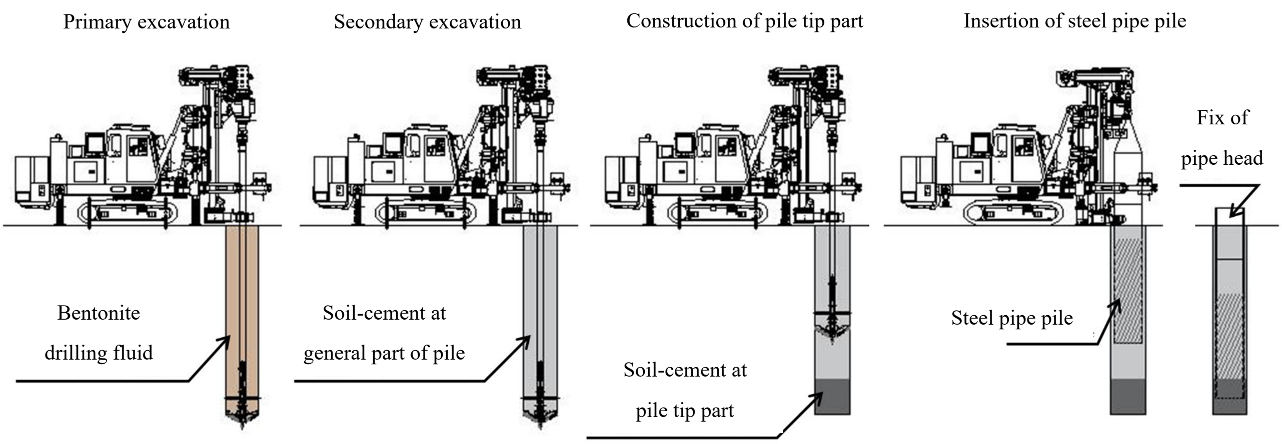


Fig. 4 Construction procedure of steel pipe soil-cement pile

4) It can measure at multiple points when the FBG is equipped in an optical fiber.

3. In-situ full scale load test

3.1. Test pile construction method

The construction procedure of the steel pipe soil-cement pile method developed in this study is shown in Fig. 4 and as follows:

1) The ground is excavated and agitated at a diameter of ϕ950mm while discharging bentonite drilling fluid from the tip of the drilling bit.
2) Cement milk for the general part of the pile is discharged from the tip of the drilling bit.
3) The soil-cement is formed by excavating and mixing the ground at a diameter of ϕ1000mm while discharging the cement milk for the general part of the pile from the tip of the bit.
4) After the soil cement for the general part of the pile is formed to the tip of the pile, the cement milk for the pile tip is discharged at the tip of the pile and the pile tip soil-cement is formed.
5) The hydraulic winch of the excavator machine is used to insert the steel pipe into the soil-cement improvement.
6) The pile head is fixed until the soil cement improvement is solidified.

In order to construct steel pipe soil-cement piles in narrow and low void conditions, the drilling capacity of this method is increased to enable drilling in hard ground by adding a vibrating mechanism to the compact construction machine. In order to shorten the time from the construction of the soil cement improvement to the completion of pipe installation, a primary excavation is provided. In addition, a hydraulic winch was installed in the construction machine to enable the steel pipes to be erected using the construction machine after the soil cement has been created, assuming that it is difficult to secure the construction space and lifting capacity to install a crane for erecting steel pipes.

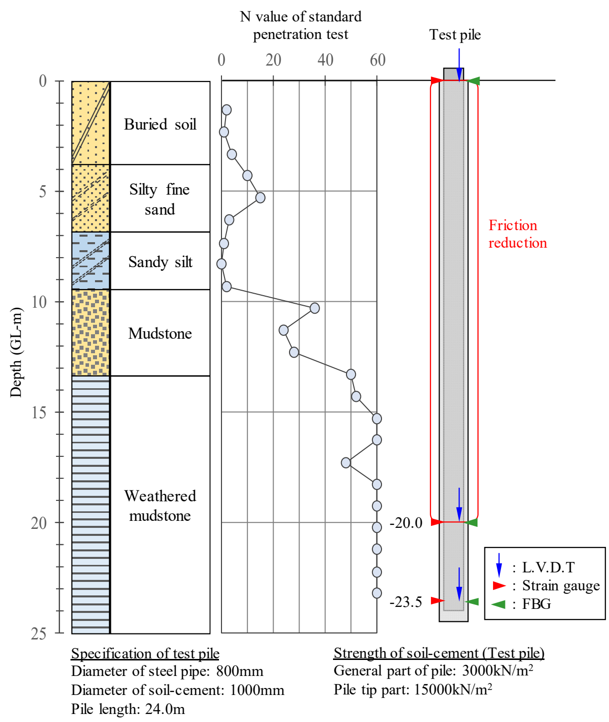


Fig. 5 Ground condition and test pile

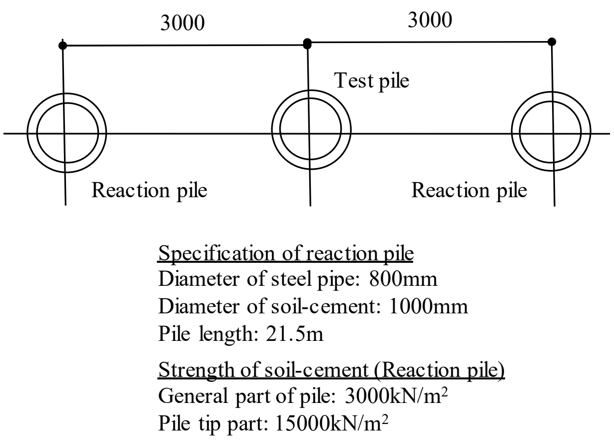
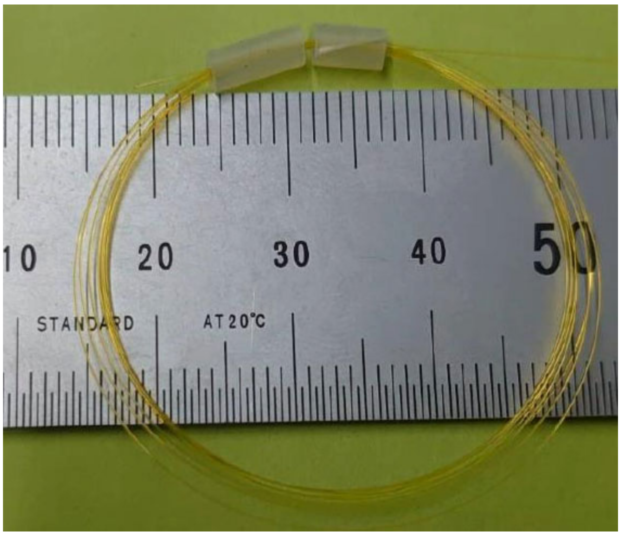


Fig. 6 Arrangement of test pile and reaction pile



(a) FBG cable

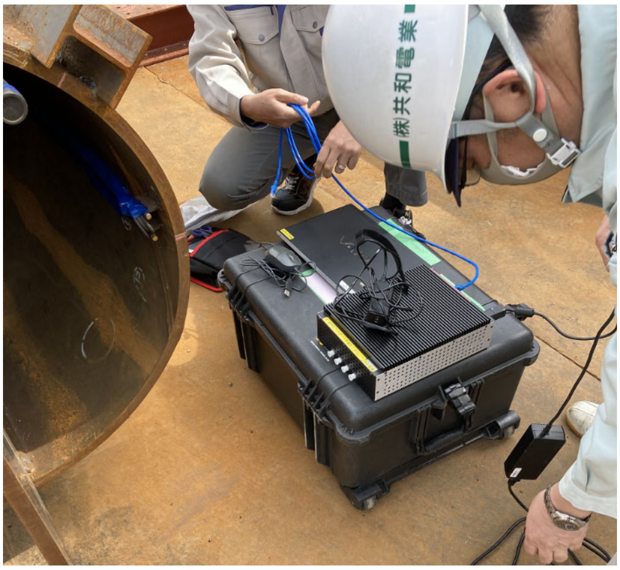


Photo 1 Measurement equipment of FBG

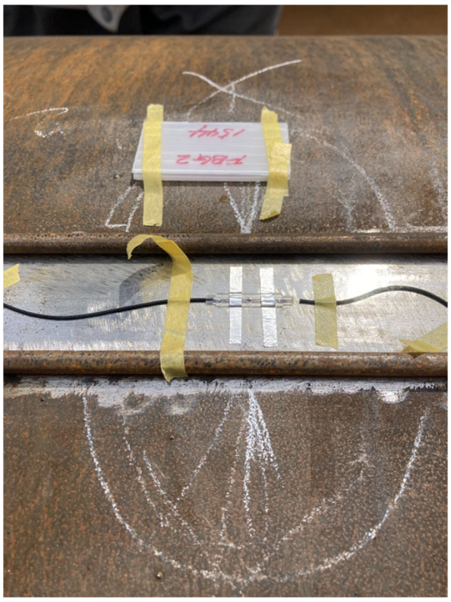
(b) FBG cable protection coating

Photo 2 FBG sensor

3.2. Test condition

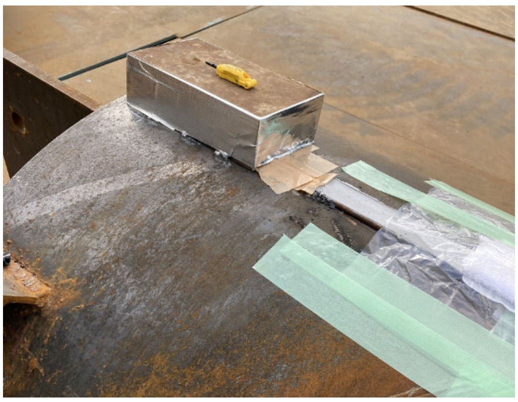
Fig. 5 shows the ground conditions and test piles. The test soil consisted of buried soil up to GL-4.0 m, silty fine sand from GL-4.0 to 6.8 m, sandy silt from GL-6.8 to 9.4 m, and mudstone and weathered mudstone below GL-9.4m.

The test piles were friction reduced to GL-20.0 m to increase the load transmitted to the pile depth. The steel pipe of the test piles were ribbed steel pipes (SKK490, ϕ=800mm, t=21mm) inserted into a soil-cement of 1000mm diameter. The target strength of the soil cement was 3000 kN/m^2 in the general part of the pile and 15000 kN/m^2 in the rooted part at the pile tip. The rooted part at the pile tip was defined as the depth below the bottom of the friction reduction to a depth of GL-20.0 m. The test specimens were placed in a soil-cement of 1000 mm in diameter.



(a) Installation of FBG

(b) Curing of FBG



(c) Setup of FBG

Photo 3 Procedure of FBG setup

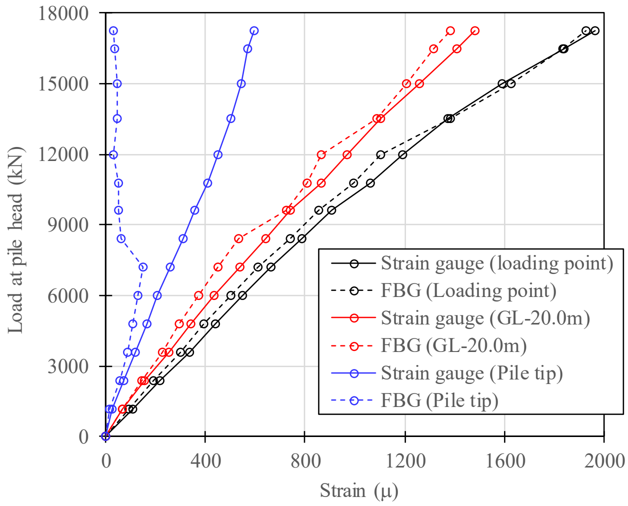


Fig. 7 Relationships between load at pile head and strain

Fig. 6 shows the arrangement of the test pile and the reaction piles. The loading tests were conducted in accordance with the "Method for Static Axial Compressive Load Test for Single Pile" (JGS, 2002). The loading method used was stepwise loading with the multi-cycle method. The items measured were the load and displacement at the pile head and the strain on the steel pipe. Displacements at the bottom of the friction cut and at the pile tip were measured by the double-tube method. Steel pipe strains were measured at the pile head and at the stratum boundary as shown in Fig. 5.

Since the purpose of this loading test was to investigate the application of optical fiber sensors in strain measurement, FBG sensors were installed at the same depth as the strain gauges to compare the strains. Photo 1 indicates the measurement equipment of FBG. The FBG sensor used in this loading test and its installation are shown in Photo 2. The FBG sensor was installed between two round steel pipes with a diameter of 5.5 mm and a separation of 30 mm on the outer circumference of the steel pipe. During sensor installation, it is necessary to cure the joints and other points where misalignment may occur in order to prevent the sensors from being damaged during loading tests. The FBG sensors were then cured by coating the entire length of the pile with epoxy resin. The procedure of FBG setup is presented in Photo 3. A special measuring device was used to measure the fiber-optic sensors.

4. Results of vertical load test

Figure 7 shows the relationship between the applied load and the strain at each section of the pile. As shown in Fig. 7, the values obtained by strain gauges and FBG sensors are almost identical when comparing the relationship between load and strain at the loading point and at GL-20.0 m, the lower end of the friction cut. Therefore, it is suggested that the FBG sensor may be applicable to the measurement of strain during loading tests. On the other hand, focusing on the load-strain relationship at the pile tip, the load-strain relationship between the strain gages and the FBG sensor is almost identical up to a loading load of about 6000 kN. However, as the loading progresses, the difference between the load-strain relationship of the strain gages and the FBG sensor becomes larger. This is presumably due to damage to the FBG sensor installed at the pile tip. In particular, ribbed steel pipes are used in the root consolidation area below GL-20.0 m, and the failure is considered to be caused by the optical fiber breaking due to the step caused by the ribs. This suggests that improvements are needed in the curing method, such as reducing the displacement of the optical fiber sensor during installation.

5. Concluding remarks

A full-scale load test was conducted to establish a strain measurement method using an optical fiber sensor. The following findings were obtained from this study.

1) Installation and strain measurement methods were established for the use of optical fiber sensors.
2) As a result, it was found that the strain measured by strain gauges corresponded to that measured by the FBG sensor.
3) This study suggests that FBG sensors can be used to measure the strain generated in the pile body. It is implied that the continuous strain measurement of the pile body can be possible by using FBG sensors.
4) In the future, we plan to establish the measurement method by improving the curing method of the optical fiber sensor and conducting further loading tests.

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