Application of optical fibers to measuring horizontal deformation of sheet piles during static load tests

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ABSTRACT

In our research and development activities on the use of steel sheet piles for non-temporary structures, it is necessary to accumulate the information on the measured deformation of steel sheet piles, during horizontal loading test or monitoring of the actual structure. Usually, inclinometers are used for measuring the deformation of sheet piles, but this method has issues like discrete depth measurements and the size of equipment and its protection. In contrast, optical fiber measurements using Fiber Bragg Grating (FBG) sensors, offer continuous depth measurements, reduced equipment size and high durability, making them suitable for civil engineering structures. Recently, the Optical Frequency Domain Reflectometry (OFDR) method, which uses FBG sensors, has been developed. This method provides high-resolution, spatially continuous strain measurements. In our study, we tested an FBG sensor with the OFDR method on press-in steel sheet piles and compared the results with those from an inclinometer. Two test piles, one with the FBG and the other with the inclinometer, were installed in sand ground using Standard Press-in and were load tested horizontally at the same time. The deformations at the pile head were measured. The results from the FBG sensor were almost equivalent to those from the inclinometer, with slight differences possibly due to the difference between the theoretical and actual neutral axis positions and thermal effects on the FBG sensors.

Key words: *optical fiber, FBG, OFDR, sheet pile, horizontal load test*

1. Introduction

1.1. Background

The press-in method is one of the construction techniques for pile foundations, in which new piles are statically installed into the ground by hydraulic force while obtaining reaction forces from the existing piles. Piles constructed by the press-in method (press-in piles) are used as social infrastructure, such as piles to control liquefaction and land subsidence caused by earthquakes, reinforce embankments to withstand tsunamis tenaciously and to deter landslides. We are currently working on research and development on the use of steel sheet piles for non-temporary structures. In some of these cases, the deformation of steel sheet piles is measured in horizontal loading tests and in monitoring actual structures.

In conventional deformation measurement, inclinometers are often used, but they have problems such as discrete measurement intervals in the depth direction, complicated wiring, size of the measurement system and sensor durability. In contrast, a newly developed measurement technique is the use of fiber optic sensors (FBG sensors). This technology uses the characteristic of

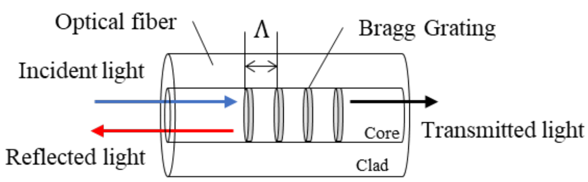

Fig.1 FBG sensor

optical fiber with gratings (diffraction gratings) to reflect a specific wavelength of incident light. When the grating interval is Λ and the refractive index of the optical fiber is n, strong reflection occurs at the wavelength $\lambda B = 2n\Lambda$, while other wavelengths pass through. As the wavelength of the reflected wave changes when Λ changes, the amount of strain can be measured from this change (Fig.1). Measurement using FBG sensors is characterized by continuous measurement in the length direction, reduced wiring, and high durability. This technology has been increasingly used for contributing to longer service life and efficient maintenance of structures. Furthermore, with the development of the OFDR (Optical Frequency Domain Reflectometry), it has become possible to measure strain distributions continuously and with high spatial resolution (Igawa et al., 2008). It works by sending a laser with a varying frequency through the fiber, then analyzing the reflected light using an interferometer in OFDR system. By performing frequency analysis on the reflected light, the distance L to the reflection point are determined (Fig.2). Measurement techniques using this FBG sensors with OFDR method are beginning to be used for monitoring in the civil engineering (e.g. Gao et al., 2022) and may be useful for monitoring press-in pile structures.

1.2. Objectives

In this study, horizontal loading tests are carried out on press-in sheet piles equipped with FBG sensors and inclinometers to simultaneously measure the deformation induced in the pile for confirming the validity of the results measured by the FBG sensors.

2. Test methods

2.1. Test pile

Two steel sheet piles SP-III (L = 7.5 m) were used as test piles (Fig. 3). One test pile (Pile C) was equipped with an FBG sensor and the other (Pile A) with multistage inclinometers (Fig. 4). The FBG sensor was fixed with glue in a section between 60 mm and 7100 mm from the pile tip at the center of the sheet pile web and covered with a protective steel plate to prevent the sensor from coming

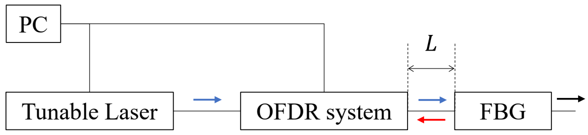

Fig.2 OFDR measurement system

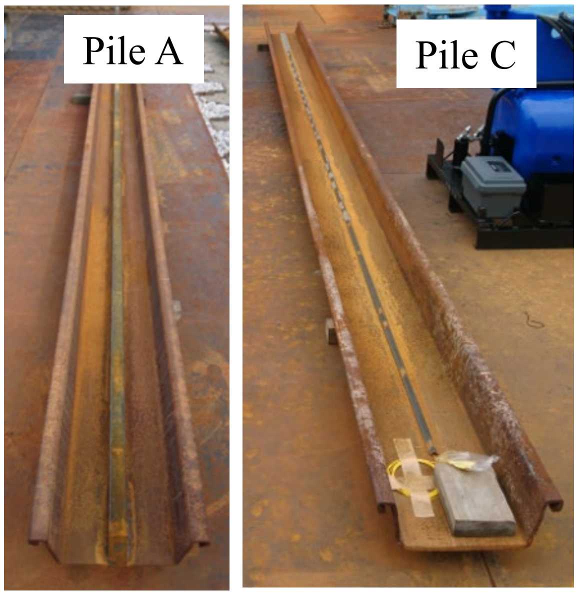

Fig. 3 Test piles

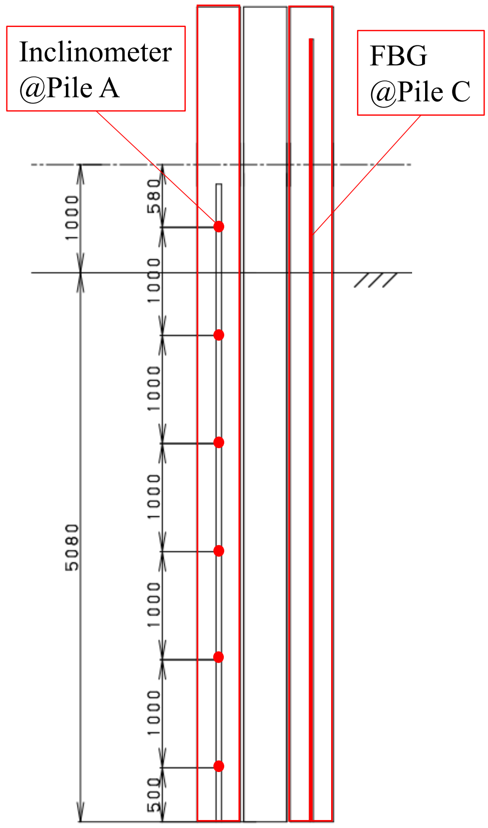

Fig. 4 Measurement points of test pile

Table.1 Soil properties

Soil name		NSK-40
Average grain size	D_{50}	0.32 mm
Internal friction angle	ϕ	31.2 deg
Cohesion	C	2.4 kPa
Soil particle density	ρ_d	2.63 g/cm^3

off during press-in. A set of 6 multistage inclinometers was installed at a pitch of 1 m in a pipe attached at the center of the sheet pile web.

2.2. Test layout

The tests were conducted in a large experimental soil tank owned by GIKEN. The size of the experimental soil tank is 7 m square in cross section and about 10 m deep. The ground consists of loose sand (Table.1) with N value of 5 and a groundwater table of 7.5 m below the ground level. Fig. 5 shows SPT N value estimated from the CPT conducted before the test.

Two test piles were installed using the standard press-in method with a press-in machine, and one sheet pile was installed between the two test piles (Fig. 6a). Each sheet pile was installed without interlock connection. The penetration length of the 3 sheet piles was 5 m.

A loading beam was placed beside the 2 test piles so that the loading point was 1 m above the GL, and the loading beams were pulled horizontally with hydraulic jacks to load the 2 test piles simultaneously. The reaction force for the loading test was taken from an existing steel pipe pile wall embedded outside of the soil tank (Fig. 6b).

2.3. Measurement system

FBG sensors were used as optic fiber sensors. The diameter of the sensor is 0.25 mm (Fig. 7). The sensor is configured in series with a single optical fiber, so the wiring can be space-saving. In addition, the use of the OFDR method enables measurement with a high spatial resolution of about 0.6 mm along the optical fiber. The data were measured at each loading stage.

A multistage inclinometer, which is commonly used in the measurement of lateral displacement of ground and earth retaining walls, was used as the inclinometer. This inclinometer measures by connecting several sensors in the vertical direction. The distance between measurement points is determined by the size of the inclinometer, which

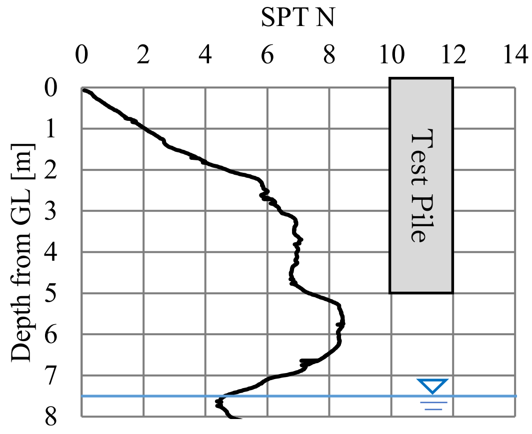

Fig. 5 Ground conditions

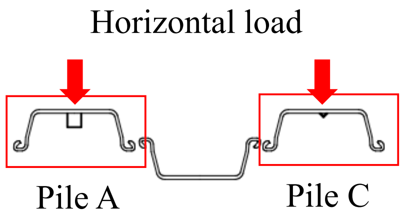

Fig. 6(a) Test layout (plane view)

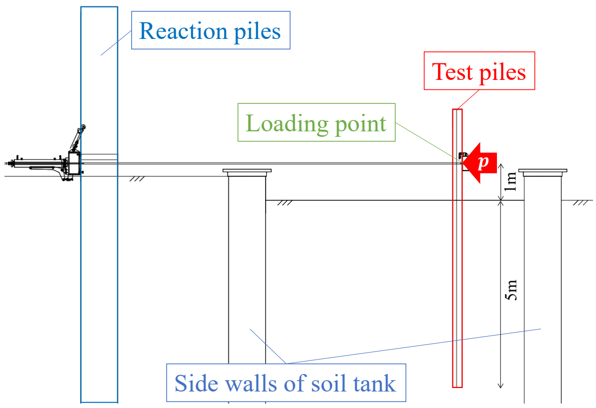

Fig. 6(b) Test layout (side view)

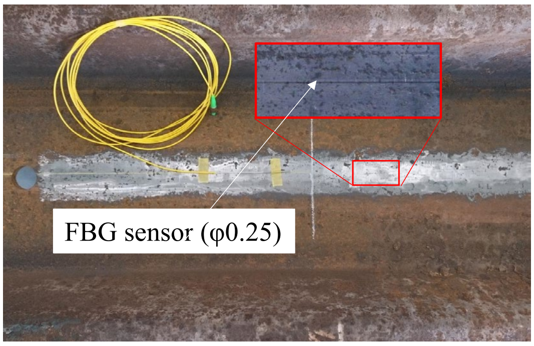

Fig.7 FBG sensor on test pile

was set at 1 m for this test.

The horizontal load p was measured using load cells and horizontal displacement at the loading point and GL positions were measured using rod type displacement transducers. The multistage inclinometer and the FBG sensor were offset to zero just before the start of the loading test.

2.4. Test procedure

Horizontal loading tests were carried out using the continuous loading method with single-cycle and one-directional load in accordance with the JGS standard JGS1831-2010 (JGS, 2010). The loading was carried out until the horizontal displacement of the pile at the ground surface was more than 15 mm. In the load test, the load was increased up to 50 kN in about 15 min. and then decreased to zero in about 10 min (Fig. 8).

2.5. Calculation method

FBG sensors measure the strains in the sheet pile. For horizontal loading tests, it is assumed that the strain in the sheet pile is dominated by bending strain and no axial strain occurs. The conversion from strain values to inclination values was carried out using the following equation.

$$\frac{d\theta_i}{dz_i} = \frac{\varepsilon_i}{h} \cdots (1)$$

Here θ is the inclination value of the steel sheet pile, z is the length of the steel sheet pile in the depth direction, ε is the strain, h is the distance from the strain measurement position to the neutral axis of the sheet pile and i is a natural number indicating the depth measurement position of the strain (Fig. 9). As the sheet piles were tested without interlocks being connected, h was set to 42 mm as the value of one sheet pile. The conversion from inclination values to deformation values was carried out using the following equation.

$$dy_i = dz_i * sin(\theta_i) \cdots (2)$$

Here y is the horizontal deformation of the sheet pile. In addition, the horizontal displacement at the GL position measured by a displacement transducer was used to calculate the deformation of the entire test pile.

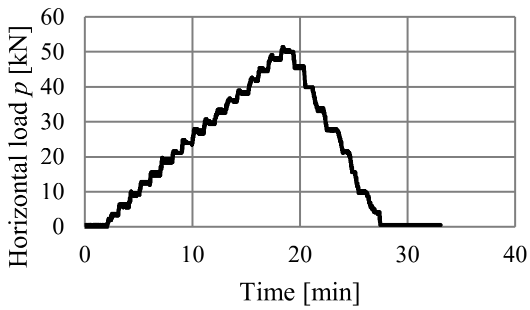

Fig. 8 Horizontal load vs time

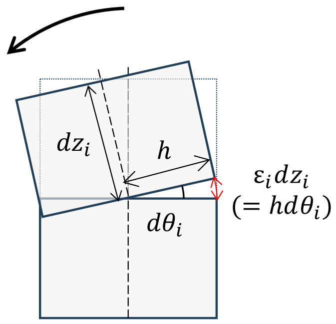

Fig. 9 Conversion from strain to inclination

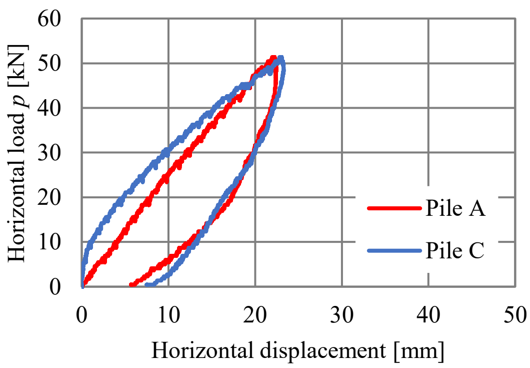

Fig. 10 Loading test result at ground level

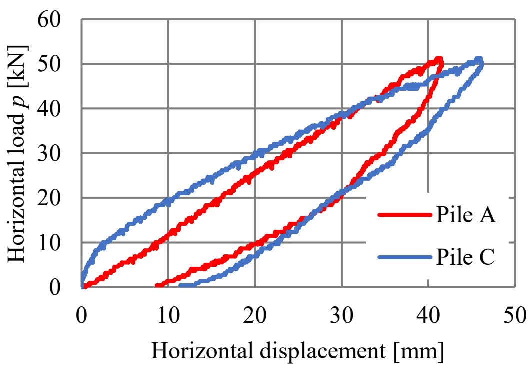

Fig. 11 Loading test result at loading point

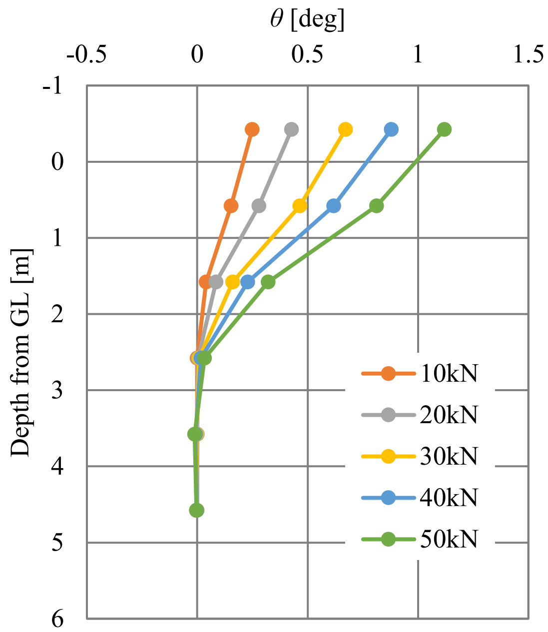

Fig. 12 Measurement values of inclinometer

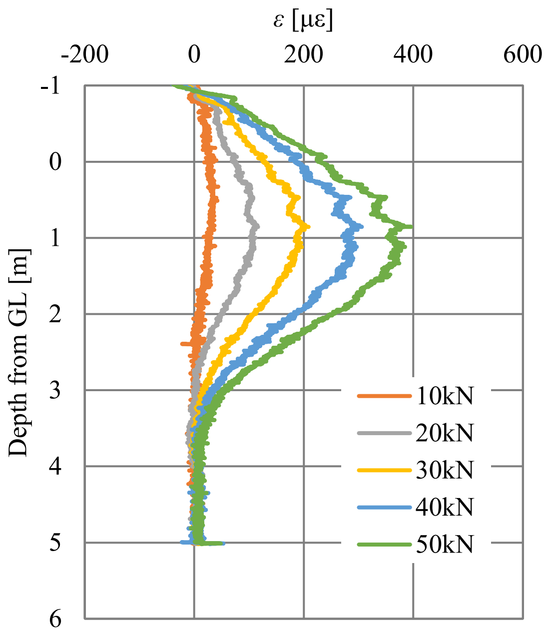

Fig. 13 Measurement values of FBG

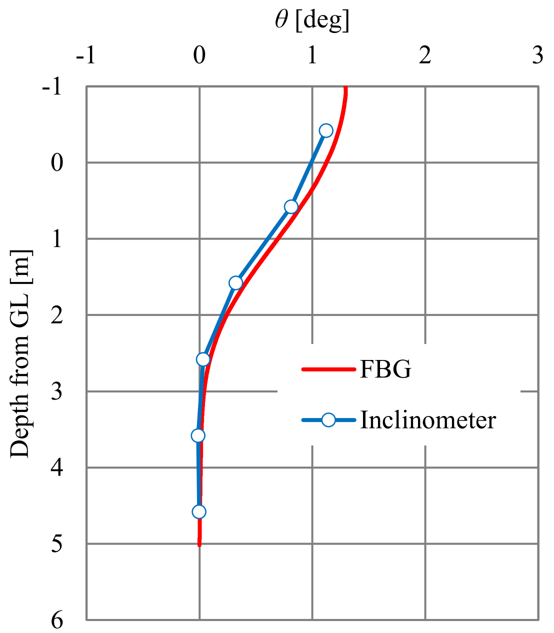

Fig. 14 Comparison about inclination at p=50kN

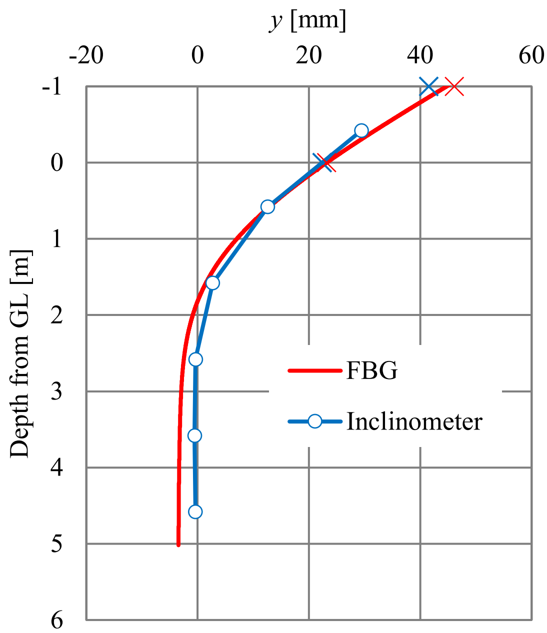

Fig. 15 Comparison about horizontal displacement at p=50kN

3. Results

The results of the horizontal loading tests are shown in Fig 10 and 11, where the vertical axis represents the horizontal load and the horizontal axis represents the horizontal displacement measured by displacement transducers, the blue line shows the horizontal displacement at the GL position and the red line shows the horizontal displacement at the loading point. It can be observed that the displacement of Pile C tends to be smaller than that of Pile A in the early stages of loading, and the difference between Pile C and A is smaller at the maximum loading. It is considered that the non-uniformity in touching between the sheet piles and the loading beam in the initial stage of loading was resolved as the loading increased to a certain extent.

The inclination values during the loading test are shown in Fig. 12. The vertical axis represents the depth from the GL and the horizontal axis represents the change in inclination value since the start of loading, with the values at each loading stage plotted. The section from 4.5 m to the pile tip was not measured due to the size of the inclinometer. It can be observed that as the loading load increases, the inclination value changes significantly at depths of 2.5 m and above.

The measured values of the FBG sensor during the loading test are shown in Fig. 13. The vertical axis represents the depth from the GL and the horizontal axis represents the change in strain since the start of loading, with the values at each loading stage plotted. The number of data points is about 11,600 in the depth direction, so the spatial resolution is high and the strain values show a smooth change. It can be observed that the strain values increase at depths greater than 3.5 m as the loading load increases.

4. Discussion

Inclination values and deformation values of the test piles during horizontal loading test were calculated and compared from the measurements of the inclinometer and FBG sensor, respectively. Fig. 14 shows a comparison of the depth distribution of inclination values at a horizontal load (p) of 50 kN. The inclinometer values were used as measured. The FBG sensor values were calculated using equation (1) to calculate the inclination changes and then integrated upwards from the lower end position to obtain the inclination value at each depth. As a result, the inclination value calculated from the FBG sensor is slightly larger than the inclination value from the inclinometer, but the two values are in close agreement with depth. The values calculated from the FBG sensor change more smoothly than those calculated from the inclinometer, making it possible to capture more detailed changes.

Fig. 15 shows the comparison of the depth distribution of horizontal displacements at a horizontal loading of 50 kN. The cross mark shows the value of the horizontal displacement at GL and the loading point of each pile as measured by the displacement transducer. The

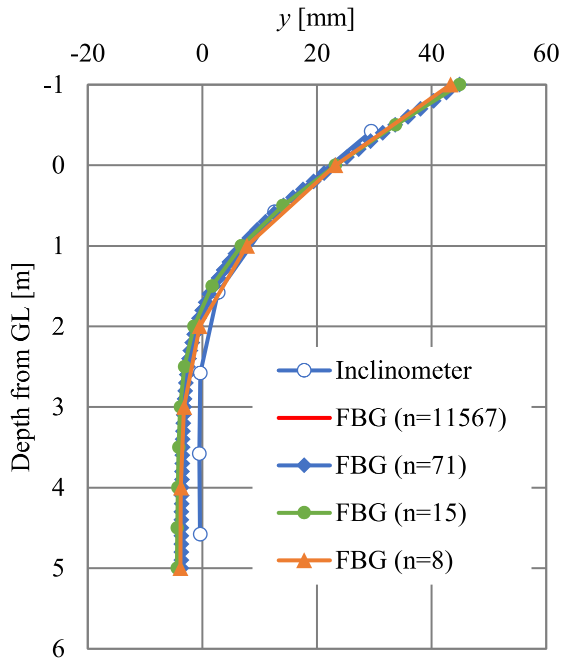

Fig. 16 Effect of the number of measurement points of FBG

displacements were plotted from equation (2) for both the inclinometer and the FBG sensor. All values were offset to match the measurement value at GL. According to this, the displacement calculated from the FBG sensor is slightly larger than the displacement calculated from the inclinometer value. In a design calculation (JRA, 1999), if the value βL obtained by Chang's formula is greater than 2.5, the pile tip can be regarded as half infinite, and the horizontal displacement near its base may be regarded as zero. The value of βL was about 3.5 in the experiment, and we can assume that the pile tip is not moving. However, the FBG sensor's value indicated an apparent displacement near the pile tip compared to the inclinometer's value. The possible reason for this could be the difference between the theoretical and actual value of h, the thermal effects on FBG sensors, and the accumulation of these measurement errors at the measurement points. According to Fig. 16, the horizontal displacement was little influenced by the number of measurement points. Therefore, the accumulation of the measurement errors will not be the major cause for the apparent horizontal displacement near the pile tip obtained by the FBG sensors.

5. Conclusion

In order to investigate the applicability of measurements using FBG sensors to press-in piles, horizontal loading tests were carried out on sheet piles with FBG sensor. The test results showed that the depth distribution of horizontal displacement captured by FBG sensors is similar to that captured by inclinometers, but there is an apparent difference near the pile tip. This was thought to be due to the errors in the neutral axis position or the temperature effect on FBG sensors.

In this study, horizontal loading tests were carried out on sheet pile single piles, where the neutral axis is assumed to be constant. However, for sheet pile walls where the interlocks are connected, the position of the neutral axis is complicated by the effect of the interlocks. Therefore, converting strain values to inclination values requires careful attention. In addition, as the FBG sensor is sensitive to temperature, treatment is needed to compensate for temperature effects in the case of structures such as earth retaining walls, which are greatly affected by outside temperatures. Although there are some considerations for on-situ use, the FBG sensor has good features for Press-in method, such as space-saving and high durability. We will continue to verify the validity of the measurement method.

6. Acknowledgements

FBG measurement by OFDR was conducted with Mr. Hamada of CITEC CO., LTD and the technical supports from LAZOC Inc. We would like to take this opportunity to express our gratitude.

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