Development of tunnel pre-displacement measurement method by fiber optic sensing

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ABSTRACT: The authors developed a measurement method by the fiber optic sensing which can evaluate vertical and lateral displacements ahead of the tunnel face. The method uses some fiber optic cable sensors named All Grating Fibers capable of evaluating the longitudinal strains along the cable with high positional resolution and accuracy by the Optical Frequency Domain Reflectometry method. The cable sensors are fixed with inflatable packer tubes in a square pipe inserted in a steel forepole drilled from the face and can be retrieved after the measurement. One advantage is therefore the fact that fibers can be repeatedly used in other pipes. This paper outlines the developed tunnel pre-displacement measurement method by the fiber optic sensing. Results of laboratory experiments and field measurements conducted in a motorway tunnel construction project are also presented.

Keywords: Pre-displacement measurement, Fiber optic sensing, All Grating Fiber, Optical Frequency Domain Reflectometry.

1 INTRODUCTION

In tunnel construction projects, monitoring of ground behavior ahead of the tunnel face is often required especially when tunneling in poor rock conditions, or in urban areas where the influence on structures existing near the tunnel should be minimized. Based on the monitoring results, some auxiliary methods and pre-supports can be studied and installed to control the behavior if required. For this purpose, the ground displacement ahead of the tunnel face (tunnel pre-displacement) is often measured by in-tunnel instruments. For example, Sakai et al. (2016) reported a case study of an underground metro station construction project in a built-up area in which settlement ahead of the tunnel face at the crown level and tunnel longitudinal displacement were measured for evaluating the ground stability ahead of the face. Chain inclinometers named Shape Accel Array concatenating with a series of 50 cm long segments of MEMS acceleration sensors were used for settlement measurement. Schneider et al. (2018) reported two measurement results of settlement ahead of the tunnel face at the crown level in the Brenner Base Tunnel construction project. The chain inclinometers of 40 m length and concatenated with a series of 2 m long segments were installed in measurement holes above exploratory tunnels at the transition from larger to smaller excavation profiles to validate the longitudinal displacement profile assumed in the tunnel support design. Other authors also reported measurement results but mainly in shallow tunnels.

One of the problems in the conventional measurement methods using chain inclinometers installed from the tunnel inside is however limited to vertical behavior: ground heaving and subsidence. As in the case after the face passage, ground behavior ahead of the tunnel face may be more dominant laterally than vertically in some deep tunneling cases where in-situ horizontal stresses pre-dominate over vertical stresses (Sato et al., 2022), or anisotropy of the rock mass properties is significant and the rock mass stiffness in the tunnel cross-sectional direction is relatively small.

Authors therefore developed a displacement measurement method by the fiber optic sensing, which can simultaneously evaluate vertical and lateral displacements ahead of the tunnel face. The method uses some fiber optic cable sensors named All Grating Fibers (AGF) capable of evaluating the longitudinal expansive and contractive strains along the cable with high positional resolution and accuracy by the Optical Frequency Domain Reflectometry (OFDR) method. This paper presents the developed tunnel pre-displacement measurement method by the fiber optic cable sensing: the configuration of measurement instrument, the OFDR method and a standard measurement layout. Preliminary results of laboratory experiments are discussed in chapter three. Field measurements conducted in a motorway tunnel construction project are also presented in chapter four.

2 PRE-DISPLACEMENT MEASUREMENT METHOD BY FIBER OPTIC SENSING

2.1 Fiber optic sensing by FBG and OFDR

Fiber Bragg Grating (FBG) sensor is well recognized as an accurate sensor and is widely used in civil engineering field (Zhou and Ou, 2005). The measurement methods, e.g., Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM), are generally used for a single measurement point at which is an average strain data is obtained in the FBG gauge length. On the other hand, recently developed Optical Frequency Domain Reflectometry (OFDR) is able to realize narrower spatial resolution than 1 mm (Igawa et al., 2005 and Tanaka et al., 2010). All Grating Fibers (AGF) drawing gratings on the entire length of a fiber cable has been developed and commercially available (Lindner et al., 2012). As shown in Table 1, the OFDR interrogating AGF can measure strain with higher accuracy and resolution than the Brillouin Optical Time Domain Reflectometry (BOTDR) method which is one of the conventional and representative methods for distributed fiber optical sensing. Hence, the OFDR with AGF has possibility of being applied to the tunnel pre-displacement measurement which was considered to be difficult for sensing with the BOTDR method.

Table 1. Comparison of distributed fiber optic sensing methods: BOTDR and OFDR.

Measurement method	BOTDR	OFDR (with AGF)
Accuracy (strain)	±20με	±1με
Range (strain)	±7500με	±10000με
Spatial resolution	1m	1mm
Time for measurement	5 to 10 minutes	several seconds
Length limit	more than several kilometer	around 20 m

2.2 Configuration of measurement instrument

Measurement instrument with optical fiber cables is inserted in the steel pipe installed ahead of the tunnel face. The AGF which has gratings throughout the length of cable is generally more expensive than optical fiber cables used in other distributed fiber optical sensing such as those in the BOTDR method. An AGF fixation method has therefore been developed as shown in Figure 1, allowing for the fiber cable retrieval after the measurement. Flat plates of polyvinyl chloride (PVC) with AGF cable attached with an epoxy resin are inserted in the long square-sectioned pipe. An inflatable rubber packer is also inserted in the center of the pipe together with the long plates. At the measurement, the rubber packer is inflated and the flat plates are stiffly impressed against the inner surfaces of the square pipe. Ground deformation changes and correspondingly deflects the longitudinal shape of steel pipe. The differences in the longitudinal strain of fibers on surfaces facing each other can provide horizontal and vertical curvature factors by the equations below:

$$1/\rho_v = (\varepsilon_t - \varepsilon_b)/H\,, \qquad 1/\rho_h = (\varepsilon_l - \varepsilon_r)/W \tag{1}$$

where $1/\rho_v$ and $1/\rho_h$ are curvature factors in the vertical and horizontal directions. ε_t, ε_b ε_l and ε_r denote cables' longitudinal strains on the inner surface of the square pipe at the top, bottom, left and right sides. H and W represent distances between the two opposite fibers, respectively. Both horizontal and vertical deflection curves of square pipe are acquired by integrating the curvature factors twice from front to end edge of fibers.

After the measurement, the flat plates with the AGF cables can be retrieved by deflating the packer system. The tunnel pre-displacement distribution is evaluated as the deflection change of the square pipe from initial reading, assuming that the front edge position of square pipe is fixed and that the tail edge is detected by geodetic measurement as conceptually shown in Figure 2.

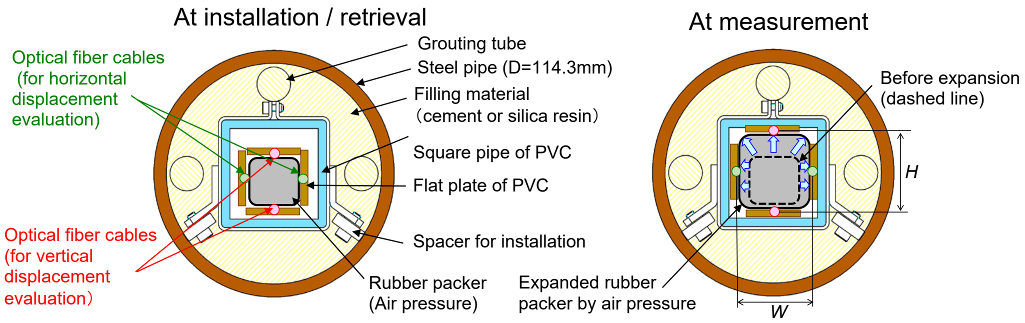

Figure 1. Structure of pre-displacement measurement instrument with optic fiber cables.

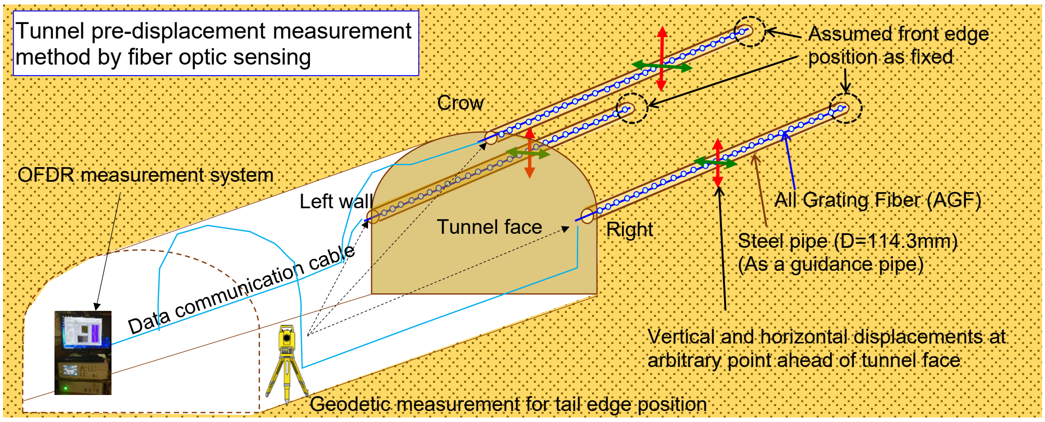

Figure 2. Tunnel pre-displacement measurement method by fiber optic sensing.

3 LABORATORY MEASUREMENT TEST

Figure 3 illustrates the schematic figure of a bending test to investigate the measurement accuracy using a 9 m long prototype without a circular steel pipe and filling material. Three square pipes and rubber packers with 3 m length were connected by steel coupling joints to facilitate transportation and installation. On the 9 m long and 3 mm thick of flat plate, a line of ditch was cut to a depth of 0.5 mm to install optical fibers. The fiber cable was attached on the plate by epoxy resin in the factory.

In Figure 3, the left periphery of square pipe was regarded as the front edge of the instrument and was fixed to the test rack constructed by an H-shaped steel support. The square pipe was then exerted to horizontal and vertical deflections at several pipe supported positions. Figure 4 shows measurement results when the vertical and horizontal displacements were given in 10 mm steps up to 50 mm at the right periphery (deflection mode A) and at the middle of square pipe (deflection mode B). Horizontal and vertical displacements were calculated on assumption that displacements at the front edge were 0 mm and those at 100 mm length from the tail edge were given by laser displacement meters of LDM(V)-1 or LDM(H)-1. The spatial resolution of optical fiber in the strain calculation by OFDR method was experimentally assumed to be 6 mm. As shown in Figure 4, horizontal and vertical displacement distributions observed by the optical fiber were generally consistent with LDM results in both deflection modes A and B. In the mode B, however, vertical displacements by the optical fiber sensing were a little less than those given displacements by LDMs(V) and the maximum difference reached about 5 mm at the position of LDM(V)-4. After the test, the flat plate with fiber cable on top of the square pipe was found to have shifted to one side. The distance between top and bottom fibers ("*H*" in equation (1)) therefore became bigger than the assumption that the fibers were vertically arranged. Thus, though 10% at the most, the longitudinal misalignment of fibers in the square pipe was one of the factors attributing to the measurement error.

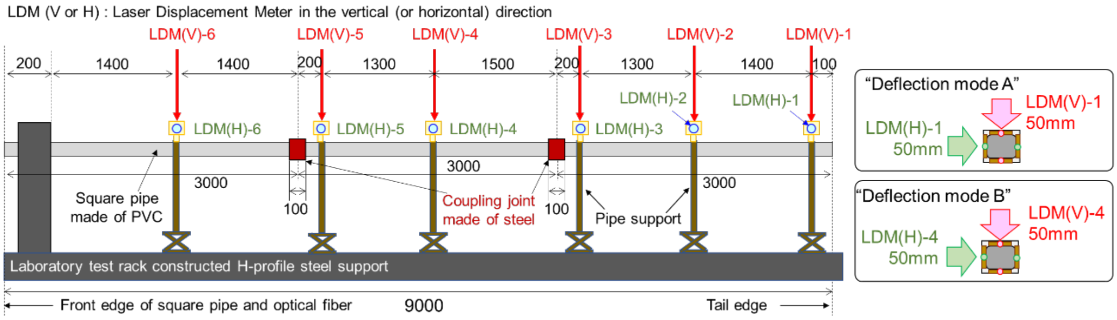

Figure 3. Bending tests layout using 9 m long of pre-displacement measurement instrument.

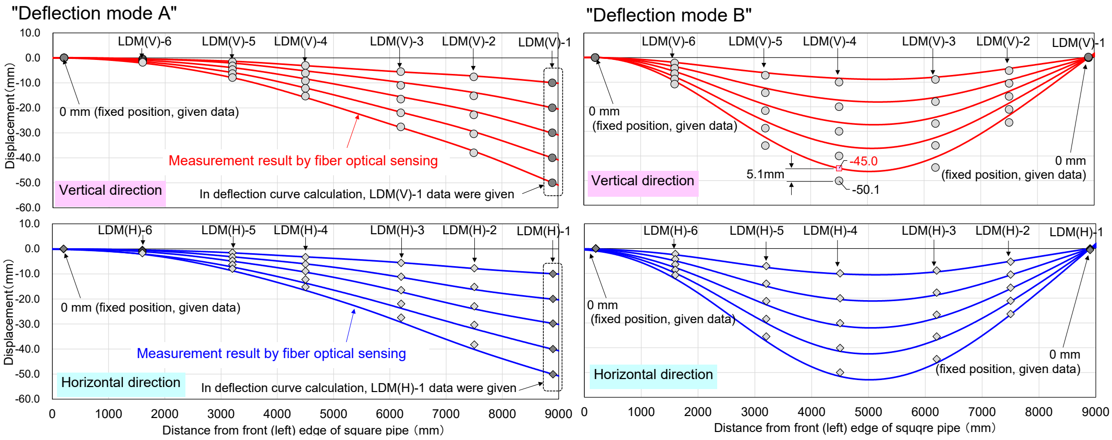

Figure 4. Bending test results: deflection modes A (left) and B (right).

4 FIELD MEASUREMENT TEST

The bending test in the laboratory verified that the AGF cables fixed to a square pipe of PVC by the packer system could measure vertical and horizontal deflection with an error of 10% at the most. In the following verification, a field measurement test was demonstrated in practice to obtain pre-displacement and to acquire know-how with respect to the instrument installation and retrieval.

4.1 Site overview and measurement condition

The field measurement test was performed at the East construction site of Takimurozaka tunnel project on route 57 in Kumamoto prefecture. This project constructs a two-lane motorway tunnel with the length of 4.8 km (the East site covers about 2.1 km) and the standard cross-sectional area of 90 m^2 (interior space after completion). The dominant geology around the measurement section was welded tuff derived from the pyroclastic flow of the Mt. Aso eruption.

The measurement instruments were installed in two locations, one at 1930.7 m (chainage No.1889) and another at 1946.2 m (No.1905) from the tunnel portal. Measurement holes retained by steel pipes with an external diameter of 114.3 mm were drilled from both sidewalls 1.3 m above the work floor of the top heading and at a horizontal angle of 6 degrees away from the tunnel advance direction. Both sidewalls of measurement cross-sections were widened by 600 mm to keep the tail edge of the steel pipes open for measurement instruments installation (Figure 5).

The measurement instruments in square pipes of PVC were assembled prior to its insertion to steel pipes to reduce the working time in the vicinity of the face. More concretely, optical fibers on PVC flat plates and rubber packers were inserted in square pipes at a material preparation area away from the face. The PVC plates with optical fibers were bundled in a circular shape with a diameter of about 1 m during transportation. In the field measurement test, the fitting bracket was supplementary added in the pipe to place vertically flat plates and avoid the misalignment error. After the flat plates were fixed in the square pipes by the expansion of rubber packers with air pressure, 12 m of square pipes were manually carried to the face and inserted in steel pipes. Silica resin was used as filling material which fixed the square pipe in the steel pipes. It was concerned that solidification heat of silica resin influenced on the strain measurement by optical fibers since the preliminary test showed that temperature in the square pipe reached around 60 degrees Celsius. The initial readings of strain measurement were therefore recorded when an excavation round finished after silica resin injection, which was when the face reached 1931.7 m (No. 1890) for the first measurement.

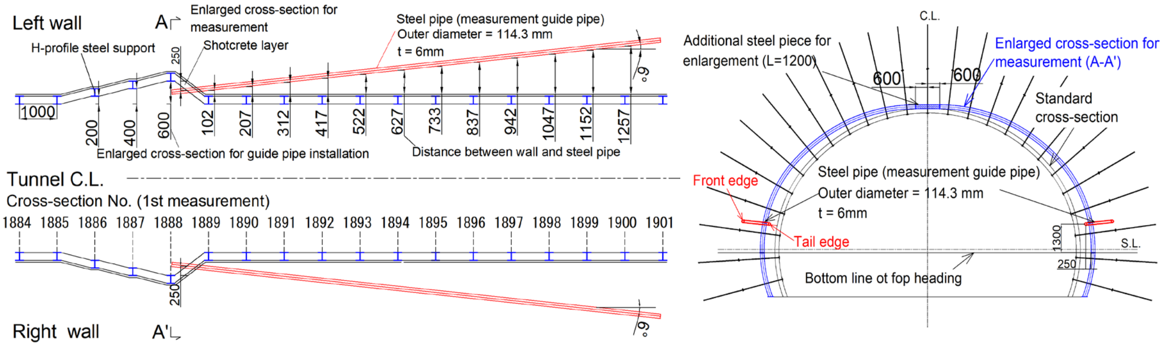

Figure 5. Plan and cross-sectional view of steel pipes for pre-displacement measurement (at 1st installation).

4.2 *Measurement results*

The left figure in Figure 6 shows displacement distributions along tunnel walls on both sides during 4 rounds of excavation after initial readings. It was assumed that the front edges of measurement instruments were fixed and the tail edges were equivalent to geodetic measurement results observed by a total station. Magnitudes of measured displacements in both horizontal and vertical directions were 6 mm at the most, suggesting that the ground was more or less stable. It is interesting to note that the measurement instruments caught ground behavior normally observed in a tunnel excavation in which displacements toward opened space significantly increase at the time of face passage. Displacements at the pipe tail edges especially along the left wall gradually decreased and became smaller than those in the middle of pipes. This is probably because they were already influenced by the tunnel excavation at the time of their initial readings, and did not include pre-displacement ahead of the face.

The right figure in Figure 6 presents the displacement characteristic curves at the cross-section of 1937.7 m (No.1896) with the distance from the face on the x-axis. In the experiment, no significant development of displacement due to face advances was observed. However it generally helps to interpret range and ratio of pre-displacement to total ground displacement in conjunction with geodetic measurement after the face passage at a cross-section of interest. The interpretation of pre-displacement also contributes to verifying given conditions for support design or auxiliary methods.

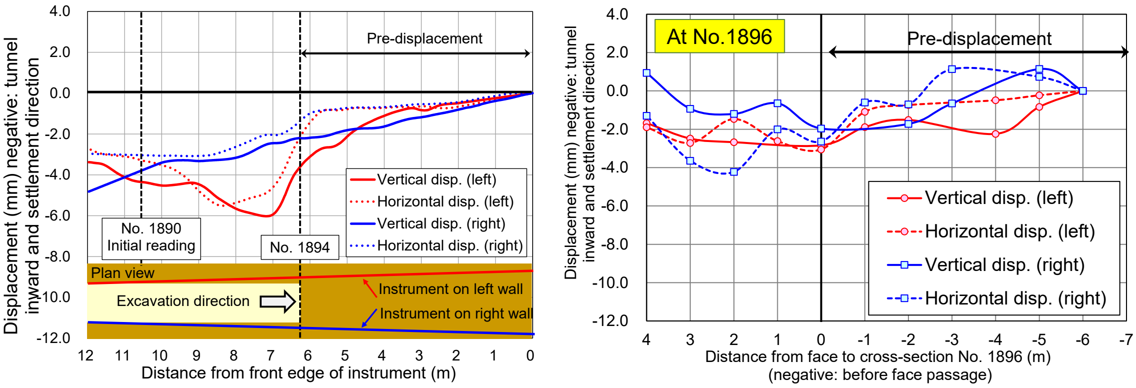

Figure 6. Measurement results: displacement distributions along side walls when face reached No. 1894 (left), displacement development due to face advances at a No. 1896 (right).

5 CONCLUSIONS

Developed in the research is a tunnel pre-displacement measurement method by the fiber optic sensing which could evaluate vertical and horizontal displacement ahead of the tunnel face simultaneously. The proposed method is considered applicable even when horizontal behavior of rock becomes dominant due to anisotropy of rock mass mechanical properties or in-situ stress conditions. The preliminary bending test in the laboratory confirms that the measurement error is not more than 10 % for displacements up to 50 mm. In the field experiment, the observed pre-displacement provided reasonable displacement distributions for the rock behavior around and ahead of the face, and the results were consistent with the geodetic measurement results. The field measurement test also verified the measurement workability at the site through practicing sequential installation and retrieval procedures. It demonstrated that optical fibers and inflatable rubber puckers can be reused in other measurement holes. It is expected that the developed method in conjunction with the longitudinal displacement measurement by an extensometer: T-REX (Sakai et al., 2016) will enable more realistically to interpret 3-D behavior of rocks ahead of the tunnel face. Though the proposed fiber optic sensing method still requires reliability enhancement by accumulating application results, it could contribute to measurement management in projects especially tunneling under built-up area with strict care to already existing structures or deep tunneling with lack of available geotechnical information before construction.

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