A Technic for Ground Anchor Force Determination from Distributed Strain Using Fiber Optic OFDR Sensor with the Rejection of a Temperature Effect

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Abstract: Anchor systems are widely used to stabilize soil slope and suppress slope failure. Thus, monitoring conditions of an anchor system is important to prevent disasters due to slope failure. The slope condition can be indirectly monitored by sensing the tensile force applied to the anchor because the slope deformation directly affects the anchor force. Previously, we propose a way to monitor the tensile force of the anchor by measuring the strain field on a bearing plate using a distributed fiber optic sensor (OFDR) and experimentally demonstrate that the anchor force has a large correlation with the strain distribution on the bearing plate. However, it was found that a spatial variation of the strain and thermal strain due to temperature change makes it difficult to get a reliable correlation coefficient. In this study, we newly propose a way to get a reliable correlation coefficient between the anchor force and the strain field on the bearing plate. We install a distributed optical fiber sensor in two concentric circles on the bearing plate and measure circumferential strain distribution. We take average values of the strain field in each circle as representative strain values minimizing the spatial variation and takes a difference of the two strains to exclude the temperature effect. We experimentally demonstrate that the proposed method gives a reliable correlation coefficient between the anchor force and the strain field on the bearing plate. This technique can be applied to various anchor systems to monitor the anchor force and manage the anchor systems safely.

Keywords: anchor force; ground anchor; bearing plate; distributed strain; OFDR (optical frequency domain reflectometry); temperature effect

1. Introduction

In the field of civil engineering, ground anchor systems are widely used to stabilize a soil slope and, thus, prevent slope failure. Since the Cheurfas dam in Algeria utilized pre-stressing technology in 1935, various anchor systems have been developed and utilized in constructions such as bridges, tunnels, and slopes [1,2]. The anchor system aims to transmit the tensile force of the anchor to the compressive force of the ground. For this purpose, the ground anchor consists of three parts: (1) ground anchor body, (2) anchor head, and (3) anchor head-related part [3]. The ground anchor body consists of two parts. One is a fixed anchor section, which is fixed under the ground and resist the tensile force of the anchor (or tendon) by using friction and compression in the ground. The other is a free anchor section, which transfers the tensile force to the anchor head on the ground. They consist of stranded cables or rods and are covered by a sheath (sleeve). The anchor head on the ground changes the tensile force of the anchor to the compressive load on the anchored structure. A bearing plate is placed in...
between the anchor head and the anchored structure. A relatively wide bearing plate distributes the compressive load and, thus, prevents stress concentration on the anchored structure. Also, various accessories, e.g., nuts and wedges of saddles, are used together for easy operation.

Soil slopes are influenced by extreme weather conditions such as freezing, thawing, heavy rains, and vibrations induced by construction processes or earthquakes. Severe deformation of slopes may cause slope failure. Thus, monitoring the condition of the slope is important to prevent disasters due to slope failure. The slope condition can be indirectly monitored by sensing the tensile force applied to the anchor because the slope deformation directly changes the tensile force of the anchor. If one identifies abnormal tensile force changes, an administration must initiate a follow-up to identify the exact reason and ensure appropriate maintenance. In addition, if the monitoring system expects a rapid slope failure, an emergency warning can be issued.

The research studies on anchor tensile force measurements have been performed using wireless force sensors [4] and fiber optic FBG (fiber Bragg grating) sensors [5,6]. In Reference [4], the wireless sensor modules were installed near each anchor, and then these electronics should be carefully protected from harsh environments. In the cases of using FBG sensors, References [5,6], these studies have difficulties on the optical fiber fabrication for embedding in the rock bolt or the anchor cable. Thus, it is required to devise more practical and reliable ways to monitor the anchor force. One possible way to monitor the tensile force of the anchor is to measure the strain field of the bearing plate and convert it to the tensile force of the anchor. Anchor force is equal to the compressive force of the anchor head, and the strain field on the bearing plate changes depending on the compression of the anchor head.

Thus, in this study, by simply attaching the sensing optical fiber on the bearing plate, we try to indirectly monitor the anchor force from the measured strain of the bearing plate. However, the strain field of the bearing plate is usually not uniform through the circumferential direction. Therefore, it is necessary to measure the strain field. Various optical fiber sensor techniques have been developing for a distributed strain field measurement, such as OFDR (optical frequency domain reflectometry) sensors using Rayleigh scattering, and BOCDA (Brillouin optical correlation domain analysis), BOTDA (Brillouin optical time domain analysis), and BOTDR (Brillouin optical time domain reflectometry) sensors using Brillouin scattering [7,8]. Among these techniques, OFDR and BOCDA sensors can achieve a spatial resolution of less than 1 m [9–11]. Our previous study [12] demonstrated that the distributed strain field can determine the anchor force. However, in this previous work, two issues were raised. One is that a temperature change affects the strain field and also the signal output of the fiber optic sensor. The other is that the strain varies depending on the measuring location. Therefore, in this time, we devise a way to exclude the temperature effect in the sensing signal and propose a way to get a representative strain value in the varying strain field. We also experimentally demonstrate that the strain measured and processed with the proposed method correlated with the applied anchor force. The rest of the manuscript is structured as follows. In Section 2, we propose a way to measure the strain field and get a representative strain value from a varying strain field. In Section 3, we explain a way for compensating temperature effects. In Section 4, we introduce an OFDR sensor system. We also explain the experimental setup in Section 5 and discuss the results in Section 6. We conclude the paper in Section 7.

2. Method for a Strain Field Measurement on the Bearing Plate

If the tensile force applies to the tendon in Figure 1, the anchor head presses the bearing plate. The bearing plate transmits the compressive load to the anchored structure. In this load transfer process, the bearing plate experiences bending deformation due to the mismatch of the loading location, as shown in Figure 1b. We numerically analyze the strain field on the anchor plate for understanding its strain distribution. We make a numerical model that an anchor plate presses an anchored structure made of concrete, as shown in Figure 2a. The anchor plate has the dimension of $200 \times 200 \times 25$ mm, and the hole diameter of 85 mm, and the material is general steel in which the elastic modulus is 200 GPa and Poisson’s ratio of 0.26. The diameter of an anchor head is 110 mm.
The anchored structure is 800 × 800 × 800 mm concrete, which has the elastic modulus of 32 GPa, and 0.1 Poisson's ratio. The bearing plate is divided as 8035 elements, and the anchored structure is modeled with 129,532 elements. The load is inflicted on the hole edge by an anchor head of a 110 mm diameter. Figure 2b represents the strain field on the top of the bearing plate in a circumferential direction. The bending deformation of the bearing plate makes a varying strain field on the top surface of the plate, i.e., high compressive strain appears near the hole at the center, and the strain decreases as it moves away from the center.

![Conceptual diagram of the ground anchor system](image1)

**Figure 1.** Conceptual diagram of the ground anchor system, (a) anchor system with the enlarged bearing plate, (b) force equilibrium of anchor system [12].

![Finite element model and angular strain distribution](image2)

**Figure 2.** (a) Finite element model and (b) angular strain distribution on the bearing plate.

We can identify that the strain variation can be minimized when the distributed optical fiber sensor is installed in a circumferential direction. In addition, the strain level is clearly distinguished depending on the radial distance from the center. Moreover, in the installation point view, this circumferential direction is the best way to install the distributed optical fiber without (or minimizing) discontinuity in a strain filling measurement.

Figure 3 compares the strains in the circumferential direction at two different radial distance, 70 mm (ø140 mm) and 90 mm (ø180 mm) in a 90° interval. It shows a minimum compressive strain at the direction pointing corner of the square plate. This is a geometry effect appearing in the square plate and may change depending on the shape of the bearing plate. However, the strain difference between the two radial distance at each angle direction is almost the same. Thus, averaging the strain measured in the circumferential direction could be a representative strain value when the sensor is installed in a circumferential direction. Moreover, the averaging of the strain field helps to minimize an
experimental error due to variations in installing the optical fiber sensor. We numerically demonstrate that the strain difference between the two radial direction changes depending on the tensile force applied to the tendon. It gives an idea to measure the tendon force indirectly by measuring the strain fields at two different radial distances.

![Angular strain distribution of the bearing plate under 10 ton anchor force](image)

**Figure 3.** Angular strain distribution of the bearing plate under 10 ton anchor force, (a) nodes of calculated strains and (b) strains due to nodes.

3. A Principle of Anchor Force Determination from the Strain of a Bearing Plate with the Rejection of Temperature Effect

The strain field on the bearing plate also changes depending on the temperature. Therefore, the strain can fluctuate depending on the monitoring time (e.g., day or night), weather conditions, and seasons. For the accurate measuring of the anchor force, we need to remove the temperature effect on the strain field. When we use a fiber optic distributed sensor, the signal output, $\Delta \omega$, is related with strain, $\Delta \epsilon$, and temperature, $\Delta T$, as in Equation (1).

$$\Delta \omega = C_\epsilon \Delta \epsilon + C_T \Delta T = C_\epsilon (\epsilon + a \Delta T) + C_T \Delta T$$

(1)

In this equation, $C_\epsilon$, is the strain coefficient and $C_T$ is the coefficient of the sensor signal change due to the refractive index of the sensing optical fiber. The proposed method mentioned in the previous section measuring strains at two different locations use the strain difference to determine the tendon force also works for excluding the temperature effect. If two sensor signals on the bearing plate are obtained (one ($\Delta \omega_a$) near the anchor head and the other ($\Delta \omega_b$) at a little distance from it) and their difference is proportional to the applied load, $\Delta F$ on the anchor, the anchor force change can be described as follows.

$$\Delta F = C(\Delta \omega_a - \Delta \omega_b) = C(C_\epsilon (\epsilon_a + a \Delta T) + C_T \Delta T - C_\epsilon (\epsilon_b + a \Delta T) - C_T \Delta T))$$

$$= CC_\epsilon (\epsilon_a - \epsilon_b) = C^* (\epsilon_a - \epsilon_b)$$

(2)

In the above equation, $\epsilon_a$ and $\epsilon_b$ are the mechanical strains at each location A and B. $a$ is the coefficient of thermal expansion and $\Delta T$ is the amount of temperature change. $C^*$ is the linear correlation coefficient between the strain difference and the anchor force change. In this equation, we observe that the thermal effects are eliminated, and only the strain change due to anchor force is considered. This works when the temperature of the whole bearing plate is the same, and there is no local constraint suppressing the thermal strain on the measuring field. To apply this equation to our study, we measure the distributed strain at two circumferential locations on the surface of the bearing plate where we can neglect the temperature variation, and we also find two strains, which are the averaged strains...
calculated from the measured distributed strains. We measure the thermal strain on top of the bearing plate and confirmed that the thermal strain is the same on the measuring field in Section 5.

4. Preparation of Fiber Optic OFDR Sensor

A fiber optic OFDR sensor, which is already fabricated from our previous work [12], is prepared in order to measure the distributed strain of the bearing plate. The schematic diagram of the fiber optic OFDR sensor is shown in Figure 4a. A tunable laser source (TLS, Agilent 8164B, Santa Clara, CA, USA) makes the light launched in a 5:95 coupler (C1). This tunable laser sweeps from 1545 to 1551 nM in which the frequency sweep range is almost 500 GHz. This sensor has two interferometers: a main interferometer and an auxiliary interferometer (AI). The auxiliary interferometer gives the light frequency spacing information during laser sweeping. A clock signal from this interferometer is generated to remove frequency tuning nonlinearity. The main interferometer is constructed by a 50:50 coupler (C2) with a local oscillator (LO) and a sensing fiber. When the light of the tunable laser source scans the sensing fiber, the Rayleigh backscattering (RBS) is generated and beat with the LO signal. This beat signal is the frequency domain data through the sensing fiber. Therefore, when this beat signal is processed by inverse Fast Fourier Transform, then the time domain data are obtained. This time domain data has the location information through the sensing fiber line. That is, a data set that divides time domain data into small segments is a bit signal at each position of the sensing optical fiber. Accordingly, by obtaining a difference in correlation between the reference data set and the data after a certain period of time, it is possible to obtain the frequency shift, which is the signal output of the fiber optic OFDR sensor due to a change in temperature or strain applied to the sensing optical fiber. A polarization beam splitter used to reject the polarization effect on the beat signal [13]. The strain measurement accuracy was already studied as less than ±2 με from our previous study [12]. This fabricated OFDR system was shown in Figure 4b.

![Figure 4. Fiber optic OFDR sensor. (a) Schematic diagram. (b) Fabricated OFDR.](image-url)
5. Experimental Setup for Thermal Strain and Anchor Tension Test

We also fabricate a bearing plate made of steel. Its dimension is 200 mm × 200 mm × 25 mm. The plate has a ø 85 mm hole at the center, as shown in Figure 5a. A sensing fiber and two electrical strain gauges (ESG) are installed on the top surface of the bearing plate to measure strain. The sensing fiber is bonded on the bearing plate in two concentric circles with diameters ø 140 mm and ø 180 mm. Two turns of fiber is bonded in each circle, and part of the fiber is used to interconnect the two circles. Two strain gauges are also installed near the circles to compare the strain measured in the optical fiber sensor.

![Figure 5. (a) Conceptual drawing of the bearing plate with a sensing fiber. (b) Experimental setup for a thermal strain measurement. (c) Anchor loading test by UTM (universal testing machine).](image)

To investigate the thermal deformation on the bearing plate strain field measured by a fiber optic OFDR sensor, a thermal chamber is prepared, as shown in Figure 5b. The bearing plate with the sensing fiber is installed in the thermal chamber. Since the bearing plate will generally be used in an atmospheric environment, it is tested by increasing the temperature from room temperature to 70°C. The signal from the optical fiber sensor is acquired while changing the temperature of the thermal chamber to cause the deformation in the bearing plate.

For the anchor tension test, a universal testing machine (UTM) is used. A box type testing jig is fabricated for loading the bearing plate with an anchor head, as shown in Figure 5c. The anchor head on the bearing plate is connected to the bottom fixing grip of the universal testing machine by a bolt through a bottom hole in the testing jig. The upper surface of the testing jig is connected to the upper grip connected with the load cell and the UTM actuator in series. When the actuator lifts up the testing jig, the bottom plate of the testing jig and the anchor head compress the bearing plate. An anchor tension test is carried out with a force of up to 10 tons while measuring the strain at 1 ton intervals. In addition, strain gauges were connected to the bridge box and collected data from the computer via a signal conditioner.

6. Test Results

Figure 6 shows the results of the temperature experiment in the thermal chamber. At each level of temperature, the thermal strain becomes almost identical for both near the anchor head (ø 140 mm circle) and the far side from the anchor head (ø 180 mm circle). In order to investigate the strain difference, the averaged thermal strain of a ø 140-mm fiber circle is calculated by the strains from 531 to 700 cm and the averaged strain of the ø 180-mm fiber circle is also calculated by using the strains from 751 to 900 cm. In Table 1, these strain differences are shown due to temperature. The strain difference slightly increase with a temperature increase. This change is due to the incompleteness of the temperature test, which does not satisfy the temperature of the bearing plate that becomes uniform. Nevertheless, the maximum value of the strain difference, 17.16 microns, is acceptable in the field.
because the anchor force, which is induced from this thermal strain difference, is small and also the
temperature difference between the current and the initial measurement is to be much less than 70 °C.
This represents that the thermal strain can be removed in the calculation of the difference between
the two strains measured at the two locations (ø 140 mm and ø 180 mm circle). Thus, we confirm
that Equation (2) is valid for applying the anchor force prediction by excluding the temperature effect,
as explained in Section 2.

Figure 6. Thermal strain distribution of the sensing optical fiber on the bearing plate.

Table 1. Difference between the averaged thermal strains at ø 140 mm and ø 180 mm on the bearing plate.

| Temperature (°C) | 25   | 40   | 50   | 60   | 70   |
|------------------|------|------|------|------|------|
| Strain at 140 mm | 210.23 | 373.18 | 477.78 | 589.25 | 707.50 |
| Strain at 180 mm | 212.76 | 378.60 | 486.37 | 603.81 | 724.66 |
| Strain difference| 2.54  | 5.41  | 8.59  | 14.56 | 17.16 |

Figure 7 shows strain distribution measured from the anchor tension test. The strain distributions
at 10 different loading steps are presented in terms of the fiber distance. From the location of 410 cm
to 607 cm, the optical fiber is wound about 4.7 turns and bonded at the ø 140 mm circle location.
The optical fiber from 620 to 810 mm is wound about 3.5 turns and bonded at the ø 180-mm circle
location. The strain valleys (maximum compressive strain) come from the direction toward the closest
point on the edge of the bearing plate, and the strain peaks (minimum compressive strain) come from
another edge of the bearing plate, similar to that in Reference [12]. Overall, the strain values at the ø
140-mm circle are larger than those at the ø 180-mm circle, and the variation in the strain distribution is
larger at the ø 180-mm circle than that of the ø 140-mm circle. This represents that the deformation,
due to the compressive force of the anchor head, increases toward the center of the bearing plate,
while the geometry effect on the strain field increases as the distance from the center increases.

After acquiring the signal output from OFDR shown in Figure 7, the average strain at the ø
140-mm circle fiber is calculated using the data between 431 and 600 cm. In addition, the average strain
at the ø 180-mm circle fiber is determined by using the data from 651 to 800 cm. These average strains
are shown with their strain differences due to anchor forces in Table 2.

Table 2. Difference between the averaged loading strains at ø 140 mm and ø 180 mm on the bearing plate.

| Temperature (°C) | 25   | 40   | 50   | 60   | 70   |
|------------------|------|------|------|------|------|
| Strain at 140 mm | 210.23 | 373.18 | 477.78 | 589.25 | 707.50 |
| Strain at 180 mm | 212.76 | 378.60 | 486.37 | 603.81 | 724.66 |
| Strain difference| 2.54  | 5.41  | 8.59  | 14.56 | 17.16 |
we use a fiber optic OFDR sensor system to measure the distributed strain on the bearing plate in order to overcome the strain variation effect on the plate. The sensor is operated through a sweeping range of a 500-GHz light frequency, and its strain accuracy is about 4 με.

After acquiring the signal output from OFDR shown in Figure 7, the strain distribution measured from the anchor tension test is presented in terms of the fiber distance. From the distributions at 10 different loading steps are presented in terms of the fiber distance. From the Figure 8 shows the difference between the averaged strain values at the ø 140-mm circle and ø 180-mm circle on the bearing plate. The strain distribution is larger at the ø 180-mm circle than that of the ø 140-mm circle. This represents the geometry effect on the strain field increases as the distance from the center increases.

The relation between anchor force and strain difference.

Figure 7. Strain distribution of the sensing optical fiber on the bearing plate.

Figure 8. The relation between anchor force and strain difference.

7. Conclusions

We propose a reliable method to correlate the bearing strain with the anchor force by excluding the effects of temperature and spatial variation of the strain field. For the experimental demonstration, we use a fiber optic OFDR sensor system to measure the distributed strain on the bearing plate in order to consider the temperature effect in Table 1, in the case of the maximum thermal strain difference, the maximum anchor force error is calculated as 1.97 ton. Since the anchor force usually has tenth of tons in a real field, this error can be acceptable.

Table 1. The standard deviation of the calculated forces using optical fiber sensors, the anchored structure, etc. The standard deviation of the calculated forces using the linear correlation coefficient between the strain difference and anchor force is 0.19 ton from the ø 180-mm circle in terms of applied anchor force using the data from Table 2. The anchor force tension can be obtained by multiply the correlation coefficient by the difference in the mean values of the strains. Thus, the anchor tension can be obtained by multiply the correlation coefficient by the difference of the average strains measured at two different radial locations on the bearing plate. Here, the correlation coefficient is 0.1146 (ton/micro-strain). This correlation coefficient depends on the bearing plate locations of the optical fiber sensors, the anchored structure, etc. The standard deviation of the calculated forces using the linear correlation coefficient between the strain difference and anchor force is 0.19 ton from the real anchor force. This value is acceptable to apply this sensor for monitoring the anchor force. If we consider the temperature effect in Table 1, in the case of the maximum thermal strain difference, the maximum anchor force error is calculated as 1.97 ton. Since the anchor force usually has tenth of tons in a real field, this error can be acceptable.

### Table 1

| Strain (micron) | Distance (cm) | Temperature (℃) |
|----------------|---------------|-----------------|
| Strain at ø 140 mm circle | 212.76 | 25 |
| | 378.60 | 40 |
| | 486.37 | 50 |
| | 603.81 | 60 |
| | 724.66 | 70 |
| Strain at ø 180 mm circle | 210.23 | 25 |
| | 373.18 | 40 |
| | 477.78 | 50 |
| | 589.25 | 60 |
| | 707.50 | 70 |

### Table 2

| Anchor Force (ton) | Strain Difference (micron) |
|--------------------|-----------------------------|
| 1                  | 2.54                        |
| 2                  | 5.41                        |
| 3                  | 8.59                        |
| 4                  | 14.56                       |
| 5                  | 17.16                       |

The correlation coefficient R² = 0.9949.
to overcome the strain variation effect on the plate. The sensor is operated through a sweeping range
of a 500-GHz light frequency, and its strain accuracy is about 4 με, respectively, when considering
the system noise when processing the signal at the condition of a 5-cm segment. In this time, we used a
fiber optic OFDR sensor, but other fiber optic-distributed sensors can also be used in this application.
We install a distributed optical fiber sensor in two concentric circles with different diameters and
measure the strain in a circumferential direction in each circle. From the temperature experiment,
there is little difference between two averaged thermal strains on the bearing plate. The maximum
thermal strain difference of 17.61 microns makes a 1.97 ton error, when the temperature difference
between the present and initial measurement time is 70 °C. We demonstrate that the difference between
the two strain values averaged in each circle excludes the temperature effect and minimizes the spatial
variation of the strain. It makes the strain difference become almost linearly proportional to the anchor
force. The standard deviation of the calculated forces using the linear correlation coefficient is only
0.19 ton. Thus, we can conclude that the proposed method is highly reliable to measure the anchor
force, and it can be applied to various anchor systems.

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