Real-time temperature compensation technique on the CPT using FBG sensor

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ABSTRACT: Since the cone penetrometer is usually made of materials with a relatively high coefficient of thermal expansion, the temperature change during the penetration causes an error in measuring the cone tip resistance. In this study, a small 7mm micro-cone penetrometer equipped with two different types of transducer are developed; conventional electrical strain gauges and the fiber Bragg grating (FBG) strain gauges with a small temperature transducer of 0.5mm diameter. The design concept includes the cone configuration, sensor installation and temperature compensation process. Application tests performed on a clay sample in the calibration chamber show that the temperature change during penetration can be effectively monitored by a FBG temperature transducer. The q_c values acquired from the conventional strain gauges and the FBG sensors show different tendencies; the former is affected by temperature change and the latter appears to be independent of the thermal variations. It is also found that q_c values measured by conventional strain gauges can be compensated through an indirect method that is consistent with those from the FBG sensor. It is verified that that FBG sensors can compensate temperature effects with high reliability.

1 INTRODUCTION

Cone penetration testing (CPT) has been acknowledged as one of the essential field test methods for soft soil characterization. The cone tip resistance, sleeve friction and pore-water pressure measured by the penetrometer are affected by temperature change because most of the penetrometer is outfitted with electrical strain gauges. Lunne et al. (1986) and Kim et al. (2009) observed from field and laboratory tests that the measurements are affected by temperature change regardless of cone size or type. To minimize the temperature effect, several standards suggest the initial baseline reading before and after the sounding (ASTM Standard D5778-95 2000, ISSMFE 1989).

The temperature change induces the shift of the base line at zero loading condition and, therefore, causes an error of cone tip resistance and sleeve friction. Despite previous studies, the temperature effect on the measurements has not been evaluated quantitatively and the test results appear to be dependent on the test condition and procedure. Lunne et al. (1986) reported the thermal zero shifts of 960kPa and 28kPa in the cone tip resistance and sleeve friction due to a temperature change of 25 ^{o}C in the laboratory test. Lunne et al. (1986) also observed the 180kPa offset in the tip resistance due to the change of 7 ^{o}C ambient temperature in the field. However, Post & Nebbeling (1995) presented the 1.3MPa cone tip resistance change caused by a temperature change of 14 ^{o}C and about 10kPa change in cone tip resistance due to the 5 ^{o}C temperature change in a data acquisition system. Buteau et al. (2005) observed the 2.5^{o}C change in the underground temperature up to 20m cone penetration in the permafrost field. However, the proper technique compensating the measurements for the continuous change in temperature could not be suggested because the uncertainty caused by the temperature change in the cone penetrometer is difficult to assess quantitatively.

In this study, the small size temperature transducer which can be installed in the micro cone penetrometer is developed by using FBG (Fiber Bragg Grating) sensor in order to assess the temperature effect on the cone tip resistance. The features of FBG sensor, temperature transducer and cone design concept, including sensor calibration, are also introduced. In addition, the temperature compensation technique by using FBG sensor is described.

2 DESIGN CONCEPT FOR TEMPERATURE COMPENSATION

FBG sensor is a kind of fiber optic sensor that has reflection band called as Bragg grating at the core. The incident light propagates through the core and the light corresponding to the specified Bragg wavelength is reflected at the Bragg grating (Lee et al. 2004). When the strain is caused by the external force or temperature change, the interval of Bragg grating is contracted or expanded. The strain or temperature change can be evaluated by analyzing the wavelength shift of the reflected light from the Bragg grating. FBG sensor is a corrosion resistant one and is free from the electromagnetic interference (Kersey et al. 1997, Zhou et al. 2003). Because of the multiplexing capability and simple measuring system, FBG sensors have been widely used to substitute for the strain gauges (Kanellopoulos et al. 1995, Gornall & Amarel 2003). In this study, FBG sensors are adopted to measure accurate strain and temperature change. The details on the FBG sensor configuration are given by Kim et al. (2009).

The temperature transducer and small size micro cone penetrometer were manufactured by using FBG sensors to correct the temperature effect during the penetration. Figure 1a shows the FBG temperature transducer used in this study. To fabricate the temperature transducer, the FBG sensor was inserted in 0.5mm diameter stainless steel tube and, then, the inner space of tube was filled up by using the cyano-acrylate based fiber optic sensor glue (CC-33A). In addition, the 7mm diameter cone penetrometer in Figure 1a is designed to measure both the electrical output voltage of strain gages and the wavelength change of FBG sensors. A couple of small strain gages with a 1.0mm sensing length and a couple of active FBG sensors are diametrically attached on the inner tube for measuring tip resistance.

Figure 1b shows the concept of real-time temperature compensation method using FBG sensors. The micro cone penetrometer consists of two active FBG sensors measuring the strain and one FBG temperature transducer, as shown in Figure 1b. The active FBG sensors measure the wavelength shift due to both the cone tip resistance and temperature change during cone penetration. At the same time, FBG temperature transducer installed in the inner tube measures the wavelength shift induced due to the temperature change around the cone penetrometer. The pure wavelength shift, $\Delta\lambda_{compensated}$, due to only cone tip resistance, therefore, can be calculated by subtracting the wavelength shift due to temperature change, $\Delta\lambda_{temp}$, from the measured total wavelength shift of the active sensors, $\Delta\lambda_{cone}$. Because of the higher resolution (100Hz) of the manufactured FBG temperature transducer, the simultaneous process of temperature compensation is possible during cone penetration. The details about real-time temperature compensation procedure are described by Kim et al. (2009).

$$\Delta\lambda_{compensated} = \Delta\lambda_{cone} - \Delta\lambda_{temp} \quad (1)$$

The FBG sensors (Technica SA), which have a range of 1520~1590nm in wavelength, and the small size electrical strain gauges (Kyowa) with 1mm gauge length were used in this study. The generation of the optical energy and the detection of the reflected wavelength were done by using an optical sensing interrogator (Micronoptics, SM130). The output voltage of strain gauge, which was amplified by a half active Wheatstone bridge with two dummy strain gauges, was measured by a digital multimeter (Agilent, 34411A). The penetration rate of the 7 mm cone penetrometer was 1mm/s, which can be considered as an undrained condition. The details about penetration rate and devices are explained in Lee et al. (2009).

3 CALIBRATION

The calibration of the temperature transducer installed in the cone penetrometer is required to compensate the cone tip resistance for the underground temperature change during cone penetration testing. The calibration was performed in the expanded polystyrene icebox which can maintain the temperature change less than 0.1 °C for 10 minutes. The temperature change was accurately monitored by using the digital thermometer with readable sensitivity 0.1 °C. Also, the measurement was compared with that of the analog thermometer.

(a) (b)

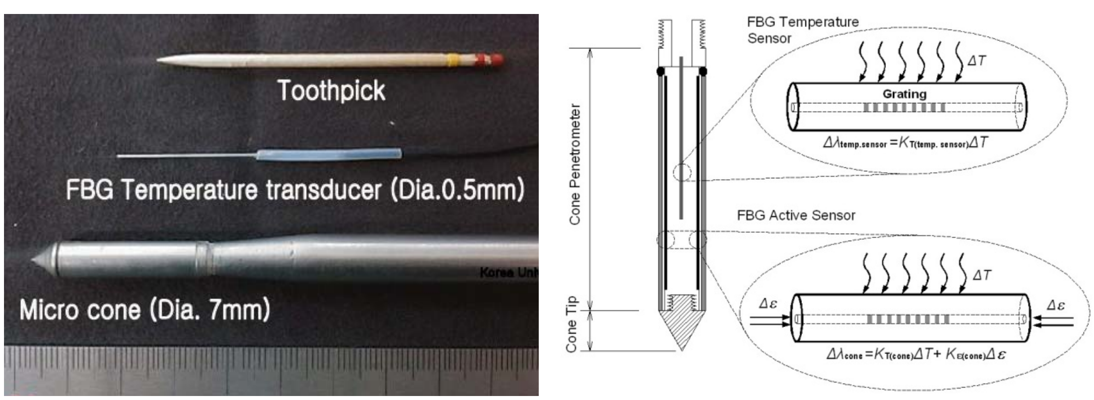

Figure 1. FBG temperature transducer: (a) FBG temperature transducer (Dia. 0.5mm) and micro cone penetrometer (Dia. 7mm); (b) Concept of the temperature compensation method using FBG sensor.

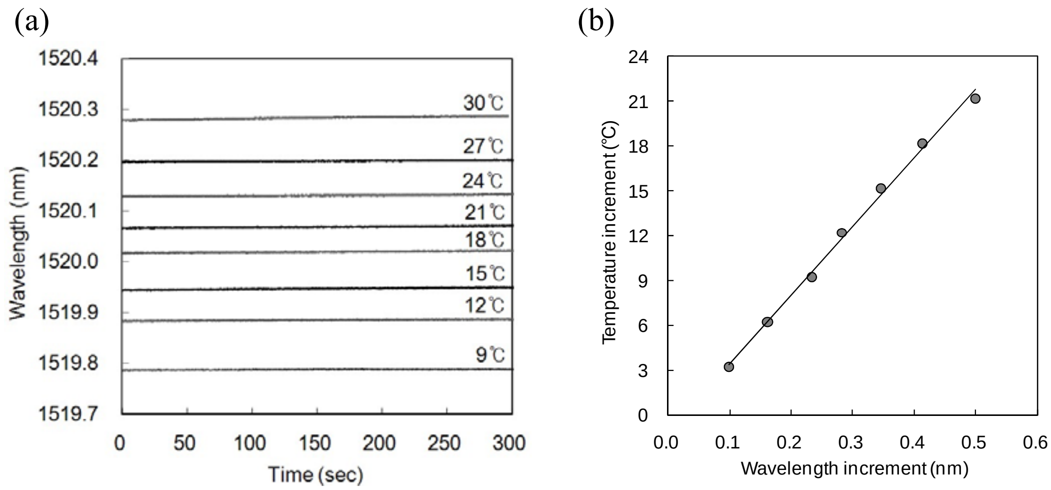

Figure 2. Calibration results of FBG temperature transducer: (a) Measured wavelength at each temperature; (b) Correlation between temperature change and wavelength shift.

FBG temperature transducer was submerged in the water filled in the icebox and, then, sealed. The wavelength shift was measured with increasing water temperature from 9 ºC to 30 ºC by stages. Figure 2a shows the constant wavelengths of FBG temperature transducer measured at each temperature. The shift of FBG wavelength is getting larger in proportion to the temperature increment, as shown in Figure 2b. The temperature change ΔT is linearly related to the wavelength shift $\Delta\lambda$ as Equation 2.

$$\Delta T = 42.7(\Delta \lambda) \quad (2)$$

4 TEMPERATURE COMPENSATION TEST

Cone penetration tests were performed in a sandy clay specimen prepared in a large calibration chamber as shown in Figure 3a. The specimen was prepared in two stages; pre-consolidation in a slurry consolidometer and K_o-consolidation in a calibration chamber. The slurry consolidometer, which consists of the upper and lower cylindrical cells of 1.2m diameter and 1.0m height, can consolidate the slurry paste by providing the pressure using a hydraulic actuator under double drainage condition. The calibration chamber, which is capable of controlling the vertical and horizontal boundary conditions, can re-consolidate the pre-consolidated specimen under desired boundary and stress conditions.

The slurry paste was prepared by mixing 50% the crushed sand (K-7) and 50% kaolin clay (GF-1250) by weight to have 82% water content using a mechanical mixing device. The basic properties of K-7 sand were: mean particle diameter D_{50}=0.17mm; maximum and minimum void ratios e_{max}=1.07 and e_{min}=0.68; coefficient of curvature C_c=0.99; coefficient of uniformity C_u=2.1; specific gravity G_s=2.65; and Unified Soil Classification System SP. The properties of kaolin clay were: liquid and plastic limits LL=67.15% and 30.75%, respectively; plasticity index 36.4%; specific gravity G_s=2.65; and Unified Soil Classification System CH. Uniformly mixed paste was filled into the slurry consolidometer up to a height of 1.6m and was consolidated for 50 days under 200kPa vertical pressure.

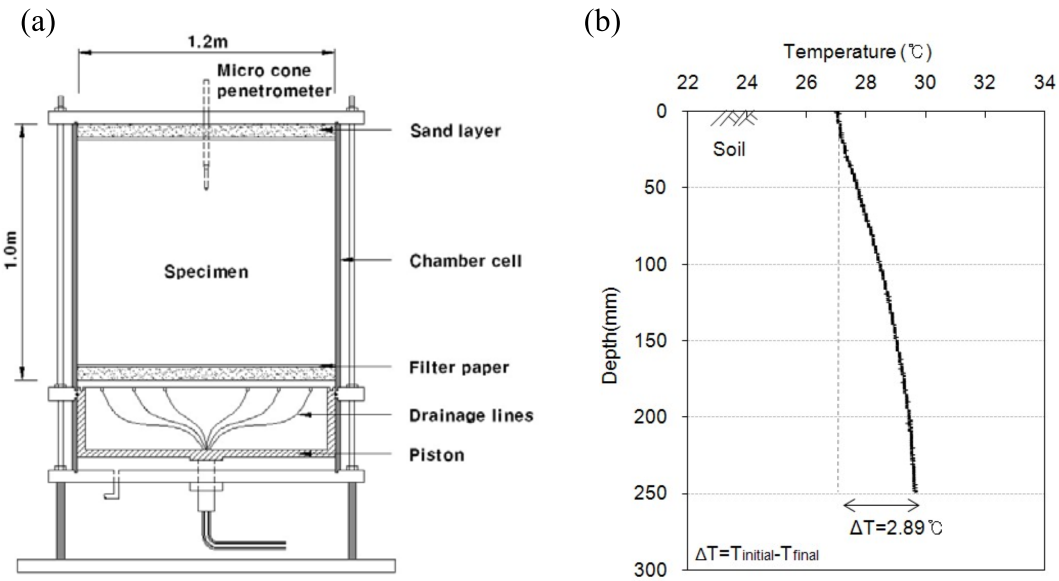

Figure 3. Preparation of cohesive soil: (a) Schematics of calibration chamber; (b) Temperature change measured by FBG temperature transducer.

When the degree of consolidation reached higher than 90%, the upper cell of consolidometer was disassembled and the extra specimen was trimmed off. The pre-consolidated specimen of 1.0m height was re-consolidated in a calibration chamber at 200kPa vertical pressure under K_o-stress condition. After the re-consolidation, a 7mm micro cone penetrometer was penetrated at a distance of 23cm from the center of the chamber cell. The initial zero reading was taken after penetrating the cone 50mm into the specimen. The cone penetration tests were performed with a 1mm/s penetration rate and the data were acquired with 10Hz resolution. Figure 3b shows the temperature change measured by FBG temperature transducer. The temperature around the cone penetrometer increases about 2.9 ^{o}C with depth.

5 TEST RESULTS

Figure 4a shows the profiles of measured cone tip resistances from strain gauge and FBG sensor with depth. The q_c value measured by the strain gauge sharply increases up to 15mm at the initial penetration and it gradually decreases with increasing depth to reach a negative value at the final depth. Since the temperature increase induces the thermal expansion of the strain gauge, the measured cone tip resistance appears as though the cone penetrometer is under tension load. However, the q_c of the FBG sensor which is directly compensated for the temperature change measured by the FBG temperature transducer based on Equation 1, shows a relatively uniform value of 320~420kPa.

In addition, a re-penetration test which was an indirect temperature compensation method was performed to measure the q_c value influenced only by the temperature. The re-penetration test was performed as followed process; firstly, performed the initial cone penetration test and measured the cone tip resistance. As soon as the initial penetration test is completed, the re-penetration test into the hollow test hole is performed to calculate the temperature effect by subtracting the data of re-penetration test from the data of initial penetration test. Figure 4b shows that the cone tip resistance of strain gauge, $q_{c(re)}$, decreases with depth even though the cone was penetrated into a hollow hole. The decrease in the cone tip resistance of strain gauge is induced due to the increased temperature of the ground. The indirectly corrected q_c of the strain gauge can be calculated by subtraction the re-penetration data, $q_{c(re)}$, from the initial penetration data, $q_{c(measured)}$.

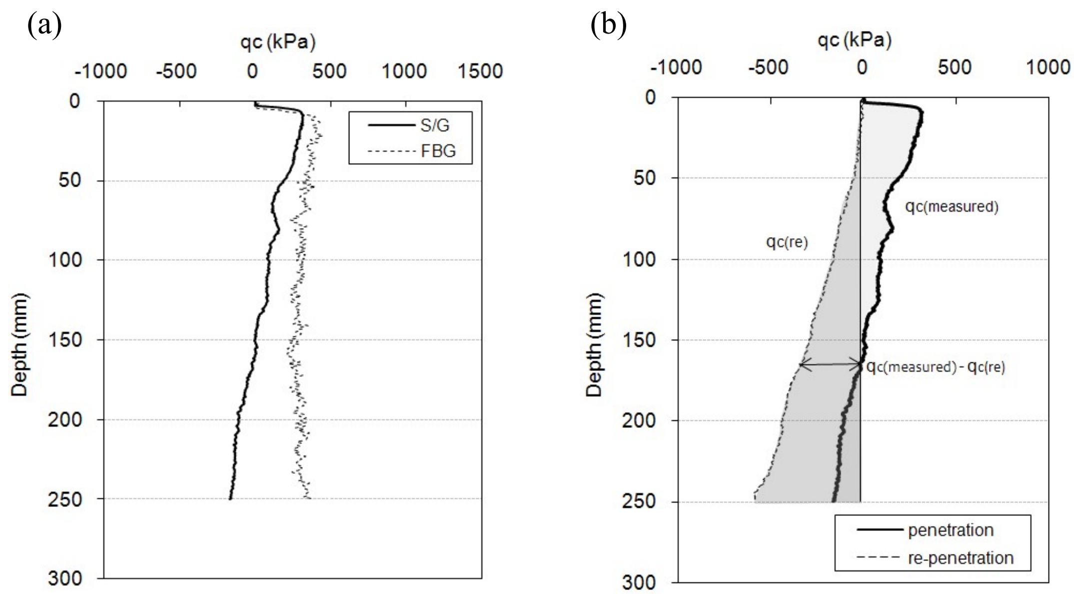

Figure 4. Temperature compensation test results on cohesive soil: (a) Cone tip resistance profile from strain gauge and FBG sensor measured by the 7mm micro cone; (b) Temperature effect of strain gauge estimated by using re-penetration test.

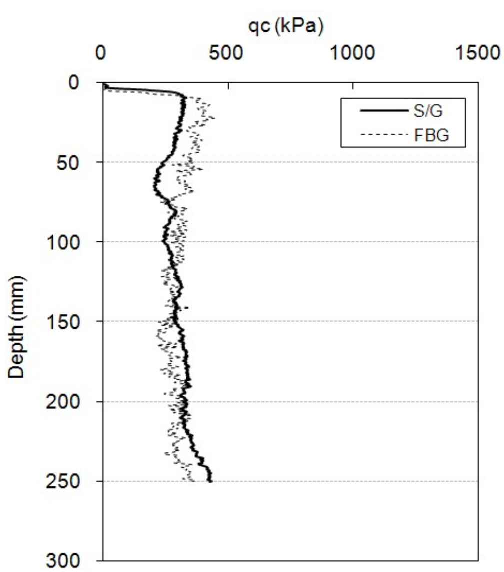

Figure 5. Comparison of the temperature compensated cone tip resistance profiles measured by strain gauge and FBG sensor.

Figure 5 shows that the indirectly compensated q_c profile by the re-penetration test is quite similar to the directly corrected q_c profile based on real-time temperature compensation technique. The compensated cone tip resistance of strain gauge showed the uniform profile with depth was a contrast to the profile of initial penetration in Figure 4a. It may be concluded from the test result that the small temperature change during the penetration test may cause a significant error on the CPT data for soft cohesive soil. In addition, the real-time temperature compensation method using FBG temperature transducer appears to be effective method to correct the effect of temperature change on the q_c measurement.

6 CONCLUSIONS

The effective temperature compensation technique was suggested and application test was performed in cohesive soil specimen prepared in calibration chamber system to evaluate the temperature effect on the CPT measurements during cone penetration. In addition, a small FBG temperature transducer of 0.5mm diameter was developed to monitor the temperature change during the penetration.

Application tests showed that the initial zero reading process recommended in several CPT test criteria could not properly correct the temperature effect because the temperature of penetrometer changes continuously during the penetration. In case of soft cohesive soil, the uncompensated cone tip resistance of strain gauges shows inappropriate cone tip resistance. However, the cone tip resistance profile that is compensated by means of real-time technique shows a uniform distribution regardless of underground temperature condition. It is concluded that there would be a significant error in the cone tip resistance unless the temperature change during the penetration is accurately measured and its effect on the measurement is properly corrected.

When cone tip resistance is compensated by using the indirect re-penetration method, the q_c profiles of strain gauge are well matched with the real-time temperature compensated results. Therefore, the suggested real-time temperature compensation method using a FBG temperature transducer can effectively compensate the effect of continuously changing underground temperature on the measurements of cone penetrometer.

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