Ground Movement Monitoring Using an Optic Fiber Bragg Grating Sensored System

Ho Yen-Te[a], Huang An-Bin[a] , Ma Jiming[b] , Zhang Baishan[c] and Cao Jingang[c]

a. Department of Civil Engineering, National Chiao Tung University, Hsin Chu, Taiwan
b. Department of Hydraulic Engineering, Tsinghua University, Beijing, China
c. Honan Province Yellow River Management Bureau, Zhengzhou, P.R. China

ABSTRACT

The authors have developed a fiber optic ground movement monitoring system using the optic Fiber Bragg Grating (FBG). A series of FBG's are glued to the outside of flexible plastic elements. These flexible elements are connected together to form a single probe. When the flexible element is bent, the FBG's sense the flexural strain as a result of the bending. Twice integration of the strains along the longitudinal axis of the probe yields the distribution of the displacement of the monitoring probe associated with the bending. The sensitivity and range of allowable bending of the monitoring probe can be adjusted according to the need in the field. The FBG based monitoring system has been experimented to measure the displacement distribution of a laterally loaded pile in Yuin-Lin, Taiwan. This paper describes the principles of the FBG sensor monitoring probe system and presents a case of field application of the sensor system.

Keyword: Fiber Bragg Grating, fiber optic sensor, ground movement

1. INTRODUCTION

S.D. Wilson of Harvard University (Green and Mickkelsen, 1988) developed the inclinometer (IP) probe in 1952. The IP is probably the most widely used technique in the detection of ground movements. An IP monitoring system consists of a plastic or aluminum inclinometer casing that is installed in a near vertical position in the ground and the IP is basically a servo-accelerometer sensor that measures the inclination of the casing. The IP system monitors the casing response to the ground movement. An electric cable is used to raise and lower the sensor unit in the casing and transmits electric signals to the ground surface. The sensor unit measures its inclination angle with respect to the true verticality.

The optic signals are immune to electro-magnetic noise. Thus, using optic fiber as a sensor can have many potential advantages. Dakin and Culshaw (1997); and Udd (1995) have reported the application of various types of fiber optic sensors in civil structures. Fuhr et al. (1991) led the way by showing it was possible to embed optical fibers within concrete. The optic fiber Bragg grating (FBG) (Hill et al., 1978; Measures et al., 1993; and Rao, 1998) is a relatively new technique in fiber optic sensors. The FBG is created by periodic variation of fiber core refractive index through exposing 10 to 30 mm segment of a single mode optic fiber to a spatial pattern of ultraviolet light. When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon interference by the FBG. The wavelength of the reflected light, or the Bragg wavelength is related to the period of the index modulation and thus longitudinal strain within the Bragg grating. The returned signal from every FBG carries a unique range or domain of wavelength, making it possible to have multiple FBG elements on the same fiber.

The development of fiber optic sensors has mostly been concentrated in structural monitoring. A technique to be referred to as the FBG Pipe Strain Gage (FBG-PSG) that followed the idea of pipe strain gage (Takada, 1965) was experimented by the authors to measure ground displacement. A series of FBG strain sensors are attached to the outside

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of a flexible pipe. This instrumented pipe is then grouted in ground.

2. THE PIPE STRAIN GAGE

Takada (1965) has reported the idea of a pipe strain gage to measure ground displacement. A series of strain gages are attached to the outside of a flexible pipe at constant intervals. This instrumented pipe is then grouted in the ground. The strain gages measure the flexural strains, ε experienced by the pipe as it is forced to deform with the ground. According to the mechanics of materials, the lateral displacement (y) relates to ε as

$$y = \frac{1}{r}\int\left(\int \varepsilon dx\right)dx + eX + f \quad (1)$$

where

r	=	outside radius of the pipe;
e, f	=	integration constants;
x	=	depth;
X	=	full length of the pipe;

In order to carry out the integration, it is necessary to assume a linear interpolation between the discrete strain measurements or use cubic Spline functions to fit the data points. Although theoretically sound, it is rather difficult to implement pipe strain gages in the field. Every strain gage demands a separate cable for power supply and signal transmission. Unless the pipe and the borehole are unusually large, the number of strain gages and thus the signal cables that can be placed underground is rather limited. The signals generated from the strain gages are subject to electro-magnetic interference and possibilities of short circuit. It is likely due to these serious drawbacks, the pipe strain gages have not been widely accepted as a primary instrument to monitor ground movements.

3. THE FBG-PSG

With its small size and the capability of multiplexing, the FBG is ideal for instruments where multiple sensors are required. If FBG instead of strain gages are used as the strain sensor then the pipe strain gage can be equipped with many strain measurement points, without the hazards of electronic/mechanical parts or bulky cables. A minimum change in Bragg wave length of approximately 1 pm (10^{-12}m) that corresponds to <1$\mu\varepsilon$ can be resolved with the currently available FBG interrogating system. The FBG readings from the interrogator are transmitted to a computer in digital form. For the case reported herein, PVC pipe segments with FBG's distributed on two opposite sides of the PVC pipe were used to make the FBG-PSG. The diameter and length of the PVC pipe segments as well as the FBG spacing can vary to accommodate the required shipping length and strain resolution of the FBG-PSG. Figure 1 shows a photograph of the FBG-PSG. The ends of the PVC pipe segments are equipped with connectors so that multiple segments can be assembled into a single, continuous monitoring tube during field installation. A support frame can be mounted on the PVC pipe at a constant spacing. The dimensions of the support frame are compatible with the inclinometer casings. The design offers an option to insert the FBG-PSG in an inclinometer casing. Or, the FBG-PSG can be grouted in a borehole without the support frame.

4. MONITORING DEFORMATION OF LATERALLY LOADED PILE BY FBG-PSG

The FBG-PSG was used to monitor the deformation of a laterally loaded pre-cast concrete pile driven in a reclaimed silty sand deposit. The load test took place within an industrial complex in Mai-Liao of Yuin-Lin County, Taiwan. A total of

60 FBG's were attached to two opposite sides of a 28 mm OD, 20m long FBG-PSG. The FBG-PSG was grouted inside of a 25 m long, 500 mm OD and 90 mm thick pre-cast, hollow concrete pile upon pile installation. An inclinometer casing was also grouted inside the pre-cast concrete pile as depicted in Figure 2. The strains according to the FBG readings taken during the lateral load test are shown in Figure 4(a). The symbols in Figure 3(a) denote the position of the FBG's attached to the PVC pipe. The corresponding lateral deformation and its comparison with the manual IP readings are demonstrated in Figure 3(b). The results showed consistent deformation distributions between FBG-PSG and inclinometer readings. The relatively smooth deformations from FBG-PSG were likely due to the fact that the deformations were obtained from integration of the strains and the strain readings were stable.

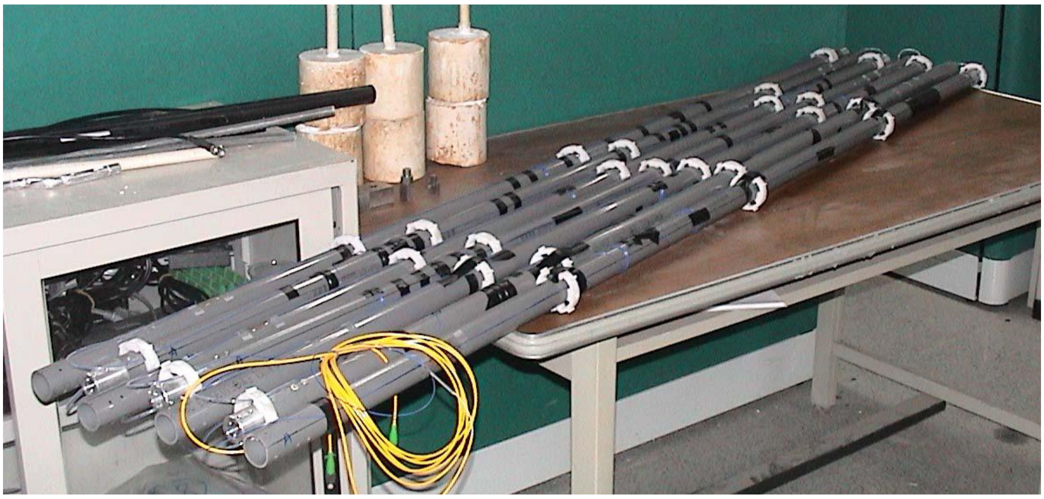

Figure 1. The FBG-PSG.

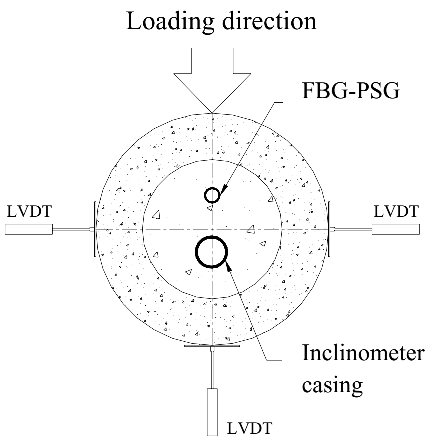

Figure 2. Positions of FBG-PSG and inclinometer casing.

5. CONCLUDING REMARKS

A ground movement monitoring technique using FBG's has been experimented. The field experiment reported in this paper have demonstrated that the FBG based monitoring technique can be practically implemented and provide adequate results. The FBG's are partially distributed sensors where a single optic fiber can carry multiple sensors. This unique capability and other advantages of the optic fiber sensors can make the FBG based ground movement monitoring system much more desirable than the conventional electronic devices.

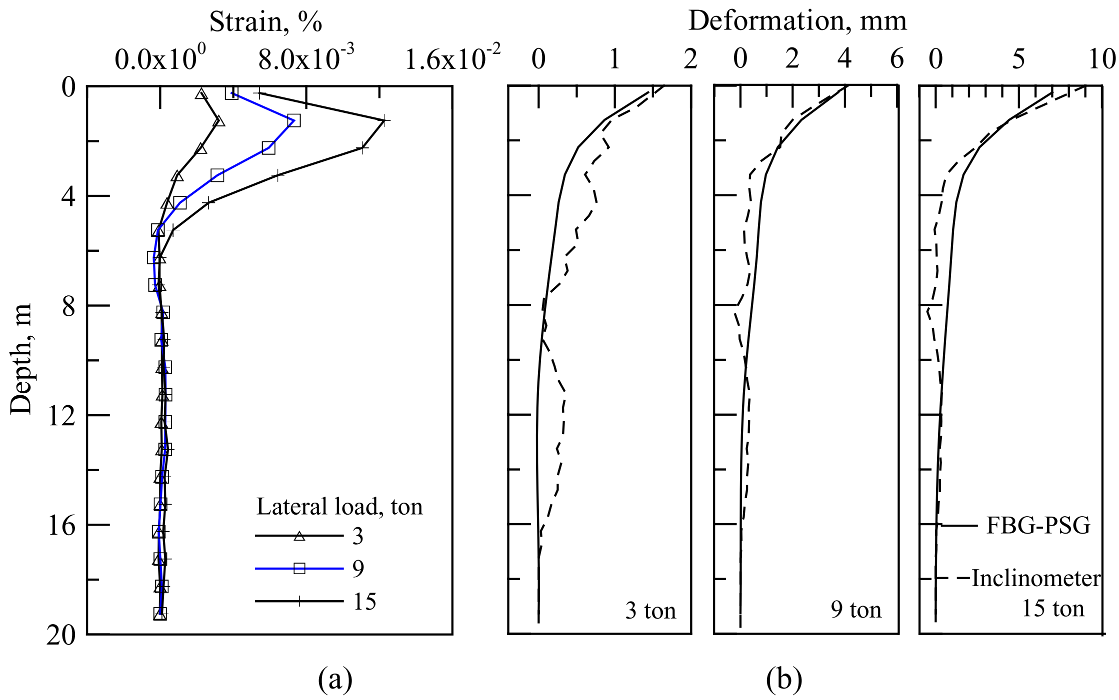

Figure 3. The FBG-PSG and inclinometer measurements.

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