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Monitoring of soil nailed slopes and dams using innovative technologies

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ABSTRACT: This paper presents (a) an integrated automatic real-time slope monitoring system using a conventional slope monitoring package and a multi-antenna Global Positioning System (GPS) package and the field monitoring results, (b) monitoring of soil nailed slopes by optical fiber strain sensors, and (c) monitoring of a model dam by optical fiber sensing bars. The authors also introduce new developments of special Fiber Bragg Grating (FBG) based sensors and potential applications for monitoring settlement profiles, vertical settlements, and lateral movement of slopes, dams, and foundations under both static and dynamic loading.

1 INTRODUCTION

70% of the land area in Hong Kong is hilly. Rain-induced landslides occurred before, having resulted in hundreds of fatalities. Landslides are still a great threat to loss of human life and property, not just in Hong Kong, but also in many other regions all over the world. Monitoring the slope movements can evaluate the stability of the slopes and give a pre-warning to people before failure. For new cut slopes, removing soil may cause settlements of adjacent buildings. Monitoring the slope and ground movements can provide valuable data whether or not the movements are excessive and endanger the buildings.

Traditional approaches using a survey methods and manually operated instruments may be used to measure settlements and lateral movements of a slope. However, these two approaches are difficult to be used for a dangerous slope since operators are at risk when working on the slope. The measurement accuracy is not satisfactory in many cases. Automatic and real-time slope monitoring is much better. This paper introduces (a) development of an integrated slope monitoring system using a conventional slope monitoring package and a multi-antenna Global Positioning System (GPS) package and the field monitoring results of a soil nailed slope, (b) monitoring of soil nailed slopes by optical fiber strain sensors, and (c) monitoring of a model dam by optical fiber sensing bars. Main monitoring results are presented and discussed.

2 AN INTEGRATED AUTOMATIC REAL-TIME SLOPE MONITORING SYSTEM AND FIELD APPLICATION

2.1 *An integrated automatic real-time slope monitoring system*

The integrated system consists of (a) an automatic conventional slope monitoring package and (b) a multi-antenna Global Positioning System (GPS) package (Yin & Ding 2004). These two packages and their integration are presented as follows.

The automatic conventional slope monitoring system consists of (a) in-place inclinometers, (b) piezometers, (c) a rain gauge and (d) a Time Domain Reflectometer (TDR). The package has a data logger, a M20T modem, a power supply and software. The data logger is a slope sentry datalogger of model 798-B-TDR Slope Sentry, which is a stand-alone datalogger for monitoring up to 10 inclinometers, up to 16 vibrating wire piezometers, a tipping bucket rain gage and up to 8 TDR cables. Its main hardware consists of a CR10X datalogger, an M20 terminal modem, an AVW4 vibrating wire interface and a PS12 power supply. The Slope Sentry provides electric power to all instruments, manages measurement schedule, records the output readings from all instruments and transfers data from the monitoring site to a computer in the office. Two external 12 volts batteries can be used to supply electric power to the Slope Sentry. An AVW4 interface is enclosed for signal transfer between a piezometer and a data logger. A CR10 X datalogger performs data recording, sensing of alarm limits and control of an alarm system. An M20 terminal modem is used to transmit data remotely. This modem allows transfer of data across a GSM900 digital cellular phone network. The M20T is a GSM digital transceiver, which is considered to be a GSM mobile telephone without a handset. The M20T has an extra interface to allow a data device to be connected and can be used to collect data from a datalogger at a speed of a land-based 9600 baud rate modem, which closely emulates a standard "Hayes style" telephone modem. Through the M20T modem and the GSM communication technology, temporarily-stored data in the datalogger can be transferred to a computer in the office. Main specifications of the M20 Terminal modern are: standard RS 232 serial port; operating temperature ranges from −29°C to +55°C.

In the conventional approach, one GPS receiver is connected to one antenna for monitoring the movement of one point only. In this newly developed GPS technology (Ding *et al.* 2002), a multi-antenna-switch is added to one GPS receiver to build up a multi-antenna GPS array, in which there are eight input ports (antenna) and one output port. After the receiver has got signal from one port, the receiver automatically switches to the next port until data from all ports are received. Since only one receiver is used instead of 10 receivers, the multi-antenna GPS is much cheaper that the standard GPS with a resulting cost saving of about 80%.

The multi-antenna GPS developed by Ding et al (2002) makes local correction by using a reference GPS receiver with one antenna on stable ground. Both the multi-antenna GPS and the reference GPS have stand alone data storage and communication devices and software. All these form a multi-antenna GPS package.

The conventional package monitors mainly the subsurface soil movements and pore water pressures while the multi-antenna GPS mainly monitors the surface movements of a slope at an array of points. The integrated system combines and enhances the advantages of the conventional sub-system and the multi-antenna GPS. Data of the subsurface movements, pore water pressures and the slip location from the conventional sub-system plus rainfall measurements are combined with the data of the three-dimensional (3-D) movements of a large number of points on the slope surface to give a complete set of data, a whole picture, and better understanding of the slope movement. The integrated system can give a more comprehensive understanding of a slope and may provide a more reliable warning before the slope starts to fail. The method of integrating the multi-antenna GPS with the conventional package is illustrated in Figure 1. A database has been developed for the integrated system data processing and display.

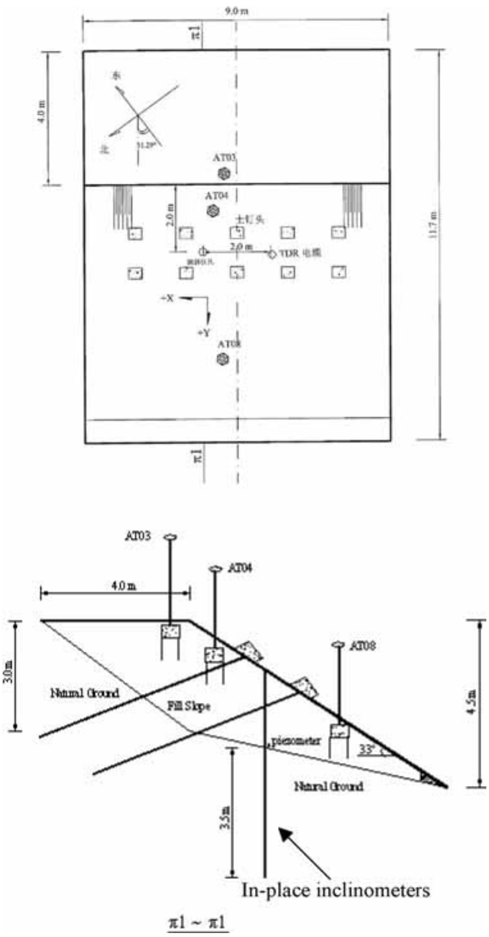

Figure 1. A soil nailed slope installed with multi-antenna GPS and conventional instruments.

2.2 *Field monitoring results of a soil nail slope*

Figure 1 shows a placement of an automatic conventional slope monitoring instruments (in-place inclinometers, etc.) and a multi-antenna Global Positioning System (GPS) package (antenna AT03, AT04 and AT08).

Figure 2 is a photo of the soil nailed slope with all instrumentation and concrete blocks on the slope crest. It shall be noted that under the loading of the concrete blocks, the slope did not slide. But, when spraying water on the slope surface, the slope was sliding and had failed. The failure model was a shallow slip mostly occurring near top part of the slope surface.

Figure 3 shows down-slope lateral movement profile with time measured using in-place inclinometers. It is seen that the lateral movements occurred above the line between the fill and the original ground. The lateral movements developed with the loading and the spraying water (simulating raining fall). Figure 4 shows down-slope lateral movement at AT03 measured using GPS. AT03 was located on the slope surface closed to the slope crest. The data from AT03 indicated an accelerated lateral movement after water was sprayed on the slope surface.

Figure 2. A view of the instrumented soil nailed slope site.

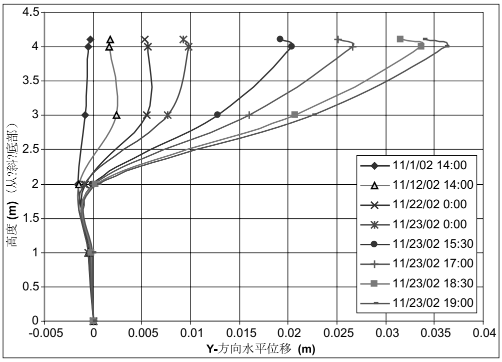

Figure 3. Down-slope lateral movement profile with time measured using in-place inclinometers.

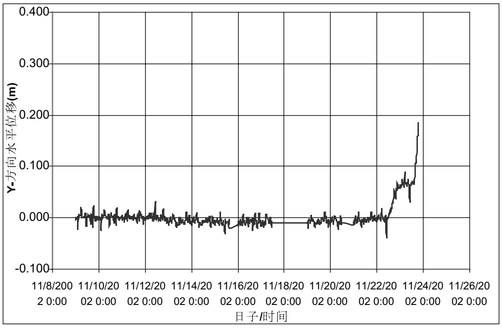

Figure 4. Down-slope lateral movement at AT03 measured using GPS.

3 MONITORING OF SOIL NAILED SLOPES BY OPTICAL FIBER STRAIN SENSORS

3.1 *Working principal*

Fiber Bragg Grating (FBG) is one of the most popular optical fiber sensing technology. An FBG is written into a segment of Ge-doped single-mode fiber in which a periodic modulation of the core refractive index is formed by exposure to a spatial pattern of ultraviolet (UV) light. According to Bragg's law, when a broadband source of light has been injected into the fiber, FBG reflects a narrow spectral part of light at certain wavelength, which is called the Bragg wavelength and dependent on the grating period and the refractive index of fibre:

$$\lambda_B = 2n\Lambda \tag{1}$$

where λ_B is the Bragg wavelength, typically 1510 to 1590 nm, n is the effective core index of refraction and Λ is the period of the index modulation. Considering a standard single mode silica fiber, the relationship between the Bragg wavelength and strain of the sensing fiber can be simplified as follow:

$$\varepsilon = \frac{\Delta\lambda}{c\lambda_0} \tag{2}$$

where c is a constant, for germanium-doped silica fiber, $c \approx 0.78$; λ_0 is the Bragg wavelength of the grating under strain-free condition. Using Equation (2), the strain can be determined if the wavelength change $\Delta\lambda$ is measured by interrogators. The measurement resolution can as high as 1 $\mu\varepsilon$.

Comparing to electrical resistance strain gauge, this optical fiber sensing technology has apparent advantages: immunity to electromagnetic interference and power fluctuation along the optical path, insensitivity to corrosion and fatigue, high precision, durability, absolute measurement, tiny size, reduced cable requirement and so on. By their multiplexible nature, hundreds of FBG sensors can be connected on a single fiber and easily integrated within a structural element without a serious negative influence on the mechanical properties.

Two types of special FBG strain sensors with special protection measures are developed, calibrated and used in lab and the field for measuring strains in soil nails. One is surface adhered bare FBG sensors; the other is average FBG sensors with bare FBGs packaged inside an aluminum tube. These two types of FBG sensors were installed on Fiber Reinforced Polymer (FRP) tube soil nails and steel bar soil nails on site and used to monitor the distribution of strain along soil nails during pull-out tests. The reliability of FBG strain sensor and protection methods are verified by lab and field tests.

3.2 *Fielding monitoring results*

The special FBG sensors were installed on soil nails at two sites in Hong Kong (Fig. 5) (Yin et al. 2007a, b). The first site was in Lantau Island of Hong Kong. Four FRP soil nails were installed into a man-made slope (Slope Registration No.10SW-C/C237) at this site for testing. All have the same dimensions: an outer diameter of 55 mm, an inner diameter of 37 mm and length of 3.6 m. The grouted nail has a diameter of 120 mm. Soil nails No.1, No.2 and No.4 in depth 1 m to 2 m were grouted using pressure grout (about 1.5 MPa). Another site was in Sha Tau Kok, New Territories, Hong Kong (Slope Registration No. 3 NW-D/C 214). The soil nail steel bars were 40 mm in diameter and approximately 6.6 m to 7.5 m long. But the grouted length was all 2 m only and the grouted diameter of 150 mm.

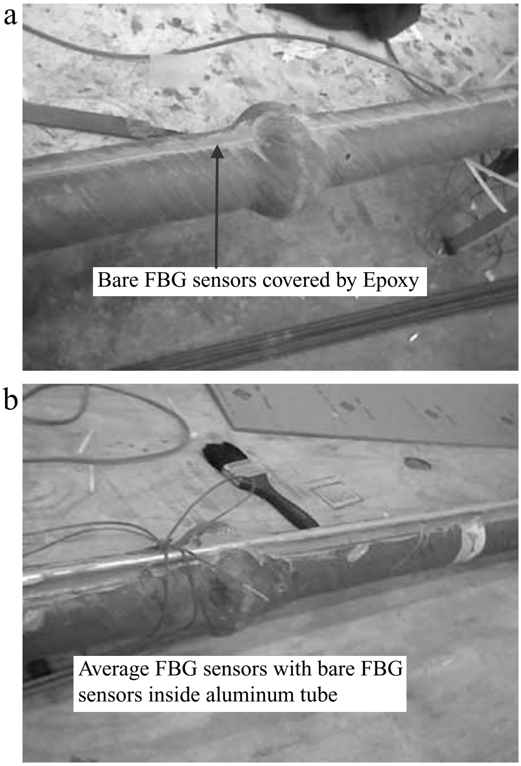

Figure 5. (a) Bare FBG sensors adhered on and covered/protected by epoxy resin and (b) average FBG sensors with bare FBGs inside an aluminum tube.

Soil nail pullout tests were carried out as shown in Figure 6. All data were collected in real-time. Figure 7 shows a comparison of axial strains along the FRP soil nail measured from electrical strain gauges, bare FBG (FBG-A) and the average FBG (FBG-B) at load of 100 kN at the site of Lantau Island of Hong Kong. It is seen that the strains from the three types of sensors are in good agreement.

Figure 8 shows typical nail pull-out test results at the site of Sha Tau Kok of Hong Kong—a comparison of axial strains along a steel soil nail from electrical strain gauges and bare FBG at load of 10 kN, 24 kN, 48 kN and 100 kN. It is seen again that the strains from the two types of sensors are similar (Yin et al. 2007a, b).

It is obvious that if FBG sensors of adequate quantity are installed to the total length of soil nails and in perpendicular direction, the distribution of shear force and bending moment can be calculated, as well as strain and axial force. Based on it, a better understanding of distribution of deformation and soil-nail

Figure 6. Field pullout test on soil nail with optical fiber strain sensors and electrical strain gauges.

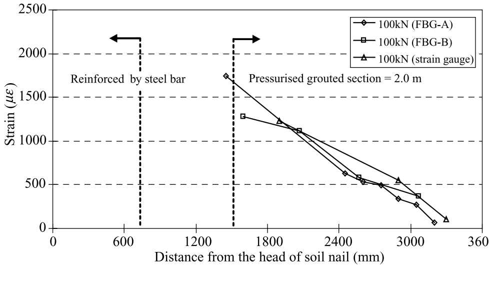

Figure 7. Typical nail pull-out test results at the site of Lantau Island of Hong Kong—comparison of axial strains along the FRP soil nail from electrical strain gauges, bare FBG (FBG-A) and the average FBG (FBG-B) at load of 100 kN.

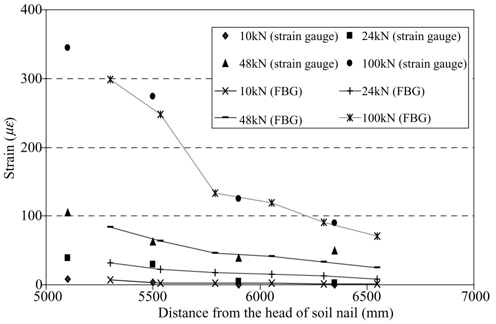

Figure 8. Typical nail pull-out test results at the site of Sha Tau Kok of Hong Kong—comparison of axial strains along a steel soil nail from electric strain gauges and bare FBG at load of 10 kN, 24 kN, 48 kN and 100 kN.

skin friction can be achieved. Meanwhile, this monitoring method also allows the determination of Young's modulus of the grouted soil nail and the occurrence of cracks, which control the quality of installed soil nail. Further work will be done to study the short-term and long-term performance of soil nails using FBG strain sensors.

4 MONITORING OF A MODEL DAM BY OPTICAL FIBER SENSING BARS

Suchuan University in China has conducted a lot of two and three-dimensional (2-D and 3-D) physical model tests on dams in laboratory. Currently in these tests, one of the difficulties is how to measure the displacements inside a 3-D model dam and dam foundation and ground next to the dam. To solve this problem, the authors have designed and made special optical fiber sensing bars for monitoring profiles of displacements, for example, lateral movement inside the dam. To verify these sensors, a 2-D dam model was constructed as shown in the top photo in Figure 9.

In this 2-D model dam, one FBG sensing bar was installed in the model dam (0.5 m height) from the top of the dam to the bottom of the same. Another sensing bar was installed in the dam foundation behind the dam (downstream). As a comparison, conventional LVDTs and strain gauges were installed at points close to the sensing bars as shown in the photo in Figure 9. The horizontal load was applied as ratio to the water pressure load. All data were recorded in real-time by interrogators and data-loggers. Figure 9 (bottom part) shows the lateral displacement profile of the dam under different horizontal loads. The largest lateral displacement occurs at the top of the dam. It shall be pointed out that these lateral displacements are relative to the bottom of the dam. The data measured using the FBG sensing bars are compared to those from LVDTs and are found to be in good agreement. Details will be published in a journal paper.

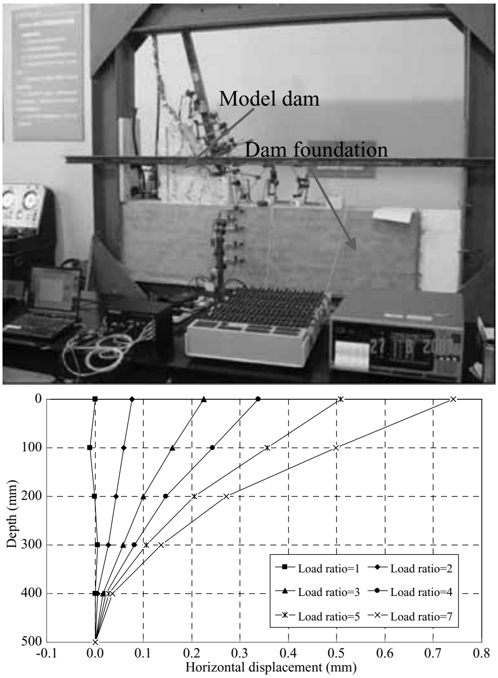

Figure 9. The model dam and foundation (top) with optical fiber sensing bars and conventional LVDTS and the later movement profiles of the dam (0.5 m height) under different loadings (bottom).

5 DEVELOPMENT OF SPECIAL FBG BASED SENSORS FOR OTHER GEOTECHNICAL APPLICATIONS

Currently at The Hong Kong Polytechnic University, new developments have been made to make special sensors for other geotechnical applications. A summary of these new developments are as follows.

5.1 *FBG Sensor tubes for measuring vertical settlements in a drill hole*

These sensor tubes are connected in a series. This series is placed in a drill hole with proper backfill. These sensor tubes can measure the vertical compression for each 1 m (or other predefined length) vertical layer. The Bragg wavelength data automatically recorded by interrogators are used to calculate the compression of each 1 m soil layer and the total settlement.

5.2 *FBG sensor tubes for measuring vertical settlement profile*

Sensor tubes with the FBG sensors connected in series have been developed for measuring vertical profile. These tubes are placed in the soil ground horizontally. Under foundation loading, these tubes will have deflection like a beam. The strains in the tubes are measured and converted to deflection of the beam. The deflection profile is in fact the vertical settlement profile. Two such sensor tubes have been successfully installed underneath a mat foundation in Hong Kong. Monitoring data have been collected periodically since Feb 2007.

5.3 *FBG sensor tubes for measuring lateral displacement of slopes under static and dynamic loading*

Similar to those in (b), sensor tubes with the FBG sensors connected in series have been developed for measuring lateral movements of a slope under static and dynamic loading. The sensor tubes can measure the lateral movements in two horizontal directions and vertical direction.

The most advanced FBG interrogators can have a scan frequency of 1 kHz and wavelength repeatability of 1 pm. Thus accurate static and dynamic monitoring is feasible.

In addition to the above developments, other special sensors can be developed for special applications, for example, measuring cracks, temperature, inclination, pore water pressures, earth pressures etc.

6 CONCLUSIONS

Based on the above presentation, the following conclusions may be drawn.

a. The integrated automatic real-time slope monitoring system using a conventional slope monitoring package and a multi-antenna Global Positioning System (GPS) package takes the advantages of both the conventional instruments and the GPS and is suitable for real-time slope monitoring. The measurements can detect the slope lateral movement profile and the absolute displacements on slope surface. The data have indicated an accelerated movement before sliding.

b. The optical fiber strain sensors are accurate and reliable for monitoring soil nailed slopes. The data from FBG sensors are in good agreement with those from electrical strain gauges. These measured data can be used to determine the extension of the nail, the friction on the nail surface, and the failure of the nails.

c. Special optical fiber sensing bars have been used successfully for monitoring displacements of a model dam (and dam foundation as well). The results can be used to analyze the dam performance under loading.

d. New developments based on FBG sensors have been made to measure settlement profiles along a horizontal line, vertical settlements in a drill hole, and relative lateral movements of slopes and dams under both static and dynamic loading. Special sensors can be manufactured and applied for special geotechnical applications in The Hong Kong Polytechnic University.

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