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MONITORING SOIL NAILED SLOPES USING BOTH CONVENTIONAL AND ADVANCED SENSORS

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Abstract

Slope monitoring is important for verifying design assumption, checking construction quality, and giving a possible pre-warning before failure. This paper introduces briefly the development and application of two approaches to slope monitoring soil nailed slopes using both conventional and advanced sensors. One approach is using an integrated automatic slope monitoring system to monitor a soil nailed slope movements in Hong Kong. The system consists of an automatic conventional slope monitoring package and a multi-antenna Global Positioning System (GPS) package. The second approach is using both electrical strain gauges and optical fibre sensors for soil nails. Type results from calibration tests and field monitoring tests are presented and discussed.

INTRODUCTION

There are numerous man-made slopes in Hong Kong. Many of these slopes are unstable, especially those constructed in the 1970's. The Hong Kong Government has spent billions of dollars in slope safety and landslide reduction work. The most commonly used technology for slope stabilisation in Hong Kong is soil nailing since more than 90% of the slopes are stabilized using soil nails. For slopes, no matter soil nailed or non-nailed, monitoring the movements of the slopes and soil nails is important since the data can be used to evaluate the stability of the slopes, quality of the soils nails and to give a pre-warning to people before failure.

Traditional manual survey methods may be used to measure the movements of a slope surface. In addition, a manually operated inclinometer may be used to measure the lateral movements of a slope. However, the two methods are difficult to use on a dangerous slope since operators are at risk when working on the slope. In this case, an automatic slope monitoring technique is used. In the past, automatic monitoring techniques, for example, using in-place inclinometers, have been developed for slope monitoring. In-place inclinometers can measure relative lateral slope movements accurately (referring to the bottom in-place inclinometer). But the cost of the measurement is high. In Hong Kong, a few trials were done on automatic monitoring of slope movements using in-place inclinometers. However this technique has not been widely used due to the high cost.

This paper introduces briefly (a) an integrated slope monitoring system which combines (i) an automatic conventional slope monitoring package and (ii) a multi-antenna Global Positioning System (GPS) package; and (b) combination of electrical strain gauges and optical fiber sensors and comparison of results. To verify the reliability and effectiveness of the two approaches in practical applications, the two systems were installed two soil nailed slopes in Hong Kong. The main monitoring results and the evaluation of the two systems are presented and discussed here.

AN INTEGRATED SLOPE MONITORING SYSTEM AND APPLICATION TO MONITORE A SOIL NAILED FILLED SLOPE

An Integrated 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. The 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 datalogger, a M20T modem, a power supply and software.

In the 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 a signal from one port, the receiver automatically switches to the next port until data from all ports are received. The one receiver in the multi-antenna GPS works in the same way as that of a standard GPS. Since only one receiver is used instead of 10 receivers, the multi-antenna GPS is much less expensive than 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.

Integration of the conventional package and the multi-antenna GPS package is briefly discussed here. The conventional package monitors mainly the sub-surface 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 give a more reliable warning before the slope starts to fail. A MONITORDATA database has been developed for the integrated system data processing and display.

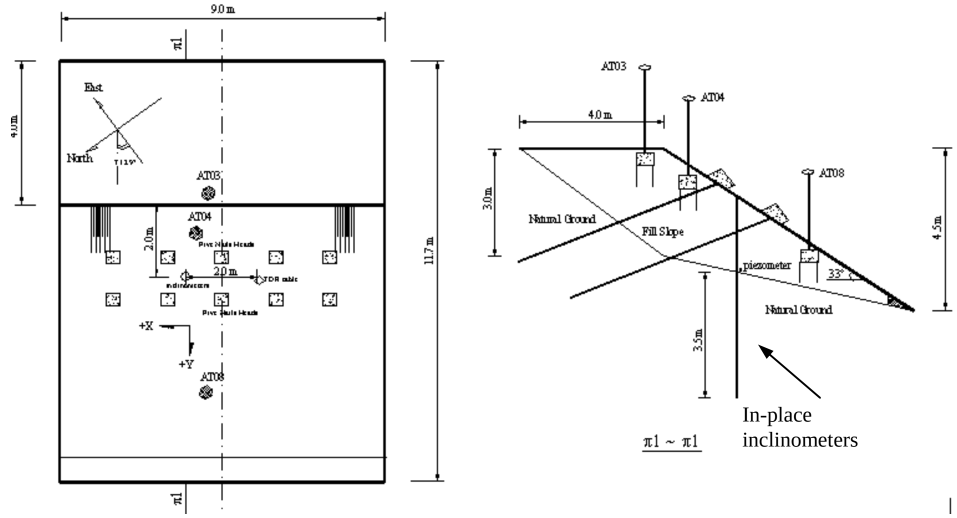

Figure 1. Dimensions of a soil nailed loose fill slope and location of instruments

Installation and Monitoring

The above integrated slope monitoring system was installed at a soil nailed, loose fill slope test site in the Kadoorie Agricultural Research Centre of the University of Hong Kong (HKU) in Yuen Long, Hong Kong (see Figures 1 and 2). The natural ground below the test slope had a slope angle of 15^o. The CDG loose fill slope has a slope angle of 33°. In plan view, the slope area was 9.0m (width)×11.7m (length) with a maximum height of 4.5m. Two rows of soil nails were installed. There was a platform of 3m ×9.0m at the slope crest. Precast concrete blocks were used as surcharge acting on the crest platform. The concrete blocks were placed gradually. Ground water table was also raised by water inflow from small pipes directly buried under the slope crest and spreading water on the slope surface as artificial rain using sprinklers.   All these were to cause the fill slope to fail under a controlled condition.

Figure 2. Photo of the slope and instruments

As shown in Figure~~s~~ 2, at the slope site, five in-place inclinometers were installed in one vertical borehole of 6.3m in depth into the natural ground beneath the test slope. One piezometer was directly buried at the interface between the CDG fill and the natural ground next to the inclinometer boreholes. An array of three steel poles (AT03, AT04, AT08) were installed on the sloping surface. The top of each pole supported one GPS antenna. One additional pole was installed on a stable ground 20m from the slope for a reference GPS antenna. All the Slope Sentry, GPS receivers, switch box and other instruments were put in a small shed close to the monitoring site (Yin et al. 2004).

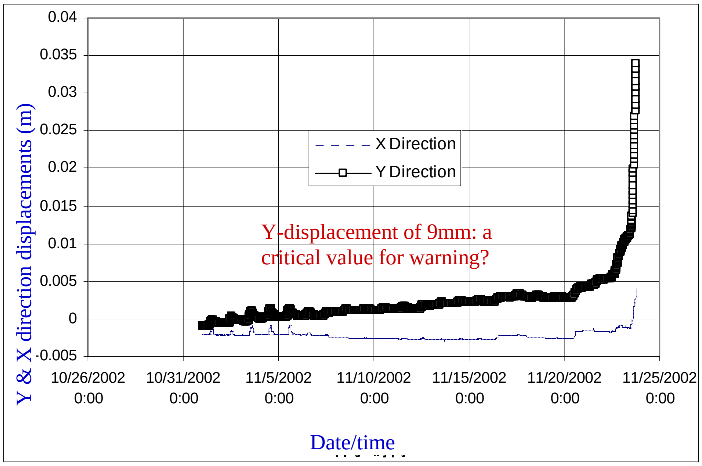

Figure 3. Y & X direction displacements - time at the in-place inclinometer casing top point on the slope surface (+Y: down slope) (in-place inclinometer measurement)

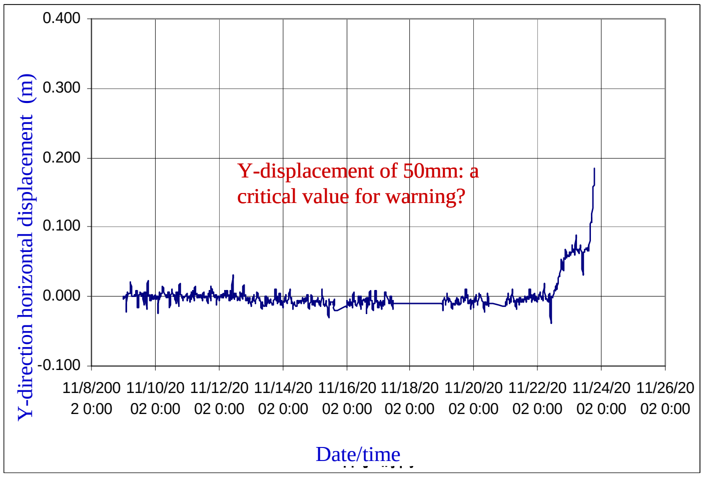

Figure 4. AT03 Y-direction horizontal displacement (+Y: down slope) (GPS measurement)

Main Monitoring Results

The loose fill slope testing (spreading water, placing concrete blocks on the slope crest, etc.) started August 2002 and ended at 7:00pm, local time, on 23 November 2002, for almost four months. The main results are presented in Figures 3 and 4. The lateral displacement profiles with time are obtained from the five in-place inclinometers in on vertical casing as shown in Figures 2 and 3. Figure 3 presents the curves of Y & X direction displacements with time at the top point (on the slope surface) of the in-place inclinometer casing. It is noted that the positive Y-direction (+Y) is the down slope direction. From Figure 4, the +Y-direction horizontal displacement increases with time. The rate of displacement is accelerated at displacement of 9mm. The maximum +Y-displacement is 34mm at failure. Figure 4 shows the curve of Y-direction displacement with time at GPS point AT03 (on the slope crest. From Figure 4, the +Y-direction horizontal displacement increases with time. The rate of displacement is accelerated at displacement of 50mm. The maximum +Y-displacement is 180 mm at failure. Both the in-place inclinometers and the GPS AT03 have indicated that the horizontal displacement has an acceleration rate before failure. This value may be considered to be a critical value for landslide warning. It is noted that the critical displacement and the maximum displacement at failure may be different at different points.

MONITROIG SOIL NAILS USING ELECTRICAL STRAIN GAUGES AND OPTICAL FIBER SENSORS

FBG Optical Fiber Sensors

Fiber Bragg Grating (FBG) sensors with special protection measures are developed, calibrated and used in lab and the field for measuring strains in soil nails. Considering a standard single mode silica fiber, the relationship between Bragg wavelength change $\Delta\lambda$ and strain ε of the sensing fiber can be simplified as follow :

$$\frac{\Delta\lambda}{\lambda_0} = c\varepsilon \qquad (2)$$

$$\varepsilon = \frac{\Delta\lambda}{c\lambda_0} \qquad (3)$$

where c is a constant, for germanium-doped silica fiber c=0.78; λ_0 is the Bragg wavelength of the grating under strain-free condition. The functional principle of FBG sensor system is schematized in Figure 1. Using Equation (2) or (3), the strain can be determined if the wavelength change is measured.

Figure 5. Bare FBG sensors adhered on and covered/ protected by epoxy resin

Installation and Field Soil Nail Pull-Out Tests

Bare FBG sensors were adhered on and covered/ protected by epoxy resin (see Figure 5). The special FBG sensors were installed on soil nails at two sites in Hong Kong. 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 55mm, an inner diameter of 37mm and length of 3.6m. 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) (see Figures 5 and 6). Another site was in Sha Tau Kok, New Territories, Hong Kong. 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

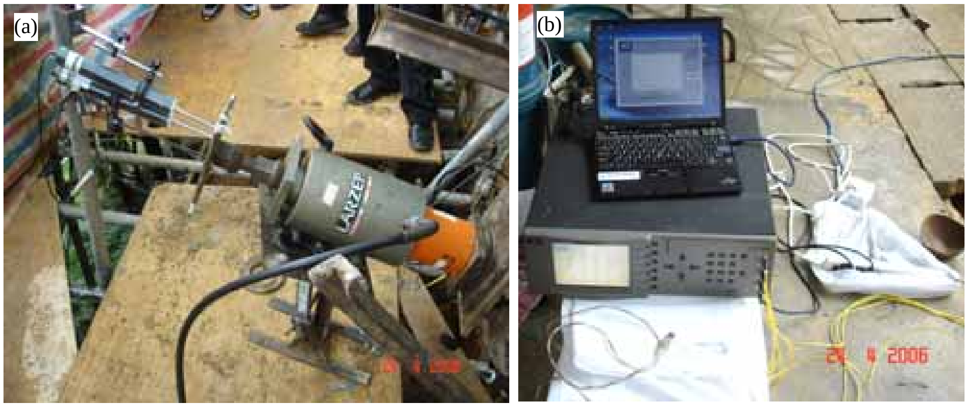

Figure 6. Soil nail pull-out test in Lantau Island of Hong Kong – (a) the pull-out setup and (b) the Micron Optics SI 425 Swept Laser Interrogator

Monitoring Results and Comparison

Typical soil nail pull-out test results from the two sites are presented in this section. Figure 7 show a comparison of axial strains along the FRP soil nail from electric 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 electric 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 in good agreement. It is obvious that if FBG sensors of adequate quantity are installed to the total length of soil nail 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 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 nail using FBG strain sensors.

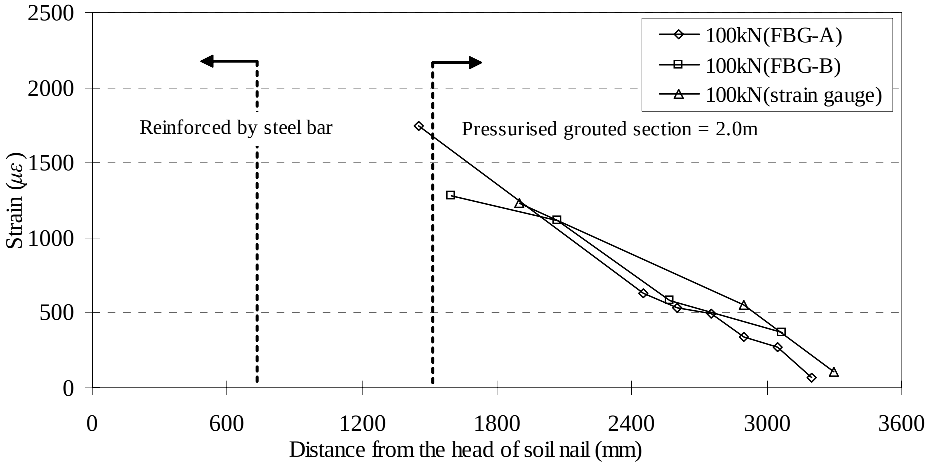

Figure 7. Typical nail pull-out test results at the site of Lantau Island of Hong Kong – comparison of axial strains along the FRP soil nail from electric strain gauges, bare FBG (FBG-A) and the average FBG (FBG-B) at load of 100 kN

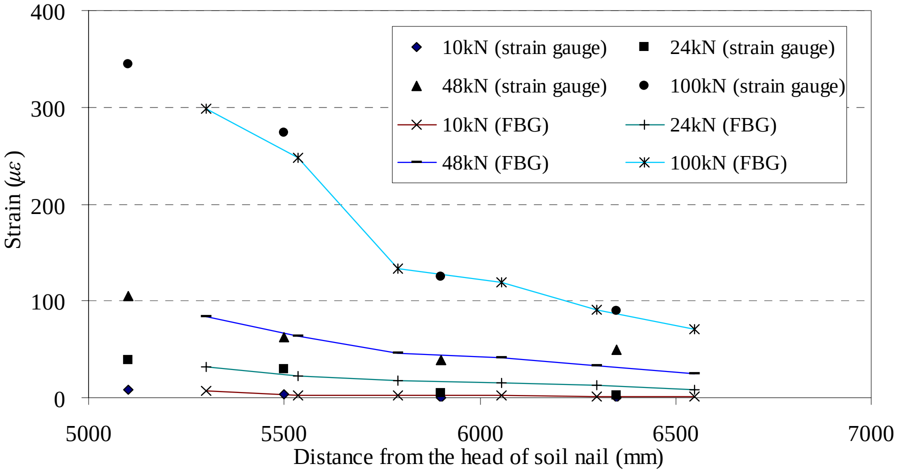

Figure 8. Typical nail pull-out test results at the site of Sha Tau Kok of Hong Kong

CONCLUSIONS

Regarding the integrated slope monitoring system and main monitoring results, it is found that (i) the integrated system take advantages of the conventional slope monitoring instruments and the GPS measurements and avoiding the short-comings of the two packages. The integrated system is more cost-effective for slope monitoring; (ii) the integrated system is reliable and accurate enough for slope morning and (iii) the down slope horizontal displacements were accelerated at certain critical values before failure.

Regarding the optical fiber sensors, it is found that FBG sensors are reliable for short-term and long-term strain monitoring and especially suitable for geotechnical structures such as soil nail and pile due to its natural characteristics. Protection methods in this paper are proved to be good to ensure both fiber protection and efficient strain transfer in both lab tests and in-situ tests.

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REFERENCES

1. Ding, X.L., D.F. Huang, J.H. Yin, Y.Q. Chen, C.K. Lau, Y.W. Yang, Y.R. Sun and W. Chen (2002). A new generation of multi-antenna GPS system for landslide and structural deformation monitoring. Proceedings of Advanced Building Technology 2002 (ABT2002), 4-6 Dec 2002, Hong Kong. In "Advances in Building Technology" (edited by M. Anson, J.M. KO, and E.S.S. Lam) by Elsevier, pp.1611-1618.
2. Yin, J-H., Ding, X.L., Yang, Y.W., Lau, C.K., Huang, D.F., Chen, Y.Q. (2004). Integration of conventional instruments and global positioning system for automatic monitoring of slopes. Chinese Journal of Rock Mechanics and Engineering (Chinese), Vol.23, No.3, pp.357-364.