Research Article

Slope Stability Analysis Based on Measured Strains along Soil Nails Using FBG Sensing Technology

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In the past few decades, slope stability analysis using numerical methods is becoming a hot issue, but it is based on extremely ideal assumptions. Soil nailing technique, as one of the most cost-effective reinforcing methods, has already been widely used for reinforcing slopes. In this study, to evaluate the safety factor of a slope, the strains on soil nails were measured by fiber Bragg grating (FBG) sensor. Strains along soil nails in the same cross section of a slope can be computed using the measured wavelength shifts of FBG sensors. In order to evaluate the stability of a slope, an optimal model was proposed to search the potential slip surfaces based on measured strain values. Maximum sum of strains on soil nails at different elevations of the same cross section was taken as the objective. Positions of soil nails, circular slip surface, and boundary conditions of the soil nails were summarized and taken as constraints. Finally, safety factors can be computed using the searched slip surface regarding the axial stress of soil nails. This method combines the limit equilibrium methods with measured axial strains on site which can reflect the actual condition of field slopes.

1. Introduction

Soil nailing technique firstly appeared in France [1, 2]. For ease of construction and some other potential benefits, soil nailing has been proven to be a practical technique for slope reinforcement [3, 4]. It is currently one of the predominant methods for slope reinforcement in Hong Kong. However, it is difficult to evaluate the working state of an in-service soil nail in a slope. In this case, measurement of the strain and stress is becoming essential in order to investigate the performance of in-service soil nails in the process of stress redistribution in slopes.

Structural health monitoring is becoming a hot issue for supplying prosperous parameters to evaluate the safety of in-service structures [5–9]. However, there are several inherent disadvantages of conventional strain sensors in monitoring strains along soil nails [10–12] including poor long-term stability, low accuracy, too many cables needed for multipoint measurement, and electromagnetic interference. In general,

the soil nail diameter is relatively small ranging from 100 mm to 250 mm. If we use conventional strain sensors to monitor a number of locations along the nail, say, 10 to 20, then many electrical cables are needed which will fill most of the hole space and thus affect the integrity of the soil nail. Fiber Bragg grating (FBG) is a relatively new optical fiber sensing technology [13, 14]. Wavelength shifts of FBG sensors vary linearly with both environmental temperature and strain changes. FBG sensors have a number of advantages, such as [15, 16]

- (i) immunity to electromagnetic interference (EMI) which guarantees quality signals and data;
- (ii) long-term stability (since measurement is based on the light wavelength changes) which makes the sensors suitable for long-term monitoring, say, 50 to 100 years in principle;
- (iii) excellent accuracy (up to 1×10^{-6} strain) which makes our measurement more accurate;

- (iv) high resistance to corrosion (since the core fiber is silica) which makes the sensors last for a long time in corrosive environments;
- (v) multiplexing for FBG sensors which can measure strains and temperatures (or other parameters specially designed transducers based on the technologies) at multipoints or full distribution along one fiber line;
- (vi) tiny size of the sensors which can be used to measure the parameters of a very small region (local strains, cracks, displacements, etc.);
- (vii) long-distance sensing which can measure over a large area or from a far distance.

For slope stability analysis, two-dimensional (2D) plane strain method is generally employed for simplicity. Based on the simplified method, the limit equilibrium method (LEM) is proposed as the most popular calculation method, which is well known to be a statically indeterminate problem and assumptions on the internal force distribution on each slice are required for the solution of the factor of safety (FOS) [17–19]. The calculus of variational approach by Baker and Garber [20] does not require the assumption on the internal force distribution, but it is quite difficult to get a solution. Besides, limit analysis methods based on the upper-bound and lower-bound theorems have also been developed but used to solve simplified problems [21–24]. However, its applications in complicated site conditions are still limited and are not widely adopted by design engineers.

In this paper, the authors developed an innovative soil nail monitoring system based on FBG sensing technique. From the strains measured by FBG sensors, the authors proposed an optimal model to evaluate the stability of the soil-nailed slopes.

2. Principle of FBG Sensor

Hill et al. [25] discovered photosensitivity in optical fiber and fabricated the FBG with a visible laser beam propagating along the fiber core. Since then, FBG sensors are widely used in military, aerospace engineering, mechanical engineering, and civil engineering. One reason for this popularity is that FBGs can measure multiple parameters at multiple points, such as temperature and strain, at a series of points along one fiber line and have a number of advantages over the conventional sensors as explained before. 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 a certain wavelength, which is dependent on the grating period and the refractive index of fiber [26]. In the reflected spectrum of an FBG sensor, the wavelength at which the reflectivity peaks is called the Bragg wavelength λ_B and can be expressed by

$$\lambda_B = 2n_{\text{eff}}\Lambda, \quad (1)$$

where n_{eff} is the effective core index of refraction and Λ is the periodicity of the index modulation.

For a standard single mode silica fiber, the relationship between the Bragg wavelength change $\Delta\lambda_B$, strain change $\Delta\varepsilon$, and temperature change ΔT can be simplified as [27]

$$\frac{\Delta\lambda_B}{\lambda_B} = c_\varepsilon\Delta\varepsilon + c_T\Delta T, \quad (2)$$

where λ_B is the original Bragg wavelength under strain free and 0°C condition, typically between 1510 and 1520 nm (10^{-9} m), and c_ε and c_T are the calibration coefficients for strain and temperature, respectively. In order to measure actual strains due to force, temperature compensation of FBG sensors is required. This can be easily achieved by adding an additional FBG into an empty copper tube and placed in the same temperature field. Once the temperature is measured, the mechanical strain can be corrected to be

$$\Delta\varepsilon = \frac{1}{c_\varepsilon} \left(\frac{\Delta\lambda_B}{\lambda_B} - c_T\Delta T \right). \quad (3)$$

A fiber with a series of FBGs with different original wavelengths is normally fixed along a soil nail by using methods of cement grouting, clamps, and so forth. Using (3), the mechanical strains along the fiber fixed along the soil nail can be obtained.

3. An Optimal Method to Search a Critical Slip Surface of a Soil-Nailed Slope

For ease of construction, a typical soil nail consists of steel rebar (from 20 mm to 45 mm) in the middle of a drillhole and grouted by cement slurry with different diameters ranging from 100 mm to 250 mm, surrounded by soil mass. As shown in Figure 1, the soil nails in the vertical cross section of a slope are constructed uniformly with a specified vertical distance and a certain inclination angle. The lengths of these soil nails at different elevations are generally designed to be different according to the preliminary numerical simulation results conducted by designers. In this condition, the stability requirements can be satisfied by the mobilization of shear resistance on the soil-cement interface.

The averaged Young's modulus of a soil nail can be simplified as

$$E = \frac{E_s A_s + E_c A_c}{A_s + A_c}, \quad (4)$$

where E is the averaged Young's modulus of the steel rebar and surrounding cement slurry; E_s and E_c are the elastic moduli of steel rebar and cement grout, respectively; and A_s and A_c are the areas of the cross sections of steel rebar and concrete, respectively.

In this study, a series of bare FBG strain sensors with different peak wavelengths were multiplexed and mounted in a pregrooved surface of a soil nail. The axial force on the i th cross section of the soil nail can be expressed by

$$N_i = E \cdot (A_s + A_c) \cdot \varepsilon_i, \quad (5)$$

where N_i is the axial force at the measurement point and ε_i is the strain value measured by the i th FBG strain sensor.

FIGURE 1: Schematic illustration of soil nails and potential slip surface in a soil-nailed slope.

In this study, the following assumptions are used.

- (a) The potential slip surface goes through the soil nails at different elevations in the same section.
- (b) The slip surface is assumed to be circular.
- (c) The bending strains are neglected along the soil nails.

The objective of the optimal model is to search for the maximum sum of strains along these soil nails in the same cross section. In this optimal model, relative positions of soil nails and circular shape of potential slip surface can be taken as constraints. Thus, intersecting points between soil nails and circular potential slip surface can be specified using the optimal model.

The governing equation can be expressed by

$$\begin{aligned}
 & \text{Max} \quad \sum_{i=1}^n \varepsilon_i \\
 & \text{s.t.} \quad 0 \leq x_i \leq a_i \\
 & \quad \quad x_i < 0.5(x_{i-1} + x_{i+1}) \\
 & \quad \quad x_0^2 + y_0^2 = r^2 \\
 & \quad \quad (x_i - x_0)^2 + (y_i - y_0)^2 = r^2,
 \end{aligned} \tag{6}$$

where ε_i is the strain value measured on i th soil nail; x_0 and y_0 are the horizontal and the vertical coordinates of the centre of circular landslide, respectively; r is the radius of the potential circular slip surface; x_i and y_i are the vertical and horizontal coordinates of the interacting point between the potential slip surface and the i th soil nail, respectively; a_i and b_i are the horizontal and vertical coordinates of i th soil nail tip, respectively.

FIGURE 2: Cross section of a slope reinforced with soil nails.

4. Slope Stability Analysis Using Limit Equilibrium Method

To conduct slope stability analysis, the slope as shown in Figure 2 can be divided into slices. The coordinates of center of the potential slip surface and intersections between slip surface and soil nails can be transmitted into Cartesian coordinates by the Helmert transformation; that is,

$$\begin{aligned}
 x' &= x \cos \alpha + y \sin \alpha, \\
 y' &= x \sin \alpha + y \cos \alpha.
 \end{aligned} \tag{7}$$

Stress analysis of the slices is shown in Figure 3. In this figure, N_j is the gravitational force of the j th slice; N_i is the axial force of the i th soil nail at the j th slice; X_{j+1} is the friction force between the j th slice and the $(j+1)$ th slice; X_j is the friction force between the j th slice and the $(j-1)$ th slice; Y_j is the friction force between the slice and the bottom part.

In this paper, FBG sensors with sequent initial wavelengths were mounted along a precut groove surface of soil nails. Based on the measured strains along the soil nails, the axial force distribution of soil nails can be calculated. In a slope reinforcement project, soil nails were employed to reinforce these cut slopes according to the complex geological condition. In this study, three vertical sections were chosen. One cross section was chosen to calculate the factor of stability in this paper. Soil nails from the top to the bottom were signed as 1–6 in this section which are shown in Figure 4.

The monitored slope (220 m long and 42 m high) consists of heavily weathered granite. In the reinforcement engineering, the drillholes for soil nails are 110 mm in diameter. The composition of the steel-mortar body is designed as 110 mm in diameter. The steel rebar (32 mm or 28 mm in diameter) is HRB335, while the mortar is of Grade 30. The authors chose three cross sections, including 18 soil nails at three stages. Among them, the soil nails at the first stage (near to the slope toe) are 9 m in length. At the second and third stages, the soil nails and anchors are 12 m and 15 m in length, respectively. Three-strain and one-temperature sensors were installed onto the soil nails. Six soil nails were instrumented with FBG strain

FIGURE 3: Slices with and without soil nail.

FIGURE 4: Schematic illustration of strain distributions on soil nails in a cross section of slope.

and temperature sensors which were used for temperature compensation.

The wavelengths of all FBG sensors have been collected for three times, from which the strain can be calculated compared with the recorded initial wavelengths. Temperature compensation can be achieved using the wavelength shifts measured by FBG temperature sensors. To fulfill the requirement of the optimal model, the strains along soil nails were fitted by polynomial functions at different collection times. Substituting these fitting polynomial equations into the optimal model, the radius of slip surface and coordinates of center of circular slip surface are simultaneously acquired. Once these landslide surfaces were searched, the calculated passive region can be divided into vertical slices as other classical theoretical methods. The axial forces are also applied on slices reinforced with soil nails which can be computed from the measured strains by the corresponding FBG strain sensors.

5. Conclusions and Suggestions

In this study, the optimal model combines limit equilibrium method with field monitoring results. The shape of slip

surface was assumed as an arc. FBG sensors were used to measure the strain along soil nails which was used to calculate the axial force of soil nails. This method can be used to evaluate a slope reinforced with soil nails. Compared to simulation results using other limit equilibrium methods, the calculated results based on the field monitoring data are more reliable. However, this newly proposed optimal method is a modified limit equilibrium method based on the assumptions including circular slip surface, maximum sum of strains and strain distribution fitting method. Further research is required to investigate the relationship between the measured strain values and the safety factor of the slope.

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