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Experimental study on a parallel-series connected fiber-optic displacement sensor for landslide monitoring

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ABSTRACT

The combined optical fiber transducer (COFT), a newly developed fiber-optic displacement sensor, has proven to be a promising monitoring tool in civil engineering owing to its obvious advantages, such as high initial measurement accuracy, wide measurement range, remote real-time monitoring and convenient installation; however, a limitation is that it cannot realize the potential sliding surface of slopes. In this paper, based on the COFT designed in our previous studies, a parallel-series connected fiber-optic displacement sensor (PSCFODS) with bowknot bending modulation has been developed to determine the location of potential sliding surfaces and monitor the inner deformation in slopes, especially rock slopes. Laboratory shear-sliding tests of the PSCFODS in a self-designed concrete direct shear apparatus with double-shear planes are carried out to test the feasibility and early-warning characteristics of this sensor, while it is monitoring deformation and determining the sliding surface of civil engineering materials or geo-materials. Four different types of test modes corresponding to four rock slope failure modes are considered to investigate the effectiveness and applicability of the PSCFODS in detecting the deformation behaviors of slopes. Results show that the PSCFODS can accurately determine the shear-sliding surface and realize the sliding distance of blocks in four different test modes, which supports its applicability in civil engineering, especially for rock slopes.

1. Introduction

China is a mountainous country prone to geological disasters, among which landslides are a significant hazard, resulting in many fatalities and much property loss each year [1,2]. Because of the complicated mechanisms that cause landslides and diverse uncertain triggering factors, e.g., rainfall, distribution of groundwater, unexpected earthquakes and human activities, it is difficult to predict landslide occurrence and determine deformation characteristics [3]. Therefore, it is crucial to provide early warning and real-time monitoring of slope instability to enable the evacuation of vulnerable people and timely repair and maintenance of critical infrastructure.

There are two main types of slope displacement monitoring, i.e., ground displacement and underground displacement monitoring. Geographic Information System (GIS) and Global Positioning System (GPS) [4], remote sensing (RS) [5], Synthetic Aperture Radar (SAR) [6] are ground-based measurement methods that are used for slope movement monitoring in large areas, hence improvements for small-scale landslides are needed. Deep displacement monitoring methods, based on geophysical exploration techniques and drillings, are of great importance to explore subsurface properties of slopes (namely direction and magnitude and rate of slope movement, and depth and areal extent of the failure plane). Conventional inclinometers [7,8] can detect changes in the inclination of the borehole casing and determine the slip surfaces or movement zones, and extensometers [9] installed within a borehole or on the slope surface can measure the axial displacement between a number of reference points in the same measurement axis. Acoustic emission (AE) developed by Smith [10,11] has been used extensively to monitor slope displacement rates continuously and in real-time. Time domain reflectometry (TDR) based on coaxial cable [12], can automatically realize slope movement at a lower cost than inclinometer casing, however TDR cannot determine the actual amount and direction of the movement. Fiber-optic displacement sensors based on optical time domain reflectometry (OTDR) [13,14], coherent optical frequency domain reflectometry (C–OFDR) [15], Brillouin optical time domain reflectometry/analysis (BOTDR/A) [16], and fiber Bragg grating (FBG) [17] have also attracted considerable interest in civil and geotechnical engineering. Marzuki A [18] presented an early system using a macro-bending loss-based optical fiber sensor to monitor land displacement of approximately 40 cm, and sensitivity of 5.9 ± 0.2 dB/cm. Tang TG

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[19] developed a distributed optical fiber sensor with the principle of micro-bending loss conveniently integrated with OTDR to monitor local slippage or deformation along the rock mass of a high slope with a high initial accuracy of 0.3 mm and small sliding distance of 3.6 mm, which prohibit large deformation monitoring usage. C–OFDR is a powerful tool for the fast and highly accurate measurement of the complex reflectivity of Rayleigh scatter in optical fiber. The use of C–OFDR has been proposed or some interesting applications including fiber identification and temperature (or strain) sensing [20]. A newly developed distributed fiber optic sensing technique using BOTDR data analysis technology [21] has been carried out in a small-scale model to ensure the stability of artificial soil slope. However, the detailed rules of the strain distribution cannot be clearly expressed owing to the distance resolution limitation associated with BOTDR. Experimental applications of BOTDA-based sensors for geotechnical monitoring [22] have proven capability for realizing real-time distributed monitoring, however installation is inconvenient because BOTDA requires incident laser from both ends of the optical fiber. Some publications about FBG-based strain monitoring programs have suggested that FBG sensors have good sensitivity and reliability [23,24]. Using the optic fiber bending loss mechanism and OTDR technology, the authors [25,26] have previously proposed a novel combined optical fiber transducer (COFT) constructed with common plastic base material, two capillary stainless steel pipes, and an optical fiber with bowknot bending modulation for landslide monitoring. The COFT simply measures the retraction displacement of a steel pipe, which converts shear zone displacements from downhole to a retraction at the top of the borehole by means of fiber optic loss measurements. Considering that some distributed fiber optic systems (e.g. BOTDR, BOTDA and C–OFDR) are very expensive, the proposed COFT which is used as localized sensor with loss measurements using OTDR has a maximum sliding distance of 30.6 mm with corresponding initial accuracy of 3.3 mm and the cost of the transducer is economical at \$0.15/m [25], which demonstrates promising economic application and high monitoring effectiveness in monitoring civil works. Furthermore, understanding the principles and performance of this COFT, based on theoretical and experimental study, has also been illustrated [27]; however, it is difficult for COFT to determine the location of potential sliding surfaces and obtain distributed measurement of complicated landslides, especially the order and interaction of multi-sliding surfaces.

Hence, based on the COFT foundation, this paper presents the design of a parallel-series connected fiber-optic displacement sensor (PSCFODS) with bowknot bending modulation, which can be used to realize quasi-distributed measurements and potential sliding surfaces in rock slopes. To study the monitoring effectiveness of the PSCFODS in rock slopes with multiple slip surfaces, indoor shear-sliding tests with a self-designed apparatus considering four different types of test modes were conducted to investigate the capability for monitoring deformation behaviors of different rock slope failures.

2. Sensing principle of optical fiber

2.1. Principle of bending loss

Ease of bending is one of the most important advantages of optical fiber. Macro-bending loss and micro-bending loss will be generated when a straight optical fiber is subjected to a small-radius bend [25]. Macro-bending loss generally means additional loss caused by bending optical fiber with a curve radius much bigger than its diameter. Micro-bending describes additional loss caused by micrometer bending created along the fiber axis [28]. This optical loss can be detected as a decrease in the sensing signal. Therefore, if the relationship between the external effect and change in the sensing signal can be found, then the displacement from this kind of fiber optic sensors can be determined.

The bending loss can be expressed as follows [29]:

$$\alpha = \psi e^{-\omega R} \tag{1}$$

where α is the bending loss of optical fiber; R is the curvature radius of bending optical fiber; and ψ, ω are constants to be confirmed, both of which are related to the diameter of the optical fiber core radius (r), covering diameter (d) and relative refractivity Δ.

Micro-bending loss α can be expressed as [30]:

$$\alpha \approx (64\xi^2\eta^6 l/\Lambda\delta^4)\left[r^4/(d^2\sigma^2)\right] \tag{2}$$

where ξ is a deformation parameter of optical fiber and is a function of time; η represents the factor relating to optical fiber and formable material; l, δ are the effective length of deformation and the factor of refractive index of optical fiber, respectively; and d, σ are the external diameter of optical fiber and the refractivity of fiber core and covering, respectively.

2.2. OTDR detecting principle

Multiplexed optical loss-based fiber optic sensors use pulsed lights like OTDR, in which a short optical pulse is launched into the fiber and a photo detector measures the amount of light that is backscattered as the pulse propagates down the fiber. The detected signal of the OTDR, known as the Rayleigh signature which is the strongest of the Rayleigh, Raman and Brillouin scatterings that occur during light transmission and cause attenuation of light intensity (see in Fig. 1(a)), presents an exponential decay with time that is directly related to the linear attenuation of the fiber [31]. The weakest Brillouin scattered light can be effectively detected by BOTDR, which is more expensive than OTDR. However, the limited sensing length is due to the weak anti-Stokes Raman signal, which is 20–30 dB weaker than that of the Rayleigh scattering light, unless Raman gain is implemented to enhance the sensing length. Based on the principle of detecting back-scattered Rayleigh scattering and reflected optical radiation, OTDR as a non-destructive method for determining the properties of optical fibers, needs access to only one end of an optical fiber. OTDR allows measurements at several points on the optical path [32]. The time information is converted to distance information if the speed of light in the fiber is known, similar to radar detection techniques. In addition to the information on fiber losses, OTDR profiles are very useful to localize breaks, evaluate splices and connectors, and in general to assess the overall quality of a fiber link. When a failure occurs in fiber properties, it appears as a sharp change (e.g., points 1 to 4 shown in Fig. 1(b)) on a reflectogram [9].

3. Structure and measurement principle of PSCFODS

The PSCFODS proposed in this paper incorporates an extremely simple bowknot bending modulation that increases its sensitivity in bending, two types of capillary steel pipes (i.e., Φ1 and Φ2) and base material. The schematic diagram of the model built with cement mortar and PSCFODS with bowknot bending modulation is shown in Fig. 2. Several capillary steel pipes of different lengths are arranged on the surface of the base material; the Φ2 capillary steel pipes will be removed once the cement mortar pre-hardens to ensure that the Φ1 capillary steel pipes can move freely in the mortar [26]. To guarantee the anchorage quality of Φ1 capillary steel pipes in a fixed range, additional fixed devices with anchor bars are used on the bottom of each Φ1 capillary steel pipe. An optical fiber (type G652B, a simple module purchased from the Wuhan Yangtze Optical Fiber and Cable Co., Ltd., Wuhan, Hubei, China) is glued to the top ends of all the Φ1 capillary steel pipes with an ample length of the fiber remaining outside the pipe, thus avoiding the light submersion loss from two consecutive events [25]. At the upper ends of the Φ1 capillary steel pipes outside the monitored segment, the fibers are wound into a bowknot that is affixed by an optical fiber clamp. The bowknot will cause a large number of losses in the "sensitive zone" and is similar to the shape of a figure of eight of the fiber-optic displacement sensor introduced by Sienkiewicz et al [33], as shown in Fig. 2(c), where the dimension D (A and B are the two points having maximum curvature) will be referred to as sensor size and S as gaze length. The geometry