Real-time and Multi-physics Fiber Optic Monitoring of Landslides in Three Gorges Reservoir Area

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Abstract. Accurate and real-time measurement of the evolution of landslides has become a great concern in recent years. Fiber Bragg grating (FBG), as a popular quasi-distributed fiber optic sensing technology, has been successfully applied to geotechnical and geohazard monitoring. In this paper, an FBG-based real-time monitoring system has been developed to capture the multi-physics evolution of creeping landslides. The system was employed to monitor the performance of the Majiagou and Xinpu landslides in the Three Gorges Reservoir (TGR) area of China, respectively. The results show that the FBG monitoring system can accurately obtain the variations of ground temperature, soil moisture, and deep displacements, which provides valuable information for evaluating the landslide deformation and failure mechanisms during the operation of the reservoir. In this way, real-time stability analysis and early warning can be achieved.

1. Introduction
Landslides in reservoir areas account for a large proportion of geohazards, which is a serious engineering problem all over the world [1, 2]. Once a reservoir landslide occurs, infrastructures along the river banks will be tragically damaged, together with numerous injuries, and death of local residents. The stability of these landslides is not only affected by the fluctuations of reservoir water levels, but also influenced by other factors such as rainfall, earthquakes, and adjacent construction activities [3-5]. Many landslides show creep characteristics and large deformation gradually accumulated with time. Therefore, to study the landslide triggering mechanism, the complicated multi-physics interaction during the operation of the reservoir should be taken into account. The development of a comprehensive and real-time field monitoring system is always a research hotspot. Many monitoring and early warning technologies have been applied to monitor landslide behaviors in the last decades [6-8]. In field instrumentation works, the landslide deformation has received the highest attention, while the variation of other physical parameters, such as pore water pressure, are not well investigated. Conventional monitoring systems also have several shortcomings concerning degree of automation, measurement stability, and durability of the instruments.

In the past two decades, the Distributed Fiber Optic Sensing (DFOS) technologies have been successfully used in geotechnical and geohazard monitoring [9-12]. Among others, fiber Bragg grating (FBG) has shown its unique features of high measuring accuracy and sampling frequency, and can
perform quasi-distributed strain and temperature monitoring. As an advanced version of FBG, ultra-
weak FBG (UWFBG) has many advantages in terms of robustness, durability, and scope of
measurement, indicating great potential in sensing multi-physics information of slopes and other geo-
infrastructures. In laboratory model tests, miniature FBG sensors have been used to investigate the
mechanism of slope failure and the initiation of debris flows [13-15]. There are also many successful
applications of FBG systems to field monitoring of engineering slopes [16-19]. The previous studies
mainly focus on strain and displacement measurements, and few of them belong to real-time and long-
term monitoring.

In this paper, the principle of FBG/UWFBG for monitoring multi-physics information of reservoir
landslides is introduced. Two case studies in the Three Gorges Reservoir (TGR) area are subsequently
presented. Finally, the current opportunities and challenges of fiber optic monitoring of landslides are
summarized.

2. Principle of FBG/UWFBG

2.1 Fiber Bragg Grating (FBG)

Fiber Bragg Grating (FBG) is a popular quasi-distributed strain and temperature measurement
technique. Through the physical or thermal elongation of the sensing section, as well as the change in
the refractive index of the optical fiber due to photoelasticity and thermo-optical effects, the Bragg
wavelength $\lambda_B$ of an FBG sensor will change linearly with the applied strain $\Delta \varepsilon$ or temperature $\Delta T$
[21]

$$\frac{\Delta \lambda_B}{\lambda_B} = (1 - p^{opt}) \Delta \varepsilon + (\alpha + \xi) \Delta T$$ (1)

where $\Delta \lambda_B$ is the change in the Bragg wavelength due to applied strain and temperature changes; $\lambda_B$ is
the original Bragg wavelength under strain-free and 0 °C condition; $p^{opt}$ is the photo-elastic parameter;
$\alpha$ and $\xi$ are the thermal expansion and thermo-optic coefficients, respectively. FBG sensors with
different Bragg wavelengths can be multiplexed in series using the wavelength division multiplexing
(WDM) technique. To avoid spectral overlap during measurement, there should be sufficient spacing of
the Bragg wavelengths for the serially connected FBG sensors. Therefore, around ten gratings can be
connected in series in most cases.

As shown in Figure 2, based on the strain and temperature sensing principle, special-purpose sensors
can be developed for geotechnical applications, such as displacement sensors, inclination sensors, soil
moisture sensors, pore water pressure cells, and earth pressure cells. It should be noted that the newly
developed FBG soil moisture sensor is a type of temperature probe with periodic active heating function,
which can be used to obtain the distribution of moisture content and seepage velocity in the soil [22-24].

Figure 2. Special FBG sensors: (a) displacement sensor; (b) pore water pressure cell; (c) soil moisture sensor, and (d) earth pressure cell.

2.2 Ultra-weak Fiber Bragg Grating (UWFBG)

UWFBG is a type of special FBG with weak reflection features, and its peak reflectivity is usually lower than -30dB. The bandwidth of the light source is no longer limited by the quantity of multiplexed sensors using the time division multiplexing (TDM) technique. Taking advantages of the difference of reflection time under the same incident light, hundreds of gratings with the same wavelength can be connected in series, and optical time-domain reflectometer (OTDR) is employed to locate the exact positions of all the gratings [25-27]. By scanning the light in a specific wavelength range, the spectrum of the weak grating can be obtained to recognize the changes in temperature, strain, and other parameters.

3. Case study I: Majiagou landslide

3.1 General information of the landslide

The Majiagou landslide is a typical creeping landslide, which was initiated when the TGR was first impounded in 2003. This landslide is located on the left bank of Zhaxi River, a tributary of the Yangtze River (see Figure 3). The topography is distributed in a nearly east-west direction, and the slope surface is generally steep (26°~35°)-moderately gentle (10°~15°)-steep (30°~45°) from top to bottom. It is 560 m long and 180–210 m wide, covering an area of 9.8 × 104 m². The rear elevation of the landslide is 285 m, and the landslide toe is submerged by the reservoir water up to an elevation of 145 m. The landslide body is a gentle slope mountain beam as a whole, and the middle axis of the landslide protrudes to form a bulge. The front edge is eroded by the Zhaxi River, forming a fluvial alluvial terrace, and a steep slope is formed on the trailing edge. The stratigraphic occurrence is about 27°, and the occurrence of the rock formations on both sides of the boundary and the front edge is obviously reversed, forming a reverse warp, with the occurrence of 200° ∠ 22°~35°. The slope has developed a multi-level gentle slope platform with many steep ridges affected by long-term deformations and artificial transformations. This landslide is mainly exposed in Jurassic Suining Formation (J₃s) and Quaternary strata (Q₄). The former is the most widely distributed bedrock stratum in the study area, with low mechanical strength, easy softening and argillization when encountering water. That is often considered as the sliding strata in the TGR area.

Geological surveys and long-term observation indicate that there are two sliding surfaces in this landslide. The upper one is the shallow sliding surface formed by the contact surface of Quaternary soil layer and underlying rock stratum (i.e., around 19 m). The sliding zone is composed of 0.5-0.8m thick...
silty clay with silty clay mudstone. The weak mudstone intercalation along the bedrock is a deep-seated sliding surface (i.e., around 35 m) [28]. To alleviate the further deterioration of the deformation, anti-slide piles, catchwaters and drainage ditches were built in the crucial deformation zones of the study area. The long-term deformation evolution of the landslide is still worthy of continuous attention.

3.2 Field monitoring
An integrated multi-physics monitoring station was established by Nanjing University to explore the multi-physics evolution characteristics of the Majiagou landslide [20, 29]. In-situ observation of the landslide was initiated in 2012. The monitoring deployments were mainly for surface and subsurface displacements, loading of anti-sliding piles, groundwater levels, rainfall records, etc. Distributed strain sensing cables were installed in two piles (A and B) and three inclinometers (OFS 1~3), and were directly embedded in six boreholes (JC1~6) and two shallow surface trenches (SL1 and SL2). In addition, FBG ground temperature sensors, ground strain sensors, in-place inclinometers, pore water pressure cells, water level gauges, earth pressure cells, load cells, and reinforcement stress meters were installed in the field to perform real-time multi-physics monitoring of the landslide.

Figure 3. Location, profile and monitoring arrangement of Majiagou landslide

![Figure 3](image)

Figure 4. Time-dependent variation of displacement with rainfall and reservoir water level[26].
Figure 4 illustrates the deformation evolution of the Majiagou landslide considering reservoir water level fluctuations and rainfall data. The results show that the reservoir water level fluctuations and seasonal precipitation are the two main triggering factors, and the seasonal precipitation is the dominant factor. It can be seen that in the three periods marked by blue zones (Zones A, B, and D), landslide deformation rapidly increased due to continuous and/or heavy rainfall. On the other hand, sharp increases in deformation corresponding to the dropdown rather than the rise of reservoir water level (Zones A and C) were observed. However, the effect has the characteristic of lag. The deformation data obtained by the FBG inclinometers and borehole-embedded sensing cables show that the position of sliding surface and deformation failure mode can be sensitively identified. It is clear that the landslide is still in the creeping deformation stage [25], and therefore real-time and long-term monitoring should be conducted to perform early warning of catastrophic collapse.

4. Case study II: Xinpu landslide

4.1 General information of the landslide

The Xinpu landslide is located in Anping Town, Fengjie County, Chongqing stretch of the TGR area, which is on the right bank of the Yangtze River (see Figure 5). The overall slope is about 2 km, the relative elevation difference is 634.4 m, and the slope is 15°~20°. The volume of this massive landslide is about $3791.83 \times 10^4$ m$^2$. The front edge of the landslide extends into the Yangtze River, which is a large wading landslide. Due to the multi-phase landslide activities of the slope, the entire slope forms a multi-level platform landform. According to ground surveys and boreholes, the bedrock is the Upper Triassic Xujiahe Formation (T$_3$xj) and the Lower Jurassic Zhenzhuchong Formation (J$_1$z), with an occurrence of $345° \angle 21°$. The slip surface is mainly divided into three layers from top to bottom: i) the local weak structural surface in the slope; ii) the interface between the crushed stone soil and the cataclastic rock; iii) the interface between the bedrock and the soils. The rear part of the landslide is in a stable state, while the deformation of the front part still develops. Therefore, the dynamic changes of the slope stability have received significant attention.

![Figure 5. Location, profile and monitoring arrangement of the Xinpu landslide](image)

4.2 Field monitoring

To figure out the deformation mechanism and evolution characteristics of the landslide, a multi-source and multi-physics monitoring system was recently established. Pipawan was determined as the first monitoring station location, where a maximum deformation of almost 400 mm occurred in June, 2020. A quasi-distributed real-time monitoring system, including FBG moisture probes, thermometers, in-place inclinometers, displacement gauges and strain sensing cable, were deployed in the field, and a new...
MEMS-based tiltmeter was also installed. An automated weather station has also been installed to obtain sufficient meteorological data for in-depth analyses of the deformation and multiple influencing factors.

Figure 6 shows the deformation evolution of the Xinpu landslide considering reservoir water level fluctuations and rainfall data. The stair-shaped deformation curves indicate that the slope is in a creeping state. The intervals of abrupt displacement increase correspond to heavy rainfall and the dropdown of water level. When the water level rises, the deformation almost increases at a slow rate. Moreover, the results from the MEMS tiltmeter and FBG inclinometer show an excellent agreement that the main movement direction is nearly the direction of the landslide. Unfortunately, the inclinometer was artificially damaged during the observation period. It should be pointed out that the tiltmeter and the inclinometer were installed at a depth of 0.5 m. Hence the impact of micro-geomorphology should also be considered. As illustrated in Figure 6(b), the variations of inclination are moderately associated with rainfall events, especially heavy rainstorms.

![Figure 6](image-url)

**Figure 6.** Time-dependent variation of shallow movements with rainfall and reservoir water level: (a) long-term monitoring results of GPS, MEMS tiltmeter and FBG inclinometer; (b) elaborate analysis of MEMS-based tiltmeter and FBG inclinometer results

In this work, the FBG-based multi-physics monitoring instruments are believed to being presented interesting findings, despite the relatively short observation period in this paper. To obtain more detailed information, a proprietary UWFBG-based multi-physics monitoring borehole was also implemented (i.e., BH 3#), the grating spacing of those optical cables for temperature and strain reaches 1 m, which provides significantly enhanced spatial resolution. It is necessary to obtain real-time multi-physics monitoring to improve the level of early detection, monitoring, and warning of landslides. Owing to the
short duration of the monitoring period in the Xinpu landslide, more details on fiber optic measurements will be presented and discussed in forthcoming publications.

5. Conclusions and outlooks

In this paper, the recent progress of fiber optic sensing technology for real-time and multi-physics monitoring of reservoir landslides is introduced. Two case studies in the Three Gorges Reservoir area are then presented. The following conclusions can be drawn in this study.

1) The FBG technology is suitable for quasi-distributed real-time monitoring of multi-physics evolution, such as strain, temperature, and soil moisture.

2) The long-term monitoring data of the Majiagou landslide provides valuable information for stability evaluation during the operation of the reservoir. The results show that the landslide is creeping, and rainfall and fluctuations of the reservoir water level are the two main factors affecting the landslide deformation.

3) The stair-shaped deformation curves of the Xinpu landslide indicate that it is in the creeping state. The rapid increase of displacement is mainly caused by continuous heavy rainfall and dropdown of the reservoir water level.

It is worth noting that although the FBG-based system has been demonstrated to be feasible and reliable for landslide monitoring, this approach is still novel to most geotechnical engineering practitioners. It is crucial to encourage the development of robust and low-cost sensing cables and the corresponding equipment. At the same time, more case studies are still needed to promote real-time landslide monitoring and give full play to the vast potential of fiber optic monitoring technology in geohazard mitigation and control.

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