Research on fibre Bragg grating monitoring in the gravel soil landslide experiment

Lei Gao1, Yuan Wang2, Yangyang Sun1, Qinghua Zhang1, Zhenglin Zhang1, Peng Zeng1

1College of defense engineering of Army Engineering University of PLA, Nanjing, People’s Republic of China
2College of Mechanical Engineering of Suzhou University of Science and Technology, Suzhou, People’s Republic of China

Abstract: Fibre Bragg Grating (FBG) sensor is a new sensor with numerous advantages. How to apply in the safety monitoring of landslide engineering is still in experiment and research stage. Here, FBG is used to monitor the landslide process of the gravel soil pile. Before monitoring experiment, the first tests FBG packaging and burying effect by two tests in lab, one is sand pile landslide test which proves vertical buried is feasible and the other is loading test on the steel bar sensor which proves the wavelength change of FBG on steel bar sensor has a good linear relationship with the loading change. Then, buried the steel bar sensor in the gravel soil slope after simple encapsulation. Stress and strain monitoring results of grating sensors are obtained in landslide which is formed through the simulation of excavation construction. The experimental data show that through correct embedding FBG sensors can effectively monitor the stress–strain change of the slope. FBG provides a new way for the landslide early warning.

1 Introduction

The gravel soil accumulation body is the natural stacked loose accumulation body under the action of gravity [1]. The geological conditions of the gravel soil slope is very fragile, if it lost stability, it will cause landslides and other disasters [2], Shenzhen Bright Hill landslide events caused by the unstable accumulation body made huge losses on 20 December 2016. The slope stability monitoring of the gravel soil accumulation body is an effective way of early warning of the landslide disasters [3, 4].

The traditional slope stability monitoring methods mainly adopts the engineering surveying method and electrometric method based on electrical signal sensors [5–7]. The fibre Bragg grating (FBG) sensor is a new sensor of non-electricity measurement, have many advantages that traditional monitoring methods do not have: such as anti-electromagnetic interference, anti-corrosion, it is easy for series setting, the series can monitor its slope surface, and internal strain at the same time, can be distributed online real-time monitoring [8–10].

Here, FBG is used to monitor the landslide process of the gravel soil pile. Before monitoring experiment, the paper first took two tests using FBG in lab which were sand pile landslide and loading test. The two tests are designed to prove that vertical buried FBG sensor is feasible to monitor landslide and the FBGs wavelength change at different pasted depth on the steel bar has a good linear relationship with the loading change. Then after packaging FBGs in series on steel bar, vertical buried in the gravel soil pile. We formed landslide by excavation and obtained the FBGs monitoring data, analysed, and summed up the characteristics of the FBG sensors in monitoring in the gravel soil pile, proved FBG an effective method for the safety monitoring of the gravel soil accumulation body.

2 FBG sensor principle

FBG is a kind of reflection filter passive sensitive components with high performance which formed spatial phase grating inside the fibre core. When the light transmission pass through the FBG, the light wave satisfying FBG will be reflected, the reflection wavelength depends on the effective refractive index \(n_{eff}\) of the grating period \(\Lambda\) and reverse coupling mode.

\[
\lambda_B = 2n_{eff}\Lambda
\]  

(1)

Anything that changing the physical process of the two parameters (such as temperature, strain) will all causes Bragg grating wavelength to shift. The strain parameter is an external factor that directly caused the wavelength to drift. Both the pulling and compression on the grating all will change the grating period \(\Lambda\) and effective refractive index \(n_{eff}\) [11].

2.1 FBG sensing properties under the uniform axial stress [12]

Equivalent formula (1) on both sides, will get:

\[
\frac{d\lambda_B}{\lambda_B} = 2\Delta n_{eff} + 2n_{eff}d\Lambda
\]  

(2)

We can detect the shift quantity of the centre wavelength of the reflected light through the demodulation devices. The two ends of the equivalent formula (2) all divided both sides of the equivalent formula (1) will get:

\[
\frac{d\lambda_B}{\lambda_B} = \frac{dn_{eff}}{n_{eff}} + \frac{d\Lambda}{\Lambda}
\]  

(3)

Within linear elastic range, there is

\[
\frac{d\Lambda}{\Lambda} = \epsilon
\]  

(4)

\(\epsilon\) is axial strain.

Do not consider the effect of fibre radial deformation on the refractive index, only consider the elastic-optic effect of axial deformation, the refractive index of optical fibre in the axial elastic deformation changed [13, 14] as follows:

\[
\frac{dn_{eff}}{n_{eff}} = -\frac{n_{eff}^2}{2}(p_{12} - \eta(p_{11} + p_{12}))\epsilon
\]  

(5)

In the equivalent formula, \(p_{11}\) and \(p_{12}\) are elastic-optic coefficient, that is the longitudinal and transverse elastic index changes, respectively, caused by the longitudinal strain; \(\eta\) is Poisson's ratio.

The equivalent formula \(P = (n_{eff}^2/2)(p_{12} - \eta(p_{11} + p_{12}))\) are composed of equivalent formula (3)–(5), will get:
For FBG, \( P \) is a constant parameter related to the material coefficient, the wavelength, and strain are linear output. The equivalent formula \( K_e = \lambda_0(1 - P) \), will get:

\[
\Delta\lambda_B = K_e \epsilon
\]

\( K_e \) is called the sensitivity coefficient of FBG strain sensor. When \( \lambda_B = 1550 \text{ nm}, K_e = 1.209 \text{ pm/μɛ} \) [11, 15]. Through the wavelength changes of FBG, will get the average axial strain of its pasted position.

3 Test preparation

3.1 Test equipment and materials

According to the test conditions, the gravel soil pile is mainly composed of >2-mm particle size. For convenient to bury and measurement, package the FBG in specific carrier. This text adopt steel bar as the carrier, the steel bar is an important anchor supporting materials, although its rigidity is great, but the strain transfer research of the grating sensor on the steel is relatively mature.

The test FBG's gate region is 2.0 cm long and its reflection wavelength is 1520 and 1550 nm. The sensor carrier is 1.5 m long and ø12 mm steel bar, the adhesives are 401 quick-drying glue, epoxy resin. The optical sensing interrogator is sm125 of Micron Optics company. The sm125 optical sensing interrogator is a compact, field proven, industrial grade static sensor interrogation module designed for robust, reliable, long-term field operation, mainly used for measuring the parameters of stress, temperature and strain with 2 Hz scanning frequency.

3.2 Packaging FBG on steel bar

The steel bar is 1.5 m long, its surface is rough, polished the surface before paste the FBG. Grinding out two surfaces at length of 0.5 and 1.0 m of the bar as Fig. 1 shown, clean surfaces with alcohol, and, respectively, paste the two gratings which reflection wavelength are 1525 and 1520 nm, first stick FBG with quick-drying glue, distributed in the steel surface in series. In order to protect the fibre grating from the damage of gravel, wrap a layer of flannel as Fig. 2 shown, then wind and fix it with wide tape.

3.3 FBG test in sand pile

In order to test the sensor's effect of vertical buried for monitoring in the landslide, this article put out sand pile landslide experiment. Pasted two FBG in series on the thin steel tube surface, first stick FBG with 401 quick-drying glue, then paint the coating epoxy resin, the finished sensor is as Fig. 3. Then, vertical buried the sensor in the sand piles, which height is 30 cm. Formed sand pile landslide, then got the strain-time chart of the FBG as Fig. 4.

Massive sand slide can cause strain big change as Fig. 4 oval ring marked. From the monitoring data, the FBGs' wavelength changes along with the development of the landslide, so vertical buried FBG sensor can reflect the landslide development process. From the second time test data as Fig. 5 shown: the FBG's strain at different position on the steel tube, had different reaction time and change width. As in the loose medium of sand heap, the FBG's landslide reflection is more sensitive on the surface of the sand pile, which is buried on the top.

3.4 linear relationship between FBG’s strain and the loading

Due to the rigidity of steel bar is bigger than the thin steel tube, in order to test the linear relationship of the FBGs' wavelength changes and load change at different pasted position on the steel bar, this article has carried out the loading test in lab. The test is as follows: fixed one end of the 1.5 m long steel bar sensor, then gradually add load on the other end as Fig. 5 shown. Then, recorded the grating strain at 0.5 and 1.0 m, after the loading is completed and after being reinforced stable, then unload the load gradually. The test results are shown as Fig. 6.

When the steel bar sensor loading, it is belong to the elastic deformation before its yield strength and satisfied the Hooke's law, the deformation and stress is proportional relationship. Taking the grating strain data in the process of loading and the loaded weight quality to make related linear analysis. Get the trend line as shown in the following Fig. 7.

Loading 500 g weight each time, after the strain become stable then continue to load to 3000 g. We got the strain data of FBG01 and FBG02 on the steel bar. Just chose the max strain after each loading, we can obtain the linear correlation of the strain and the loading weight as Fig. 7 shown. According to the results, the linear
The correlation of the grating strain and loading weight are good. It illustrates the grating strain can accurately reflect the loading changes on the steel bar. The two gratings strain changed at the same time from the load beginning. The grating strain of FBG01 is almost half of FBG02, which is related to their pasted position. It is similar to the experimental results with the sand pile.

3.5 Sensors buried in the gravel soil pile
The rock soil pile is about 8 m high, respectively, setting one steel bar sensor at about 6.5 m high and about 4.5 m high. The sensor number is shown as following Fig. 8.

The two steel sensors are both put 1525 nm FBG above, its buried depth is about 0.5 m, the 1520 nm FBG is below and its buried depth is about 1.0 m. The position of No.1 steel bar sensor and No.2 steel bar sensor buried in gravel soil slop is as Fig. 9 shown.

4 Analysis of landslide experiment results
Taking the gravel soil pile as the test object which height is 8 m, we formed landslide for two times. The first time, start excavation artificial bottom to form landslide as Fig. 10a. The second time formed landslide by forklift as Fig. 10b.

4.1 First landslide experiment by manual excavation
First time, we adopted manual excavation at toe of slope, with the increase of the excavated volume, small area landslide of the gravel soil pile gradually evolved into large-area landslide. Sensor01 was buried on the top of the gravel soil pile as Fig. 9 shows, its’ buried depth is 1.4 m. It is 4.5 m away in horizontal from the excavation position. Sensor02 is located in the slop waist which is near the digging position. After landslide, the FBGs’ wavelength response is as Figs. 11a and b show.

The wavelength-time chart shows the top FBG is more sensitive to excavation process, sensor02 is more sensitive and better precision than sensor01.

One point needs to explain is Fig. 11a, the wavelength of top FBG of sensor02 should change with the increase of artificial excavated volume, when large-area landslide happened, its’ wavelength change is indistinctive. That is because the top FBG is close to the top, after several small gravel slide, it is no longer located beneath the soil, so its strain is no longer apparent.

Still, the deep FBG-buried depth of sensor02 is about 1 m, it’s reflection of excavation process and landslide is relatively stable, and not reflect the small disturbance in the process of excavation, it has obvious signal for the small area landslide, as the decrease of covered soil, the strain has larger changes. The deep FBG of sensor02 shows three small gravel soil slipping and one large-area landslide, which is consistent with field situation. After the landslide process finished, the wavelengths of FBGs on sensor01 and sensor02 are gradually stable again.

4.2 Second landslide experiment by forklift excavation
The second time we formed landslide by forklift excavation. The buried depth of sensors is about 1.35 m. The two FBGs of each steel bar sensor are all buried under the gravel soil. After the forklift excavated, landslide happened, Fig. 12a and b are pictures of scene, the main landslide position is where yellow arrowhead pointed in Fig. 12b. After landslide, the FBGs on the steel bar sensors are not exposed to the surface of the earth.

The FBGs’ wavelength-time chart is as Figs. 13a and b. Forklift excavation caused greater slope disturbance than artificial excavation. As soon as Forklift excavation began, the
wavelength of FBGs on No.2 steel bar sensor began to change. As Figs. 13a and b show the top FBG and the deep FBG on sensor02 has obvious wavelength change to the forklift shovel process. FBGs’ wavelength change on sensor01 is not obvious, only when landslide happened have a visible change. The top FBG on sensor02 reflects the slope situation more obvious than the deep FBG. For safety monitoring of gravel soil slop, with steel bar as carrier packaged FBG sensors need to be close to the slope surface, too deep is not sensitive enough. The carrier material with small stiffness for FBG would have a better effect, but the stiffness cannot be too small that the carrier and FBG cannot have a compatible deformation, and the FBG is unable to gather the data.

Wavelength of the top FBG and the deep FBG on No.1 steel bar are shown in Figs. 14a and b. Due to relatively simple grating sensor package, after buried twice, wavelength change by the uneven deformation impact noise becomes large as Figs. 14a and b black line. In order to highlight the wavelength change caused by landslide, use the period moving average method for data processing to smooth noise, after took the 12 period moving average, get the white trend line in Figs. 14a and b. The white trend line displays visible change of FBGs’ wavelength at the time of the landslide occurred, and then re-enter the stable state. Mainly because No. 1 steel bar is at the top of the slop, away from the landslide location, internal strain is small. So for safety monitoring of media stacked body loose gravel soil, monitoring points adopting FBG sensors using reinforced carrier must have a certain density.

4.3 Strain results
According to formula (6) and (7), calculate the strain of the FBGs in two experiments, the strain-time charts are as Figs. 15–18 shown.

Since the FBG measured axial strain, and the rigidity of steel is much larger than gravel soil, so the FBGs’ strain cannot be equal to the actual strain of slope. So here, the strain value have few specific engineering significance. We can judge the security of the state of the slope depending on the wavelength or strain change tendency.

The problems existing in the test:
i. The FBG sensors buried in the landslide tests is not fixed end, the whole sensor may happened whole displacement along with the development of the landslide; we have not considered this kind of situation in the test data.

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As the amount of excavation cannot be accurately counted, so the paper could not make the corresponding analysis of the monitoring data and the quantity of landslide soil.

There are many factors which can cause landslides, the paper just studied FBG monitoring data under the phenomenon of the gravel soil landslides caused by excavation, not considering the influence of water and other geological factors.

The FBG is easy to be broken, the packaging and burying process are very important, which decide whether it can be widely used in the engineering.

Although landslides experiments time was about 1 h, but the landslide process is only several minutes, so we do not consider the influence of temperature on the FBG, but the actual slope monitoring is a long-periodic work, FBG would be affected by the weather climate and the temperature.

In the landslide process, the influence factors of FBG strain mainly have two aspects, one is the impact formed by the gravel soil sliding; Second, after the gravel soil slipped down, the covered soil thickness changed. The gravel soil slipping shocks are short and intense, it induces the FBGs' wavelength or strain produce a big change. The reaction of the covered thickness changes are after slipping, the wavelength of FBG sensor experienced the changing process of stable-unsable-stable. The covered soil thickness changes are mainly reflected in the wavelength changes between two stable states.

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