Postprint of Research on Small Deformation Monitoring of Subgrade Based on FDM and FBG Technology

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Abstract

This study addresses railway subgrade health monitoring by developing a small deformation monitoring system based on FDM (Fused Deposition Modeling) and FBG (Fiber Bragg Grating) technologies. An FBG sensor monitoring model with encapsulation and anchor plates was designed using FDM and FBG sensing technologies. Calibration experiments established the relationship between load and soil displacement, revealing a good linear relationship with a correlation coefficient of 0.99. The calibration tests measured a maximum displacement of 0.25 mm and a minimum displacement of 0.05 mm, with sensor sensitivity reaching 4 nm/mm and minimum resolution achieving 0.62 μm. Sensor feasibility was verified through two experimental conditions: monitoring subgrade displacement under static and dynamic loads. Under static loading, monitoring data showed stepwise increases in wavelength and displacement over time, successfully capturing a minimum subgrade displacement of 0.004 mm. Dynamic load monitoring tests demonstrated the sensor' s rapid response to vertical pressure generated by vehicle model loads.

Full Text

Study on Small Deformation Monitoring of Embankment Based on FDM and FBG Technology

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Abstract

This study develops a small deformation monitoring system for railway embankments based on FDM (Fused Deposition Modeling) and FBG (Fiber Bragg Grating) technology. Using FDM technology and FBG sensing technology, an FBG sensor monitoring model with encapsulation and anchor plates was designed. Calibration tests established the relationship between load and soil displacement, revealing a strong linear correlation with a correlation coefficient of 0.99. The tests measured a maximum displacement of 0.25 mm and a minimum displacement of 0.05 mm, with sensor sensitivity reaching 4 nm/mm and minimum resolution achieving 0.62 µm. The sensor' s feasibility was verified through two experimental conditions monitoring embankment displacement under static and dynamic loads. Static load monitoring data indicated that wavelength and displacement increased stepwise over time, successfully capturing minimum embankment displacements of 0.004 mm. Dynamic load monitoring test results demonstrated that the sensor can rapidly reflect vertical pressure generated by vehicle model loads.

Keywords: FBG sensor; FDM technology; embankment; displacement; health monitoring

With the advancement of national comprehensive strength, civil engineering has developed considerably, and health monitoring for these structures has garnered increasing attention. In civil engineering projects and simulation tests such as bridges and tunnels, monitoring displacement changes at critical locations is essential for accurately evaluating structural safety performance and damage extent [1-3]. Microscopic displacement in embankments, if not promptly controlled, not only affects structural aesthetics but also jeopardizes structural safety. Therefore, health monitoring of embankment displacement represents a critical research priority. Lü Congru et al. [4] studied embankment settlement measurement using embedded laser settlement meters, which offer convenient operation and high precision. Yan Hongye et al. [5] proposed a novel practical assembled layered settlement observation device with high precision and stability. Among various methods, sensors are gradually gaining widespread use due to their simple installation, compact size, and adjustable measurement range.

Fiber Bragg Grating (FBG) sensors are among the most widely applied sensor types. An FBG sensor is a Bragg fiber grating sensor, representing a new type of intelligent sensing element [12] that belongs to the wavelength-modulated nonlinear fiber optic sensor category [13]. FBG sensors consist of optical fiber and gratings, where optical fiber is a fiber made of glass or plastic. Figure 1 [Figure 1: see original paper] illustrates the internal structure of an optical fiber, which comprises three layers from inner to outer: core, cladding, and coating layer.

Fiber optic sensing technology originated in 1977 and has undergone over three decades of development. Fiber optic technology has not only achieved significant advancement across numerous industries but has also become an important indicator for measuring a nation' s informatization level. Currently, commonly used sensors include electronic sensors, resistance sensors, and optical sensors. Li Guangwei et al. [6] utilized capacitive acceleration sensors for embankment displacement monitoring, which offer good temperature stability and simple structure. Zhang Bin et al. [7] employed Hall electromagnetic sensors for measuring transverse profile settlement of embankments, benefiting from high sensitivity and compact size. However, since embankments are exposed to natural environments, electronic sensors are susceptible to weather effects and electromagnetic interference, while Hall sensors suffer from poor interchangeability, temperature-dependent signals, and nonlinear output. Consequently, Bragg fiber grating sensors, as photosensitive sensors, have found extensive applications in energy, environmental protection, and industrial sectors due to their compact size, strong anti-magnetic interference capability, and low transmission loss [8-11].

This study combines fused deposition modeling technology to encapsulate, protect, and fix Bragg fiber grating sensors. Considering current embankment conditions in China, an embankment model was constructed to simulate actual train operation, with sensors embedded inside the track embankment to monitor small soil deformations.

2.1 Working Principle of Fiber Bragg Grating (FBG) Sensing Technology

The working principle of FBG sensors is as follows: when broadband light enters the FBG sensor, a portion is reflected while another portion is transmitted. The reflected light wave returns to the coupler and passes through to the fiber grating demodulation device, which receives the signal and measures the change in wavelength . Figure 2 [Figure 2: see original paper] shows the sensor schematic diagram. is related to the core refractive index n and grating period Λ, expressed as:

$$\lambda_B = 2n\Lambda$$

where n is the core refractive index and Λ is the grating period.

When pressure changes, the grating period Λ of the FBG sensor changes by ΔΛ, and the reflected wavelength increases. Ignoring temperature variations, the wavelength change caused by fiber grating axial strain is:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon$$

where Pe is the effective photoelastic coefficient of the core (taken as 0.22), and

Ke is the sensitivity for strain measurement. Most FBG sensors have center wavelengths varying from approximately 1520 nm to approximately 1570 nm.

2.2 Design and Fabrication of the Novel Displacement Sensor

Fused Deposition Modeling (FDM) is a type of 3D printing technology that enables rapid prototyping based on digital model files. The FDM working principle involves heating and melting filamentous thermoplastic material at the nozzle. According to the model configuration information, the printer nozzle deposits material onto the workbench through designed model dimensions. As the nozzle moves along the part cross-section, extruding melted material that rapidly solidifies to form one layer, the platform then descends by one layer thickness before applying the next layer until the nozzle forms a solid object. Materials typically used include thermoplastics such as wax, nylon, Acrylonitrile Butadiene Styrene (ABS), and Polylactic Acid (PLA). This experiment used a FINDER 3D printer with 100-micron printing precision and 410 cubic inch printing volume, employing PLA material. Figure 3 [Figure 3: see original paper] shows the 3D printer fabricating anchor plates.

The novel FBG displacement sensor consists of two anchor plates and a long-gauge sensor. The anchor plates have a diameter of 60 mm and thickness of 4 mm. The long-gauge sensor comprises a transparent PVC (Polyvinyl chloride) protective layer (2 mm diameter) and an internally isolated FBG sensor, with a length of 100 mm. The sensor end connects to armored jumper wires for protection. Figure 4 [Figure 4: see original paper] illustrates the novel displacement sensor based on FDM and FBG technology. Using CATIA software, anchor plates were designed with reserved channels at the center. Due to the susceptibility of FBG sensors to damage under compression and the complexity of embankment environments, the entire length of the FBG sensor requires PVC protection. FDM technology encapsulates the protected FBG sensor at the center of the anchor plates. During monitoring tests, the FBG sensor is directly embedded within the soil. When load acts on the soil, the anchor plates are compressed by the soil, causing FBG compression or tension and resulting in center wavelength changes.

2.3 Calibration Test

Calibration tests were conducted in a constant-temperature laboratory. One end of the FBG displacement sensor was fixed, while the other end underwent stepwise loading of 20 g increments at 20-second intervals for three cycles, followed by sequential unloading. Sensor wavelength and displacement changes were recorded during each loading and unloading cycle.

Two sensors were selected to analyze the relationship between wavelength and displacement. As shown in Figure 5 [Figure 5: see original paper], the relationship between sensor displacement and wavelength yields fitted correlations of y

= 3.982x + 1531.5 and y = 4.0274x + 1549 for the center wavelength versus displacement. Consequently, the sensor sensitivities are 3.982 nm/mm and 4.0274 nm/mm, respectively. Given the grating demodulator precision of 0.0025 nm, the resolution for both sensors is calculated as 0.62 µm.

Figure 6 [Figure 6: see original paper] shows the relationship between FBG sensor displacement and load during calibration tests. The results demonstrate that sensor displacement increases linearly with load, achieving an ideal linearity with correlation coefficients up to 0.99. The calibration tests measured a minimum displacement of 0.05 mm and a maximum measurement range of 0.25 mm. During calibration, since the anchor ends of the novel FBG sensor were not yet fixed, the FBG sensor experienced relatively large tensile forces and correspondingly large displacements.

3.1 Establishment of Embankment Model

The test employed an acrylic model box with dimensions of 70 cm × 50 cm × 50 cm. The embankment model, shown in Figure 7 [Figure 7: see original paper], includes sensors, embankment body, and cables. The embankment was constructed using standard sand, with a length of 70 cm and road surface width of 12 cm. The embankment adopted a 1:1 slope ratio with both slope length and height of 9 cm. Standard sand parameters are listed in Table 1 .

3.2 Sensor Layout

Four FBG displacement sensors were installed in the middle section of the embankment model, with specific positions shown in Figure 8 [Figure 8: see original paper]. The spacing between adjacent sensors was 17 cm, with the end sensors positioned 9.5 cm from the model box walls. The four displacement sensors were numbered 1#, 2#, 3#, and 4# from left to right, with corresponding initial wavelengths of 1536 nm, 1532 nm, 1544 nm, and 1552 nm. After sensor installation, 40 mm of standard sand was placed over the FBG sensors, followed by track panel placement. Embankment cross-section dimensions and FBG positions are shown in Figure 9 [Figure 9: see original paper].

3.3 Embankment Monitoring Test

The embankment monitoring test platform comprises an embankment displacement monitoring terminal, wireless signal acquisition terminal, grating demodulator, and signal receiver. Figure 10 [Figure 10: see original paper] shows the established embankment monitoring platform. When the embankment experiences load, the FBG sensor wavelength changes, and signals are wirelessly transmitted to the signal receiver through the wireless acquisition terminal, with the grating demodulator monitoring wavelength variations.

The fiber grating demodulator used for test data acquisition features wide scanning range and high resolution, enabling long-term high-precision monitoring of physical quantities including temperature, strain, pressure, displacement, and acceleration. The demodulator can connect more than 40 FBG sensors on a single fiber and can be expanded to 32 optical channels at any time. This embankment displacement monitoring test employed two loading conditions using different weight masses to simulate vehicle loads.

Condition 1: Static Load Simulation. Loading range was 1–5 kg with stepwise incremental loading of 1 kg per step at a collection frequency of every 20 seconds.

Condition 2: Dynamic Load Simulation. The train model moved at a constant speed of 0.001 m/s from sensor 1# to sensor 4# with a loading range of 1–5 kg.

The force diagram of the FBG sensor inside the soil is shown in Figure 11 [Figure 11: see original paper]. Under load, soil deformation compresses the anchor plates, which exert axial forces on the optical fiber. The stress-strain relationship is as follows. According to Poisson' s ratio:

$$\varepsilon = \frac{\sigma}{E}$$

From Hooke' s law, the relationship between wavelength and vertical stress is:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\frac{\sigma}{E}$$

4 Monitoring Results and Discussion

Figure 11 shows the relationship between wavelength and displacement over time for the four FBG sensors. Test results indicate that sensor wavelength increases stepwise with time, with initial increments of 0.05 nm, 0.04 nm, 0.06 nm, and 0.04 nm, and maximum increments of 0.25 nm, 0.14 nm, 0.21 nm, and 0.24 nm, respectively. The displacement increases linearly, with minimum displacement reaching 0.004 mm and maximum displacement reaching 0.019 mm. The monitoring data demonstrate that FBG sensors possess high sensitivity. Additionally, displacement shows stepwise increases over time, with progressively faster growth rates. During loading, displacement undergoes sudden changes, while remaining stable during unloading periods.

The study focused on analyzing monitoring results from sensor 2#. Figure 12 [Figure 12: see original paper] illustrates the relationship between sensor displacement and time under 1–5 kg dynamic loading. Figure 12(a) shows sensor 2# displacement variation under 1 kg load. The sensor wavelength 突变 at 25 s, with displacement increasing to 0.003 mm at 30 s. After the train passed sensor 2#, the soil returned to its original state, indicating elastic deformation. Figures (b), (c), (d), and (e) show sensor 2# displacement under 2 kg, 3 kg, 4 kg, and 5 kg loads, respectively. In each case, sensor wavelength peaked at 30 s with maximum displacements of 0.0072 mm, 0.016 mm, 0.017 mm, and 0.021 mm. After the train passed sensor 2#, the soil did not return to its original state, indicating plastic deformation. The ratios of residual deformation to peak deformation were 34%, 35%, 38%, and 37%, respectively. Dynamic load tests monitored minimum displacements of 0.003 mm and maximum displacements up to 0.021 mm, with approximately consistent peak and residual deformation ratios occurring at identical times. The monitoring results demonstrate that FBG sensors exhibit high sensitivity, capable of monitoring small embankment deformations under dynamic loads, and can determine whether soil has undergone plastic deformation and the degree of such deformation. In practical applications, the system can not only monitor soil deformation in real-time but also statistically determine the number of different train types passing over a road section based on peak values.

5 Conclusions and Recommendations

Addressing the objective requirements for embankment health monitoring using FBG sensors, this study designed a novel FBG displacement sensor with anchor plates and investigated its performance under various working conditions, yielding the following conclusions:

(1) The embankment displacement monitoring system was successfully designed based on FDM and FBG technology. The system offers several advantages: PVC protective tubes effectively safeguard FBG sensors; FDM technology and PLA materials enable rapid printing of anchor plates for sensor fixation; and the protection of bare fibers from damage allows better performance of FBG sensors.

(2) Calibration test results indicate that the novel FBG displacement sensor can monitor maximum displacements of 0.25 mm and minimum displacements of 0.04 mm. The relationship between load and displacement demonstrates excellent linearity with a correlation coefficient of 0.99. Sensor sensitivity is 4 nm/mm with a resolution of 0.62 μm.

(3) Static load monitoring results demonstrate that FBG sensors successfully measured minimum displacements of 0.005 mm with high precision, confirming the capability of the novel FBG displacement sensor for small deformation measurement. Dynamic load monitoring results show that sensors can rapidly reflect vertical pressure generated by vehicle model loads, successfully monitoring minimum displacements of 0.003 mm and maximum displacements up to 0.021 mm. When trains pass over sensors, wavelength undergoes sudden changes, confirming high FBG sensor sensitivity. Under small loads, soil experiences elastic deformation with recoverable displacement, while under large loads, soil exhibits residual strain with deformation ratios reaching 38%, indicating plastic deformation.

Due to the limited test conditions and number of experimental runs, certain shortcomings require improvement. Subsequent research will expand test conditions and scope, such as investigating embankment settlement and surface deformation.

References

[1] Wonseok CHUNG, Donghoon KANG. Full-scale test of a concrete box girder using FBG sensing[J]. Engineering Structures, 2008, 30: 643-652.

[2] 肖裕民, 黄仁富. 隧道围岩体内位移监测分析 [J]. 西部交通科技, 2009, 28(10): 93-96.

[3] 陈伟民. 大跨径拱桥多维位移的光电组合监测技术研究 [D]. 重庆: 重庆大学, 2008.

[4] 吕聪儒, 楼云, 张鹏. 埋入式激光沉降仪测量法及工程应用 [J]. 水利水电科技进展, 2014, 34(S2): 42-44.

[5] 闫宏业, 蔡德钩, 姚建平, 等. 装配式分层沉降观测装置在路基沉降观测中的应用 [J]. 铁道建筑, 2008(6): 83-85.

[6] 李光伟, 董林玺. 基于 MEMS 加速度传感器的位移检测系统 [J]. 传感器与微系统, 2014, (7): 79-81.

[7] 张斌, 冯其波, 杨靖, 等. 路基沉降远程自动监测系统的研发 [J]. 中国铁道科学, 2012, 33(1): 139-144.

[8] 梁敏富, 方新秋, 薛广哲, 等. 光纤光栅测力锚杆的标定试验 [J]. 煤矿安全, 2015, 46(1): 44-46.

[9] 李伟, 李川. 双悬臂梁式光纤 Bragg 光栅位移传感器 [J]. 微计算机信息, 2011, 27(9): 52-53.

[10] 丁腾蛟. 基于悬臂结构的大量程光纤 Bragg 光栅位移传感器 [D]. 武汉: 武汉理工大学, 2012.

[11] 尹兴彬, 马伟宏, 曹慧, 等. 一种高精度光纤光栅位移传感器设计研究 [J]. 科技信息, 2012(6): 170-171.

[12] LI Hongnan, LI Dongsheng and WANG Suyan. Study and application of health monitoring by fiber optic sensors in civil engineering[A]. ASME, Pressure Vessels and Piping Division, 2003, 468: 217-224.

[13] B. CULSHAW, Smart Structures and Materials[M]. London: Artech House Publishers, 1996. 2-3.

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