Safety monitoring of the Yellow River dike using a fiber optic sensor system

La sécurité surveillant de la digue de la Rivière Jaune en utilisant un système capture optique fibre

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ABSTRACT

The Yellow river of China is known for having its bed that is higher than the neighboring land. For centuries, the river dikes have been an imperative part of the protection for those who live along the river. The river dikes are massive with its total length in excess of 2000 km. Manual inspection from the shoreline has been used to monitor the integrity of the river dike below the muddy water surface. This procedure is time consuming and dangerous, thus making an automated system highly desirable. A feasibility study on the use of an optic fiber Bragg grating based ground deformation monitoring device was conducted as a potential means for automated safety monitoring of the Yellow River dikes. Inclined boreholes were drilled and the sensors installed from the inside of the river dike. The dike surface scouring causes an unloading effect on the underlying soil mass. By detecting the ground deformation results from this unloading effect, the dike surface scouring can be detected at its early stage. The paper describes the principles of the fiber optic monitoring scheme, results of field experiment and discusses the implications in the safety monitoring of Yellow River dikes.

RÉSUMÉ

La rivière Jaune de la Chine est connu pour avoir son lit qu’il est élevé que le territoire voisin. Pour quelques siècles, les digues de rivière a été une partie impérative de la protection pourqu’ils peulent vivre de long de la rivière. Les digues de rivière sont massif avec sa longueur totale au-dessus de 2000 km. L’inspection manuelle à partir de la ligne du rivage a été utilisées pour surveiller l’intégrité de la digue de rivière au-dessous de la surface de l’eux fangeux. Cette procédure est consommé le temp et dangereux, donc en train de se faire le système automatique très désirable. La possibilité de l’étude sur l’utilisation du fibre optique Bragg grillage basé au appareil de la déformation du terrain a été conduit à un moyen potentiel pour la sécurité de surveillance automatique des digues de la rivière Jaune. Les perçages inclinés sont percées et les captures installées à partir du intérieur de la digue de la rivière. La surface de digue frottée cause l’effet déchargant sur le sous-jacent sols masses. En détectant les résultats de la déformation du terrain à partir de celui-ci l’effet déchargant, la surface de digue frottée peut être détectée dans sa première période. Cet article décrit les principes du système surveillant optique fibre, les résultats de l’expérience chianter et discute les implications dans la sécurité surveillant des digues de la Rivière Jaune.

Keywords : river dike safety, fiber optic sensor

1 INTRODUCTION

History shows that a breakage of the Yellow river dike could devastate the neighboring land. The section of Yellow River within Henan Province, China that needs to be protected is 444 km in length. The River is guarded by two primary dikes on both sides. These dikes are earth embankments built with compacted sand obtained locally. The distance between the primary dikes varies from a few to well over ten kilometers. The actual river channel, with no more than a few hundred meters in width, meanders within the primary dikes. If left uncontrolled, the river channel could change its course randomly. The river channel, if flowing in a sharp striking angle can jeopardize the safety of the primary dikes. A series of regulatory structures have been built within the primary dikes to confine the river channel in a more gentle wavy form. A typical regulatory structure consists of 20 to 30 embankments extending out from the shoreline at an angle of 70° pointing to the downstream direction. These embankments, approximately 100m long and 15m wide, are spaced at approximately 110m and built with compacted sand. The embankment is locally referred to as the T-dike.

The damage of a T-dike in the regulatory structure could start in many forms but the process of failure usually involves scouring at the toe of the dike. The water in Yellow River has very high sediment concentration and thus is muddy and yellowish in color. Because of the muddy nature of the river, underwater dike scouring is usually not visible from the surface. A long steel rod inserted from the shoreline has been used historically to sense under-water irregularities by hand. This procedure is time consuming and dangerous, thus making an automated system highly desirable. For the automated monitoring system to be feasible, we have to be able to implement such a system massively in a practical fashion. Earlier attempts using infrared and sonar systems to detect underwater soil scouring have been experimented but with limited success. From geotechnical engineering point of view, a river dike made of compacted sand is an earth slope; the dike toe scouring may be considered a shallow slope failure.

Techniques of laying optic fiber serving as linear extensometers on the slope surface in a zigzag fashion have been reported as a means to monitor the integrity of river dikes (Kihara et al., 2002) as conceptually described in Figure 1. A surface slope failure would stretch the optic fiber crossing the failure zone and cause the strain readings within that part of the optic fiber to increase. A warning signal indicating the location of the failure can thus be generated. Similar ideas have been experimented on the Yellow River dikes. The optic fiber was replaced with electronically sensored extensometers. With proper layout, the extensometers had the necessary sensitivity to detect dike surface failure. However, such a surface installation is sacrificial in nature as the dike failure can severely damage.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)
© 2011 IOS Press
doi:10.3233/978-1-60750-031-5-3503
the instrument. If implemented in a large scale as it would be required for the Yellow River, the maintenance frequency and costs can be impractically high for such sacrificial schemes. The in-place inclinometer was also considered but abandoned later due to its high cost.

![Image](https://via.placeholder.com/150)

Figure 1. Layout of optic fibers on the slope surface to detect failure (after Kihara et al., 2002).

Because of the above reasons, it was decided that a sensor system installed from within the embankment, on a non-sacrificial basis would be more desirable. The instrument should be located in such a way that it is capable of detecting loss of embankment material in its early stage. The scouring or removal of soil causes an unloading effect to the underlying ground mass. By extending the instrument from above water, not affected by the scouring to a distance below the expected zone of scouring, the instrument should reflect the effects of non-uniform ground movement in a form of deflection. If the lost soil is backfilled quickly, then there should be no irreversible damage to the instrument, thus render the system reusable. Earlier research has indicated that ground movement at a distance from failure zone is expected to be small (Burland, 1989). For the instrumentation scheme to be effective, sensitivity is imperative. The sensitivity is increased by placing the instrument close to the potential failure zone. However, close proximity to the failure zone can also jeopardize the longevity of the instrument. With these considerations in mind, the authors explored the possibility of using an optic fiber Bragg grating segmented deflectometer (FBG-SD) for the purpose of providing early warning of dike toe scouring.

The instrumentation scheme was evaluated by field installations at a test site. The effects of soil scouring were simulated by gradual removal of a pile of rock pieces initially placed on the surface of the dike. Readings from the instruments were taken during the piling and removal of the rock pieces.

2 THE OPTIC FIBER BRAGG GRATING SENSOR

Hill et al. (1978) suggested that gratings can be generated by sustained exposure of an optic fiber core to laser radiation under a controlled pattern of interference. Following this concept, Meltz et al. (1989) pioneered the techniques of producing in-fiber Bragg grating (FBG) sensors. A periodic variation or modulation of fiber core refractive index is formed by exposing that 1 to 20 mm segment of single mode optic fiber to a spatial pattern of ultraviolet light. When the FBG is illuminated by a broadband light source, a fraction of the light is reflected back upon interference by the FBG. The wavelength of the reflected light, or the Bragg wavelength, \( \lambda_B \) is related to the period of the index modulation, \( \Lambda \) and effective fiber core index of refraction, \( n \) as

\[
\lambda_B = n\Lambda \tag{1}
\]

Longitudinal strains within the Bragg grating, \( \varepsilon_B \) induced by variations in temperature or stress can cause a change in \( \Lambda \) and thus a shifting of \( \lambda_B \), with the following approximate relationships (Rao, 1998):

\[
\Delta\lambda_B = 0.74\lambda_B\varepsilon_B \tag{2}
\]

and

\[
\Delta\lambda_B = 8.9\times10^{-5}\lambda_B\Delta T^\circ C \tag{3}
\]

where \( \Delta T \) is the change of temperature in degree Celsius. The constants in Equations (2) and (3) can vary, depending on the photoelastic properties of the optic fiber. The returned signal from every FBG carries a unique range or domain of wavelength \( \lambda_B + \Delta\lambda_B \), making it possible to have multiple FBG elements on the same fiber. The multiplexing among various sensors on a single fiber can be accomplished by wavelength division addressing as conceptually described in Figure 2. There is a limited bandwidth of the light source and as the light passes an FBG there is a loss of its intensity, the number of FBG sensors that can be placed on a fiber is not more than 20 with the currently available FBG interrogation systems.

3 THE FBG BASED GROUND DEFORMATION MONITORING SYSTEM

The FBG based ground deformation monitoring system described in this paper is referred to as the FBG Segmented Deflectometer or FBG-SD. Details of the optic fiber Bragg grating segmented deflectometer (FBG-SD) design and its principles have been reported by Ho et al. (2006). An FBG-SD sensor unit consists of two rigid segments that are made of casted aluminum tubes. These two rigid segments are connected through a hinge as shown in Figures 3 and 4. A flexible rod is fixed on one of the two segments with two bolts, passes through the hinge and is only supported on the other segment by a pin. The FBG-SD is equipped with spring loaded wheel sets which are compatible with the conventional inclinometer casings. The distortion of the inclinometer casing induced by ground movement causes a relative rotation between the rigid segments of the inserted FBG-SD. This relative rotation creates bending in the flexible segment which behaves as a cantilever. The bending, in turn, causes flexural strains to a pair of the FBGs attached to the opposite sides of the flexible rod. This arrangement allows the FBG’s to sense flexural strains and nullify the thermal effects due to temperature variation.

![Image](https://via.placeholder.com/150)

Figure 2. FBG sensor array (after Kersey, 1992).

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Figure 3. Schematic view of an FBG-SD unit.

The amount of FBG-SD deflection relates to the wavelength shifting of the light signals reflected from the FBG’s. Figure 5 shows a laboratory calibration results of an FBG-SD. The results show change of FBG peak wavelength in pm \((10^{-12}m)\) and its relationship with the angle of rotation of the FBG-SD in degrees. As demonstrated in Figure 5, a pm of wavelength change corresponds to 0.0012 degree in FBG-SD rotation. These relationships are highly linear and repeatable as the coefficients of correlation \( R^2 \) are greater than 0.999. The
FBG-SD is designed to perform with the above specifications to a maximum rotation of 2.0 degrees. The amount of lateral movement is computed based on the distribution of the segment deflections. For field deployment, a series of 750mm long FBG-SD units were connected together as the assembly was inserted into the pre-installed inclinometer casing. More space can be added by inserting aluminum tubes between the FBG-SD sensor units. Multiple FBG-SD units share the same optic fiber because of the partially distributive nature of FBG (Ho et al., 2006).

The sensor probe was embedded inside the dike body and thus not likely to be damaged by the dike surface deterioration. The effectiveness of the design concept and sensitivity of the sensor system were verified by loading and subsequent unloading simulations on the dike surface. A 2m wide wedge shaped pile of rock was formed along the face of the dike slope first to a maximum height of 2m and then removed in stages. The sensor readings were taken as the rock pile was formed and removed.

The top of BH4 was destroyed during an emergency operation prior to the field testing of November, 2003. No test was conducted for the sensors installed in BH4. Figures 8 and 9 show the deformation profile of the inclinometer casing as interpreted from the series of FBG-SD readings in BH3 during loading and unloading, respectively. The deformations shown in Figures 8 and 9 are perpendicular to the longitudinal axis of the inclinometer casing. For readings taken during loading, the first stage of rock pile had a total volume of 5.0m$^3$ and the second 4.7m$^3$, placed on the slope surface directly above the line of BH3 (the centerline of rock pile had 0 offset from that of BH3). The unloading readings were taken after complete removal of the rock pile. The negative deformation points downward as a result of rock pile loading from the slope surface. The deformation reading during unloading was in reference with the inclinometer reading after removal of the rock pile. In all the cases, the FBG-SD has the potential to repeatedly reflect the effects of loading/unloading. However, some plastic deformation is inevitable. By offsetting the position of the rock pile by as much as 0.75m, the FBG-SD could still reasonably reflect the effects of loading/unloading. For tests over BH5, the

Figure 6. Plan view of T-dike No.24.

Figure 7. Cross sectional view of the field installation.
deformation was more significant in the case with rock pile placed at offset position than not. This is likely caused by the fact that the borehole might have been drilled in an inclined position both in vertical and horizontal plane. Readings in BH5 showed similar sensitivity and pattern as those in BH3. For rock pile with offset larger than 1m, the FBG-SD showed no significant readings as a result of loading/unloading. The amounts of deformation are consistent to the findings by Burland (1989) who stated that movements in soil mass caused by loading or unloading are usually small in areas away from the failure zone.

5 CONCLUDING REMARKS

The field tests demonstrated that the FBG-SD system developed by the authors can be effectively used for the purpose of monitoring the Yellow River dike. The FBG based sensors have the necessary sensitivity to monitor ground deformation in its pre-failure stage when the soil behaved in linear or non-linear elastic fashion. In this manner, the sensor is not easily damaged or sacrificed in order to perform its duty for safety monitoring. The fact that the FBG-SD performs its duty in a “non-sacrificial” way should make this system durable and less demanding in maintenance.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>BH</th>
<th>Offset m</th>
<th>Vol. of rock pile m³</th>
<th>Max. def., mm</th>
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<td>0</td>
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<td>-0.183</td>
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<td>+9.7</td>
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<tr>
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<td>5</td>
<td>0.5</td>
<td>-10.8</td>
<td>0.637</td>
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</table>

(a) First load test at BH3 with 0 offset
(b) Second load test at BH3 with 0 offset
(c) Deformation in reference to the initial position
(d) Deformation in reference to the position at the end of loading

REFERENCES