

Safety Monitoring of the Yellow River Dike
A Feasibility Study on Various Instrumentation Schemes

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Abstract

The Yellow river of China is known for having a river bed that is higher than its neighboring land. For centuries, the river dikes have been an imperative part of the protection for those who live along the river. Manual inspection from the shoreline has been the normal procedure to monitor the integrity of the river dike below water surface. This procedure is time consuming and dangerous, thus making an automated system highly desirable. Several schemes were evaluated in order to investigate the possibility of a practical and automated method to safeguard the river dikes. Systems tested included strain gauged steel angle, vibrating wire extensometer, and optic fiber Bragg grating based ground displacement monitoring devices. A test site was set up at a dike in Wu-Tze County, Henan Province. Inclined boreholes were drilled and the test instruments installed from the inside of the river dike. In order to validate the effectiveness of the design concept and sensitivity of the sensor systems, a rock pile was formed along the face of the dike first and then removed. The unloading simulated the effects of a dike scouring. The sensor readings were taken as the rock pile was removed. This paper describes the principles of the various monitoring schemes, presents results of the field experiment and discusses the implications in the safety monitoring of Yellow River dikes.

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 that is locally available. 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^o 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 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 erosion have been experimented but with limited success. From geotechnical engineering point of view, the dike toe scouring may be considered as a form of slope surface failure.

Techniques of laying optic fiber sensors 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.

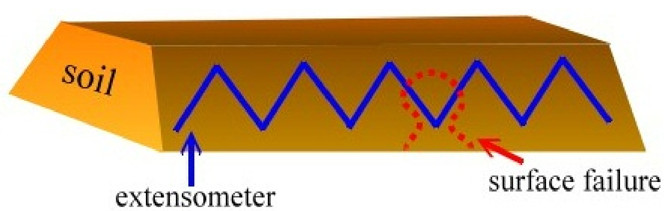


Figure 1 Layout of optic fibers on the slope surface to detect failure.

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 was sacrificial in nature as the dike failure can severely damage 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.

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 to detect the 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 and/or longitudinal displacement. If the eroded 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 an important consideration. The sensitivity is increased by placing the instrument close to the potentially erodible zone. However, close proximity to the failure zone can also jeopardize the longevity of the instrument. With these considerations in mind, three schemes were selected initially to evaluate their feasibility for the purpose of providing early warning of dike toe scouring. These schemes included:

1. Strain gauged steel angle;
2. Vibrating wire rod extensometer; and
3. Optic fiber Bragg grating segmented deflectometer (FBG-SD).

These instrumentation schemes were evaluated by field installations at a test site where the sensors were inserted in inclined boreholes at a distance from the slope surface. 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. The paper describes the design concepts of the instrumentation schemes, field experiments, and discusses implications in future deployment of these systems in light of the study.

The Field Set Up

The experiment was carried out at dike No.24 in Wu-Tze County of Henan Province. Dike No.24, second from the downstream end of a series of 25 T-dikes, belonged to a 3.6km long regulatory structure on the north side of Yellow River. A plan view of the T-dike is shown in Figure 2. Completed in 1996, Dike No.24 had been backfilled 69 times as of 2004 with a total backfill volume of 5655m^3, due to various levels of damages.

Five 120mm diameter boreholes inclined at 45^o from vertical and 2m inside the dike's upstream surface were drilled at the test site. Figure 3 shows the cross sectional view of a borehole and its relationship with the dike body. The distribution and length of various instruments installed in the boreholes are summarized in Table 1. Inclinometer casings were inserted in boreholes BH3, BH4 and BH5. A series of FBG-SD were installed in each of the three inclinometer casings. In the other boreholes, where FBG-SD was not used, the instrument was grouted in the borehole.

In case of dike scouring, heavy vehicles would move in to quickly backfill the cavities caused by the scouring. To protect the monitoring system, all instruments were terminated at approximately 500mm from the ground surface. All signal transmission cables were buried in trenches that lead to an underground storage chamber (see Figure 2) where all the cables were assembled and connected to their respective readout units. Electric power was provided by a solar panel and batteries. The electric signals were converted into optic forms and then transmitted through fiber optic cable to a field control office at 1.5km away. The same fiber optic cable was also used to transmit the optic signal for the FBG-SD to the field control office. No power or signal conversion was required for the FBG-SD at the dike.

The Instrumentation Schemes

The types of instruments selected for the project ranged from rather simple and/or conventional to advanced techniques. The following sections provide a brief description of these instruments and their field installation.

Strain gauged steel angle

The purpose of the steel angle was to sense the bending experienced by the soil mass as a result of the ground movement caused by surface scouring. The instrument was made of 1.5m long, 30mm by 30mm steel angles with a thickness of 3mm. A single strain gauge with its long axis in line with the longitudinal direction of the steel angle was attached to the edge on each of the two flanges of the steel angle. The strain gauges were spaced at 1m apart. Multiple pieces of strain gauged steel angles were end-to-end bolted together to form an instrument with the desired length. The assembled steel angle was than grouted in the borehole. A separate strain gauge was hung freely near the top of the steel angle assembly to serve as a reference of temperature fluctuation. During field installation, one of the flanges was pointing in the vertical direction to maximize its sensitivity to the upward ground movement as a result of the surface scouring.

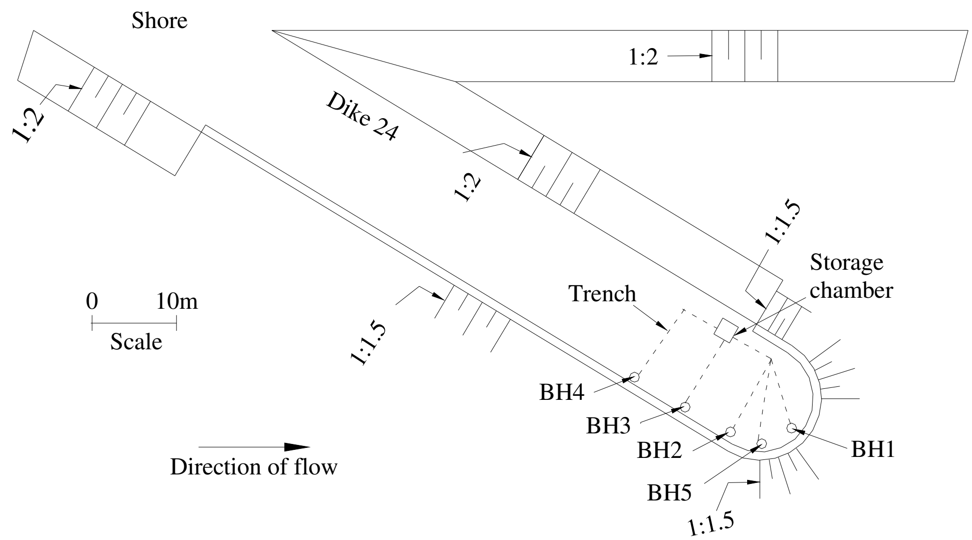


Figure 2. Plan view of Dike No.24.

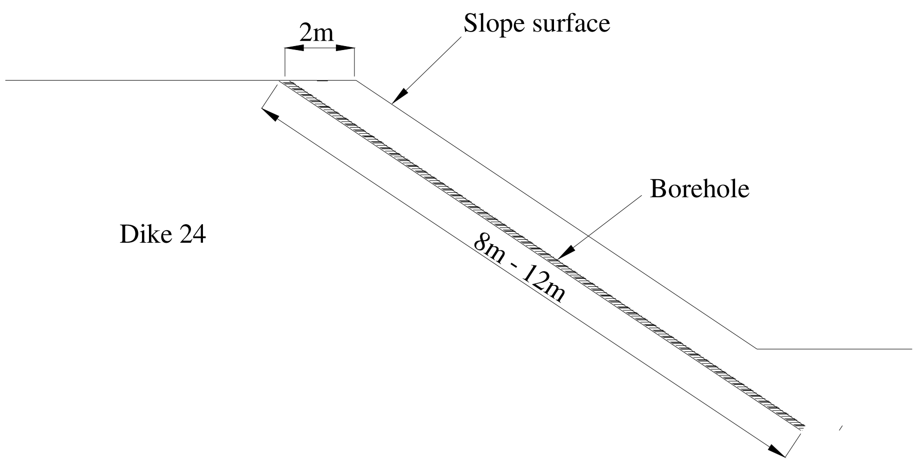


Figure 3. Cross sectional view of the field installation.

Vibrating wire extensometer

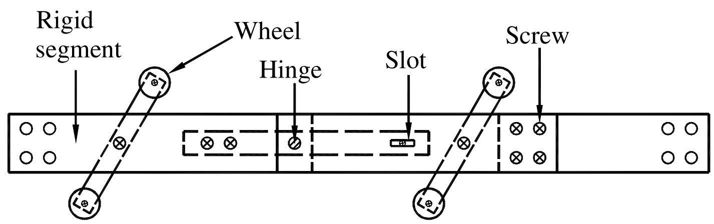
A single point, rod extensometer with a range of 150mm and resolution of 0.025mm was used in the field. The basic idea was to fix a groutable anchor at the end of the borehole. The 3/16-inch (4.8mm) diameter fiberglass extensometer rod along with its protective tubing and anchor were grouted in the borehole. The reference head and the vibrating wire displacement transducer were installed at the borehole collar near the ground surface. For the extensometer to serve its purpose, the upward ground movement as a result of its surface scouring should cause the extensometer rod to bend and thus displace longitudinally (pulling) between the head and anchor of the extensometer.

Table 1. Distribution of instrumentations.

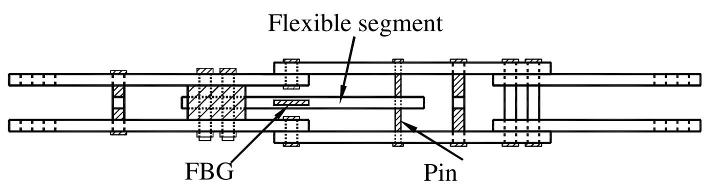
Borehole No.	Type(s) of instrumentation	Length of installation, m
BH1	Strain gauged steel angle	8.7
BH2	Vibrating wire extensometer	12.0
BH3	1. FBG-SD 2. Strain gauged steel angle	1. 8.0 2. 8.0
BH4	1. FBG-SD 2. Vibrating wire extensometer	1. 8.0 2. 8.5
BH5	1. FBG-SD 2. Vibrating wire extensometer	1. 8.0 2. 8.5

The 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). The FBG-SD evolves from the electrically sensored deflectometers (Dutro, 1977; Dunnicliff, 1988; and Kumbhojkar, 1991). An FBG-SD sensor unit consists of two rigid segments that are made of aluminum plate. These two rigid segments are connected through a hinge as shown in Figure 4. A flexible rod (i.e., the flexible segment) is fixed on one of the two segments with two bolts, passes through the hinge and simply supported on the other segment by a pin. The FBG-SD is equipped with spring loaded and wheeled studs 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 as shown in Figure 5. 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. The amount of FBG-SD deflection relates to the wavelength shifting of the light signals reflected from the FBG's. The FBG-SD had a resolution of 0.001 degree in FBG-SD rotation. The relationship between FBG-SD rotation and wavelength readings are highly linear and repeatable as the coefficients of correlation (R^2) are usually greater than 0.999. The FBG-SD can withstand a maximum rotation of 2.0 degrees. The amount of lateral movement is computed based on the distribution of the segmented 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. Multiple FBG-SD units can share the same optic fiber because of the partially distributive nature of FBG (Ho et al., 2006).



(a) Side view.



(b) Top view.

Figure 4. Schematic views of a single FBG-SD unit (from Ho et al., 2006).

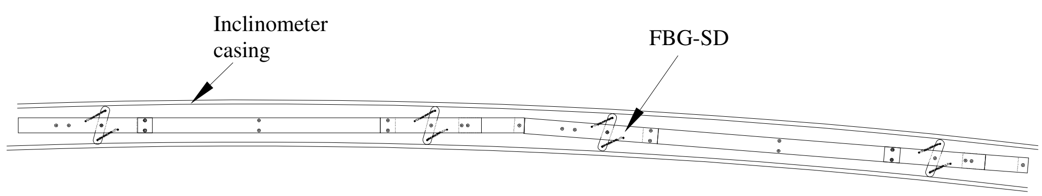


Figure 5. Rotation of FBG-SD caused by casing deflection (from Ho et al., 2006).

Field Loading Tests

The borehole drilling and installation of sensors were completed in August, 2003. Field testing was initiated in November, 2003. Ideally, the effectiveness of the instrumentations should be tested by excavating parts of the dike from below the water surface while taking the instrument readings. Because of the risks involved, the effectiveness of the design concept and sensitivity of the sensor systems were verified by loading and subsequent unloading simulations on the dike surface, above water. The sensor readings were taken as the rock pile was formed and removed. The placement and removal of rock piles were carried out by hands as the weight of the machinery could be comparable or more than the rock pile itself. The field tests started in November, 2003 and continued until June, 2006. For demonstration purpose, only some of the representative or final test results are presented in the paper.

For testing the strain gauged steel angle installed in BH3. A 2m wide wedge shaped pile of rock pieces was formed along the face of the dike slope directly above the line of BH3, to a maximum height of 2.5m and then removed. The total volume of the rock pile was approximately $10m^3$ (density of rock pile = 1.7 metric tons per m^3). Table 2 shows the distribution of the strain gauges on the steel angle installed in BH3. Some of the strain gauges were damaged during installation. Figure 6 shows a sequence of 6 sets of strain gauge readings taken in BH3, on November 12, 2003. All strain gauge readings are in micro-strains and referenced to the respective initial readings. The rock pile was placed between reading sequence 4 and 5 and removed before reading sequence 6. As shown in Figure 6, no significant correlation between the loading history and strain gauge readings can be identified. The scheme of strain gauged steel angle was eliminated from the remainder of the field experiments due to the lack of sensitivity.

Table 2 Location of strain gauges attached to the steel angle in BH3.

Distance from Bottom of borehole	1m	2m	3m	4m	5m	6m	7m
Vertical flange	2-1	2-3	2-5	2-7	2-9	2-11	2-13
Horizontal flange	2-2	2-4	2-6	2-8	2-10	2-12	2-14

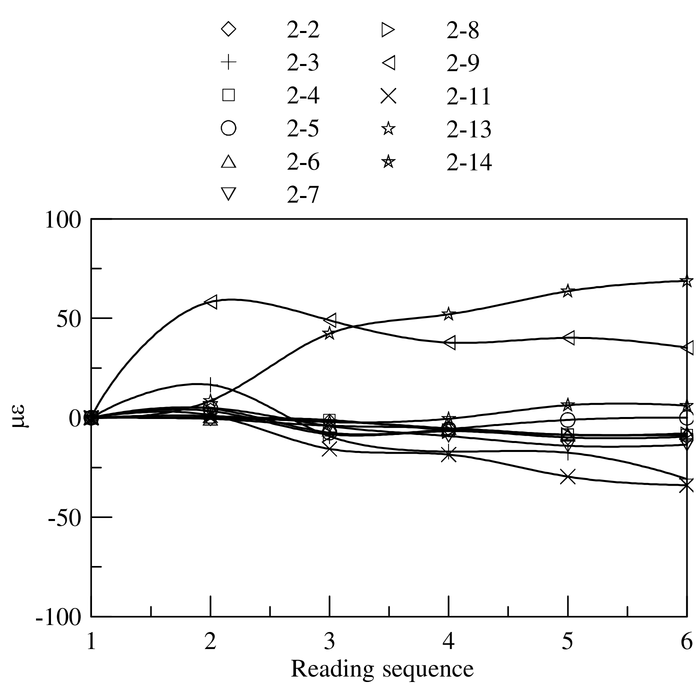


Figure 6. Strain gauge readings from BH3.

For testing the vibrating wire extensometers, a rock pile with a total volume of 59 m^3 was placed on the slope surface extending from BH2 to BH5 which were spaced at 2.4m. Figure 7 depicts the displacements obtained at the reference head in BH2, during unloading. Apparently, the placement of rock pile pushed the soil mass downward and caused a stretching of the extensometer rod. The negative readings indicate shortening in distance between the extensometer rod anchor and the reference head as a result of unloading. The displacement albeit small, was consistent in reflecting the effects of unloading. The change in extensometer readings of BH5 during the same unloading process was however, extremely low. The sensitivity of the extensometer was probably disrupted by the mixture of extensometer rod with the inclinometer casing in BH5.

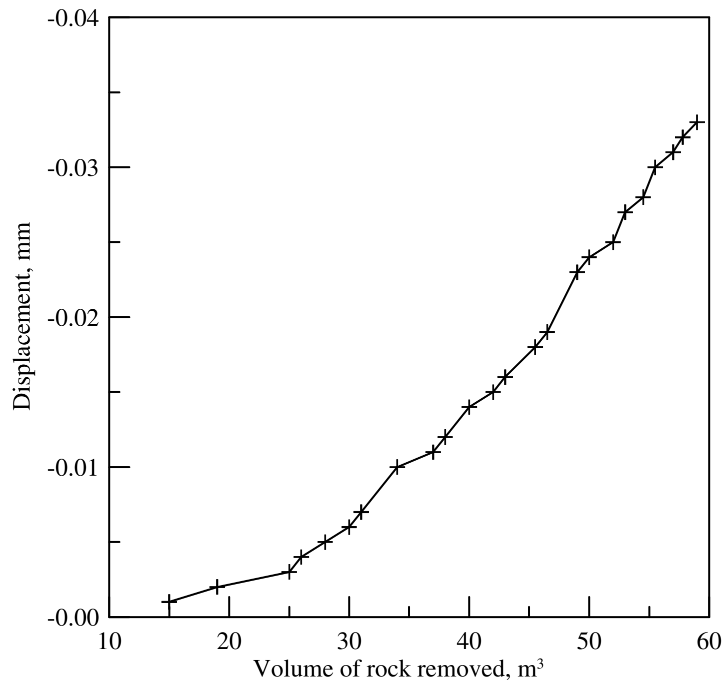


Figure 7. Displacements from extensometer in BH2.

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. For the FBG-SD placed in BH3 and BH5, the process of loading and unloading was repeated 5 times in different configurations. Figures 8 and 9 show the deflection profile of the inclinometer casing as interpreted from the series of FBG-SD readings. The displacements 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 displacement points downward as a result of rock pile loading from the slope surface. The displacement reading during unloading was in reference with the deflection of the inclinometer casing and the end of loading. The positive displacement indicates an upward rebound of the inclinometer reading after removal of the rock pile. In all the FBG-SD measurements during the simulation tests, the maximum displacement always occurred at the bottom of the inclinometer casing.

Table 3 summarizes the maximum displacement readings obtained from all the loading and unloading tests on FBG-SD. A comparison between Test No.3 (a repeat of Test No.1) shows that 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 displacement 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 otherwise, 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.

Concluding Remarks

The experiment described in the paper showed that both the vibrating wire extensometer and FBG-SD have the potential to monitor the stability of Yellow River dikes on a non-sacrificial basis. The FBG-SD has higher sensitivity as it measures deflections in a direction that is most influenced by the unloading effects in case of scouring, in addition to the higher sensitivity of the sensor itself. In case of actual scouring, the unloading occurs within the soil mass, and thus should induce more significant readings to the sensors. For limited installations, the vibrating wire extensometer is more economical than the FBG-SD mainly due to the high cost of FBG interrogation system. When deployed in large scale, the FBG-SD can be more competitive, as the FBG is a partially distributed sensor. A single interrogation system coupled with optical switches can be shared by multiple FBG-SD installations that are over 10 kilometers apart and not losing the quality of signals. By placing the instruments at a distance away from the potential failure zone, the sensors are less likely to be damaged while serving their functions. A disadvantage of non-sacrificial deployment is that the installation of sensors requires the drilling of inclined boreholes. Also, the field experiment shows that the instrument installed in a single borehole may be effective only for scouring occurrences within 1m in lateral direction from the borehole. It would be difficult or costly to make a full coverage of the dike surface for safety monitoring. In any case, more tests may be required to ascertain the long term stability of the systems as a means to safe guard river dikes.

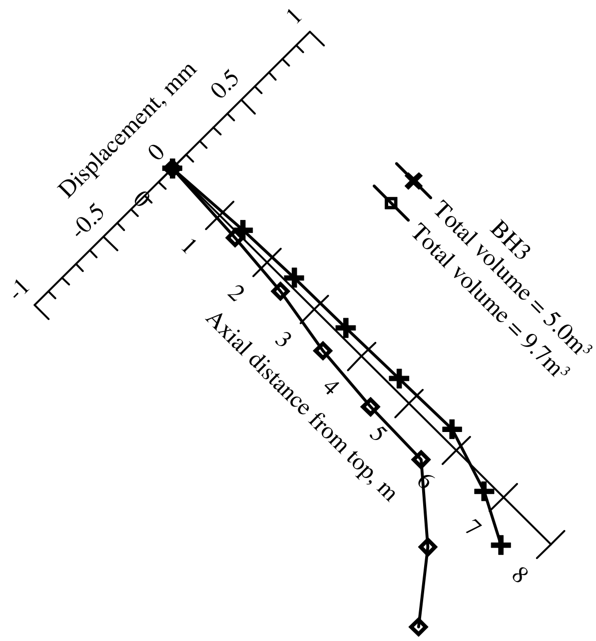


Figure 8. Displacement profile in BH3 from the first loading test.

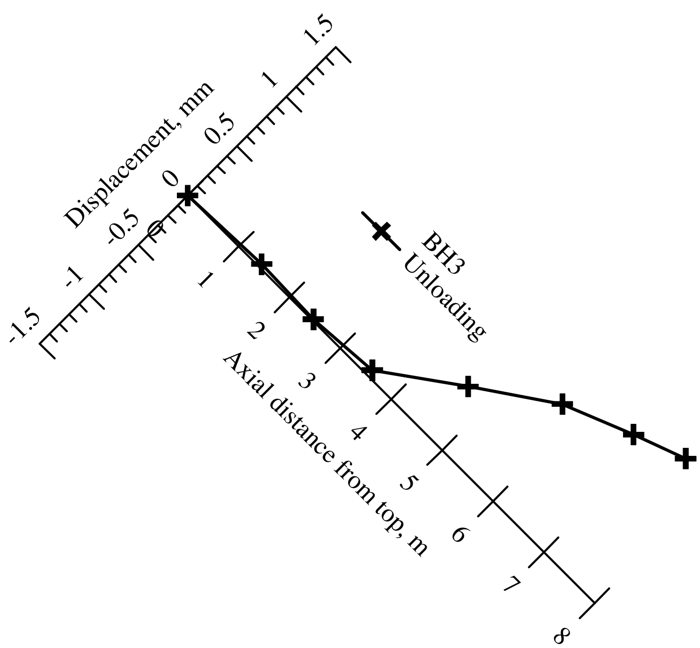


Figure 9. Displacement profile of BH3 after removal of $9.7m^3$ of rock pile.

Table 3. Maximum FBG-SD displacement readings

Test No.	Borehole	Offset, m	Total volume of rock pile placement/removal, m^3 + : placement; -: removal	Maximum relative displacement, mm + : up[(c)] -: down[(d)]
1	BH3[(a)]	0	+5.0	-0.183
1	BH3[(a)]	0	+9.7	-0.782
1	BH3[(a)]	0	-9.7	1.192
2	BH3	0.75	+5.3	0.028
2	BH3	0.75	+8.2	-0.264
2	BH3	0.75	-8.2	0.058
3	BH3[(b)]	0	+5.9	-0.163
3	BH3[(b)]	0	+10.3	-0.626
3	BH3[(b)]	0	-10.3	+0.783
4	BH5	0	+4.7	-0.036
4	BH5	0	+9.9	-0.314
4	BH5	0	-9.9	0.414
5	BH5	0.5	+6.7	-0.101
5	BH5	0.5	+10.8	-0.925
5	BH5	0.5	-10.8	0.637

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

References

Burland, J.B. (1989). "Small is Beautiful-the Stiffness of Soils at Small Strains." Canadian Geotechnical Journal, 26 (4), 499-516.

Dutro, H. B. (1977). "Borehole Measurements Using Portable Borehole Deflectometers", *Proceedings of 18th symposium on Rock Mechanics*, Keystone, CO, Colorado School of Mines Press, Golden, Co, pp. 5C4-1 to 5C4-5.

Dunnicliff, J. (1988). "*Geotechnical Instrumentation for Monitoring Field Performance*", Wiley-Interscience, New York.

Ho, Y.T., Huang, A.B., and Lee, J.T. (2006). "Development of a fiber Bragg grating sensored ground movement monitoring system," Journal of Measurement Science and Technology, Institute of Physics Publishing, 16,733-1740.

Kumbhojkar, A. S., Israel, T. D., Arnstan, D., and Lee, S. M. (1991). "Development of a Combination Inclinometer-Deflectometer and ADAAS", *ASTM Geotechnical Testing Journal*, 14(4), 451-456.

Kihara, M., Hiramatsu, K., Shima M., and Ikeda, S. (2002). "Distributed Optical Fiber Strain Sensor for Detecting River Embankment Collapse", *IEICE TRANS. ELECTRON*., E-85-C(4), 952-960.