US 20070069115A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2007/0069115 A1

Huang et al.

(43) Pub. Date: Mar. 29, 2007

(54) **FIBER BRAGG GRATING SENSORED SEGMENTED DEFLECTOMETER FOR GROUND DISPLACEMENT MONITORING**

(75) Inventors: **An-Bin Huang**, Ciyueng Lin Township (TW); **Yen-Te Ho**, Taipei City (TW)

Correspondence Address:
BUCKNAM AND ARCHER
1077 NORTHERN BOULEVARD
ROSLYN, NY 11576 (US)

(73) Assignee: **National Chiao Tung University**, Hsinchu (TW)

(21) Appl. No.: **11/342,927**

(22) Filed: **Jan. 30, 2006**

(30) **Foreign Application Priority Data**

Sep. 23, 2005 (TW) 094133010

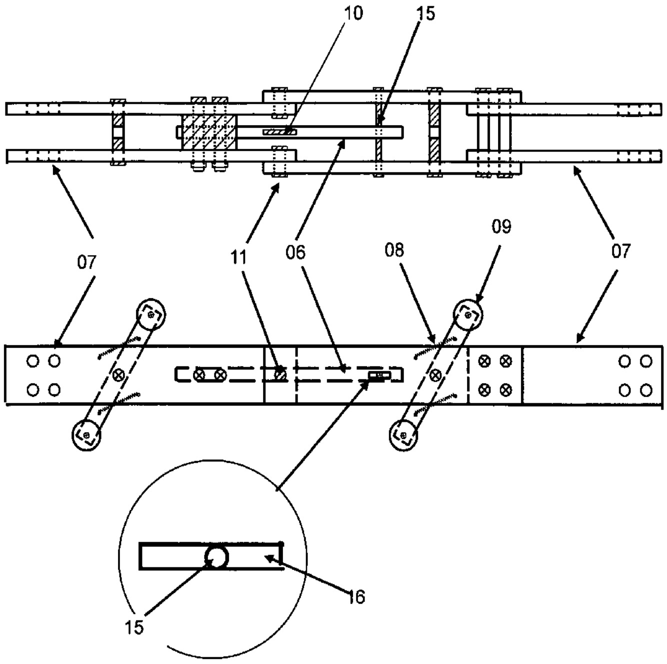
Publication Classification

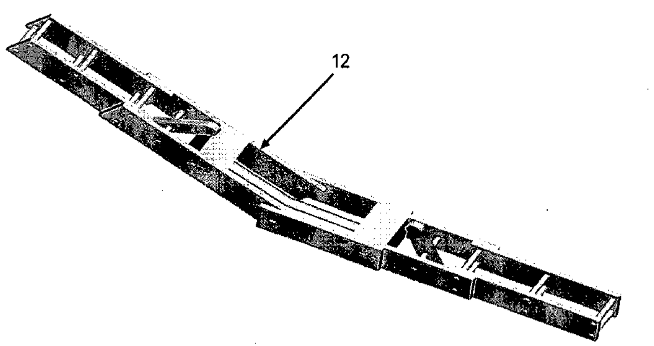
(51) **Int. Cl.**
G01J 1/04 (2006.01)

(52) **U.S. Cl.** **250/227.14**

(57) **ABSTRACT**

The invention provides a monitoring device mainly for sensing ground displacement, including the fiber Bragg grating sensored deflectometer and the signal interrogator/computer system. The device uses a segmented design that consists of a flexible tube (referred to as the flexible segment) and two rigid segments and thus referred to as the FBG segmented deflectometer (FBG-SD). For field installation, multiple FBG-SD units are connected together to form a string as it is inserted into a grouted-in-place inclinometer casing. The distortion of the inclinometer casing induced by ground movement causes relative rotation of the inserted FBG-SD. All of the FBG-SD units are connected to an FBG interrogator/computer system situated on ground surface. The FBG signals are recorded and analyzed by the interrogator/computer system.





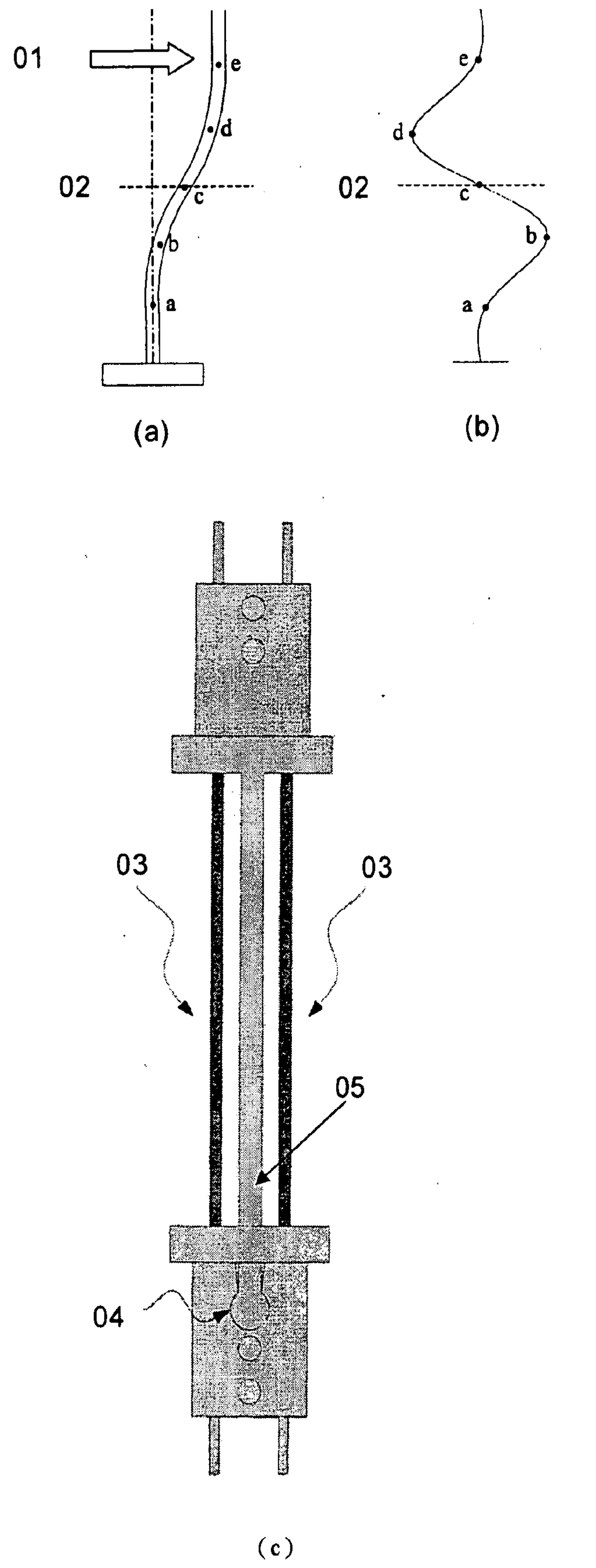
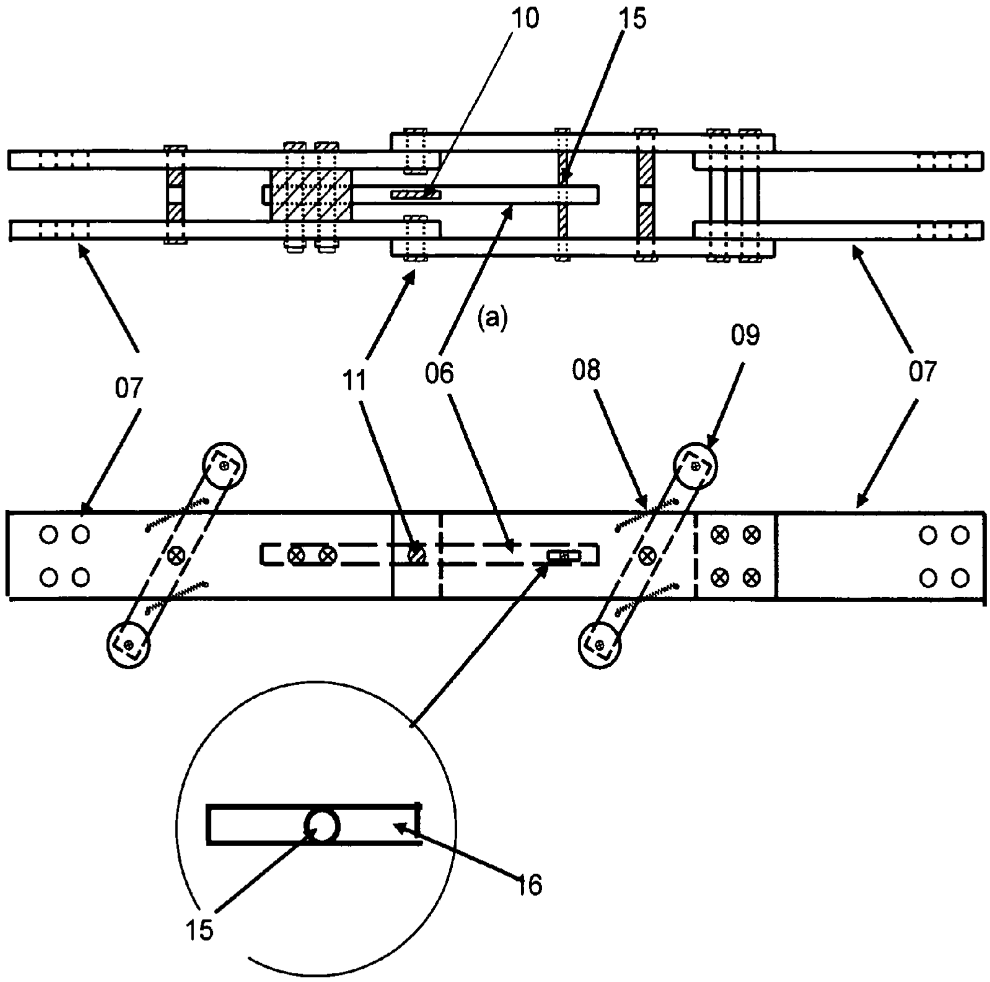
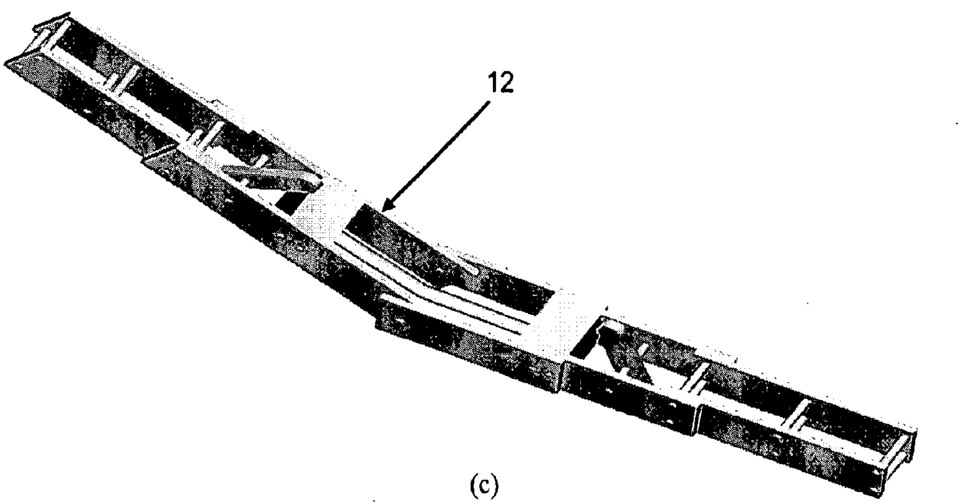


Fig. 1(a)、1(b)、1(c)





(c)

Fig. 2(a)、2(b)、2(c)

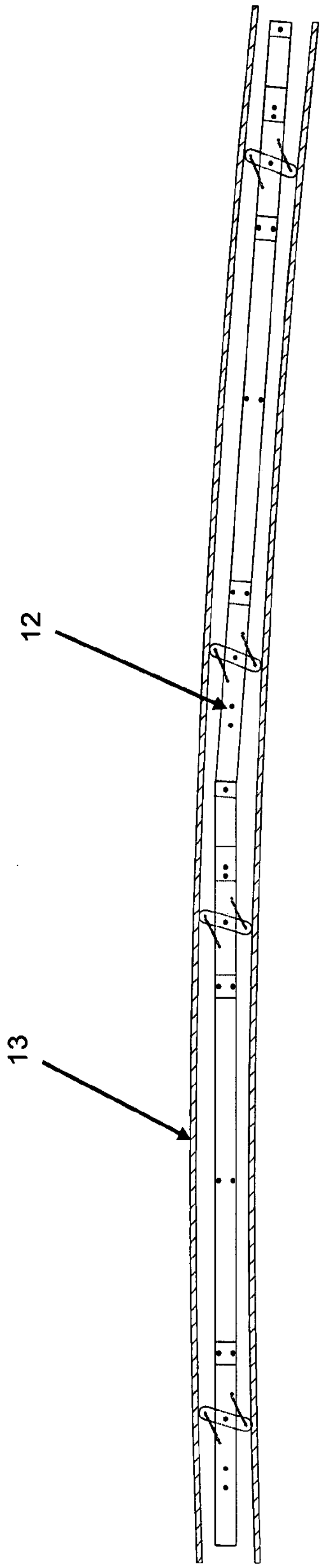


Fig.3

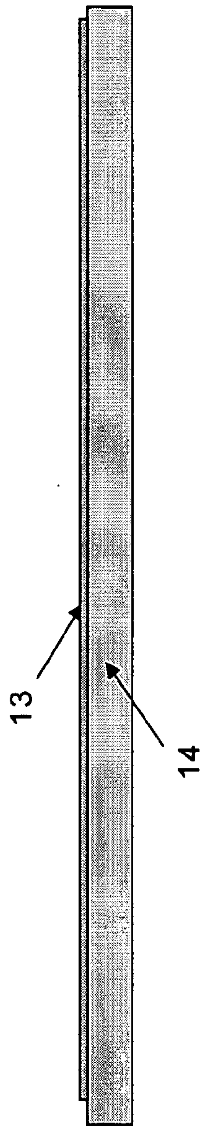


Fig.4

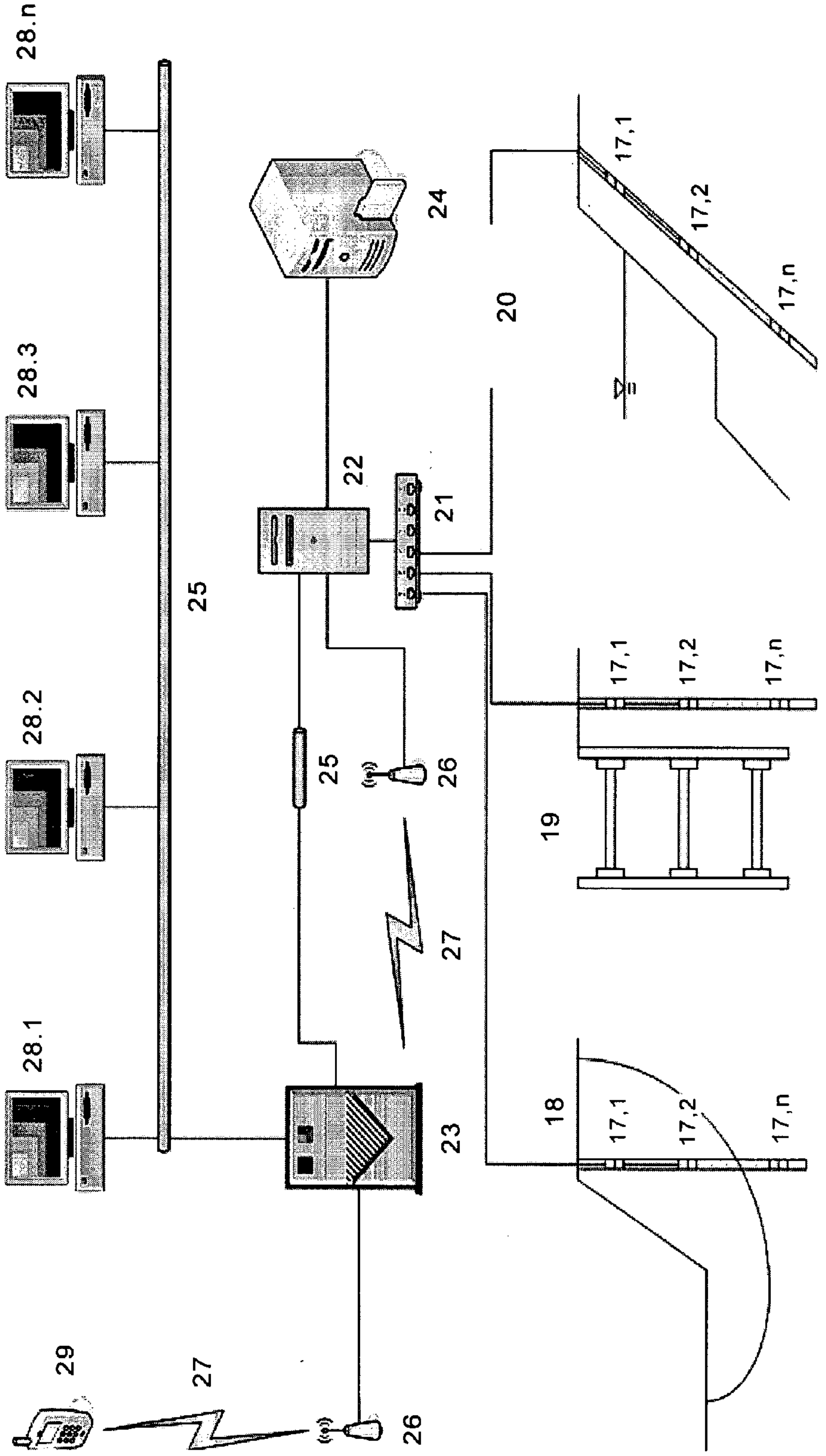


Fig.5

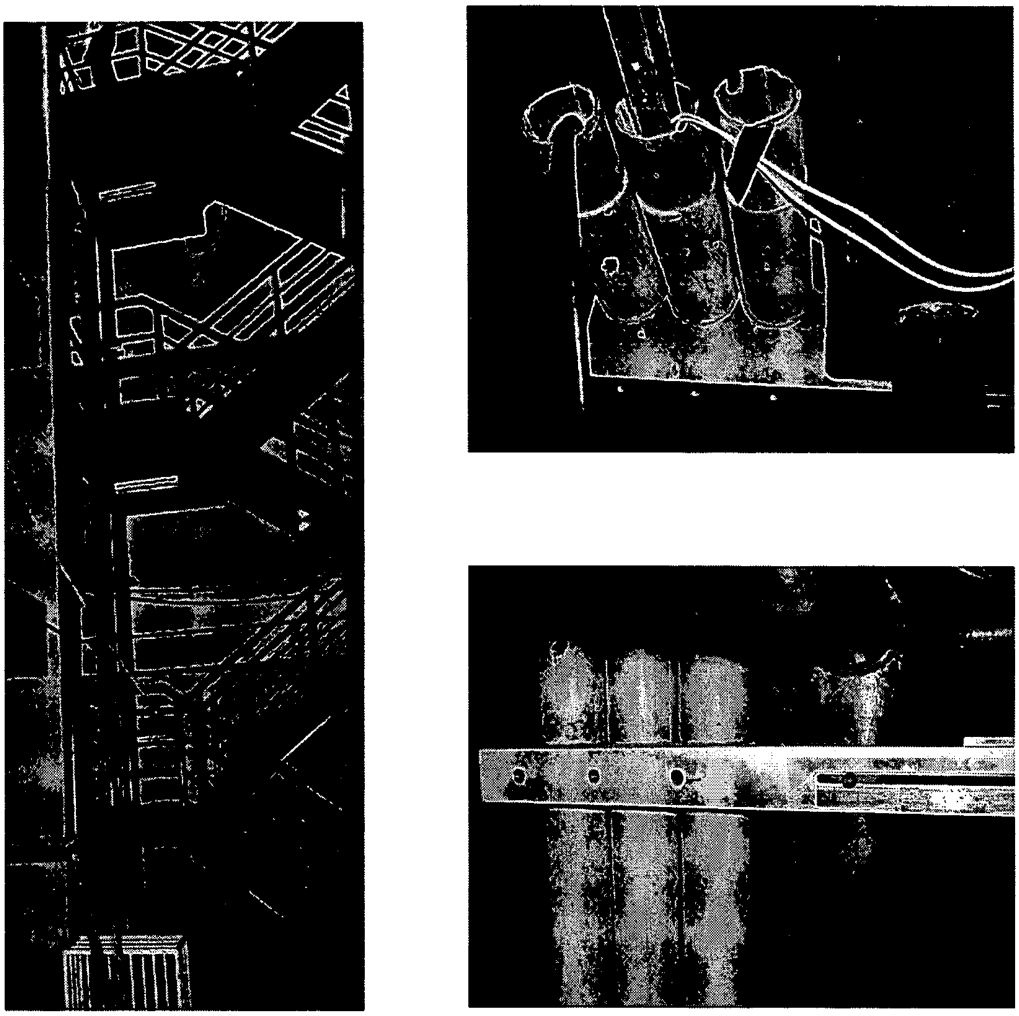


Fig.6

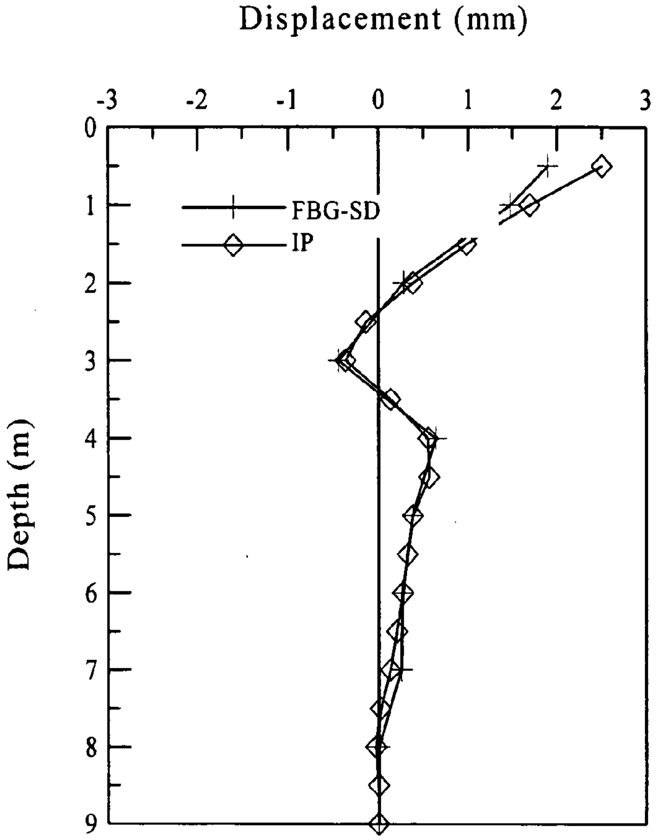

Displacement (mm)
-3
-2
-1
0
1
2
3
0
1
2
3
4
5
6
7
8
9
Depth (m)
FBG-SD
IP

Fig.7

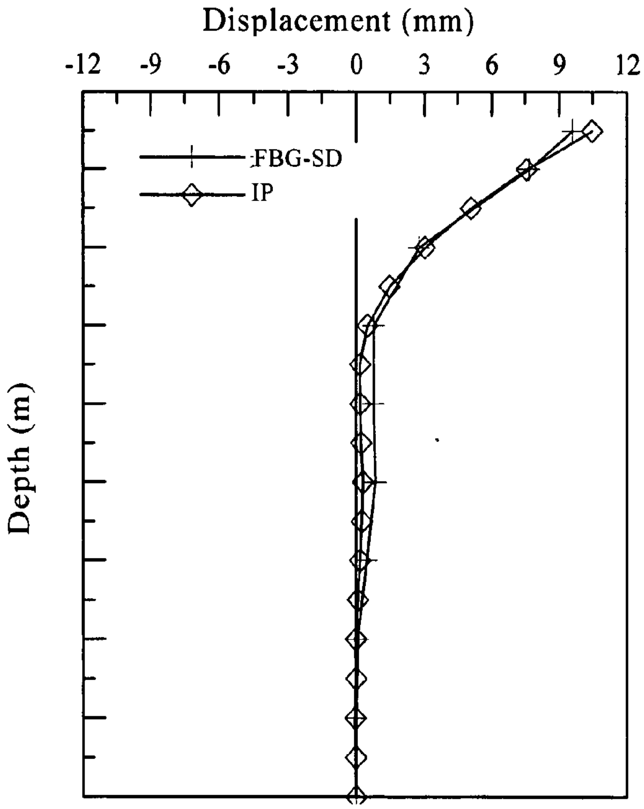

Displacement (mm)
-12
-9
-6
-3
0
3
6
9
12
Depth (m)
FBG-SD
IP

Fig.8

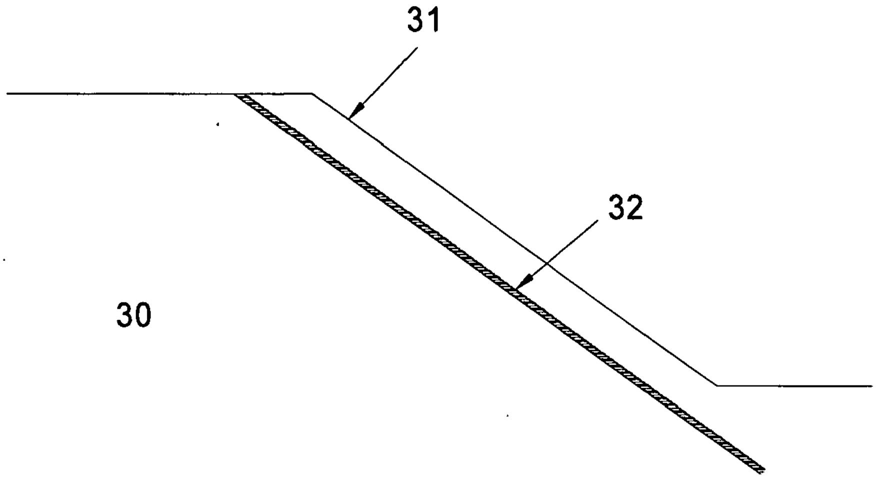


Fig.9

Fig.10

Fig.11

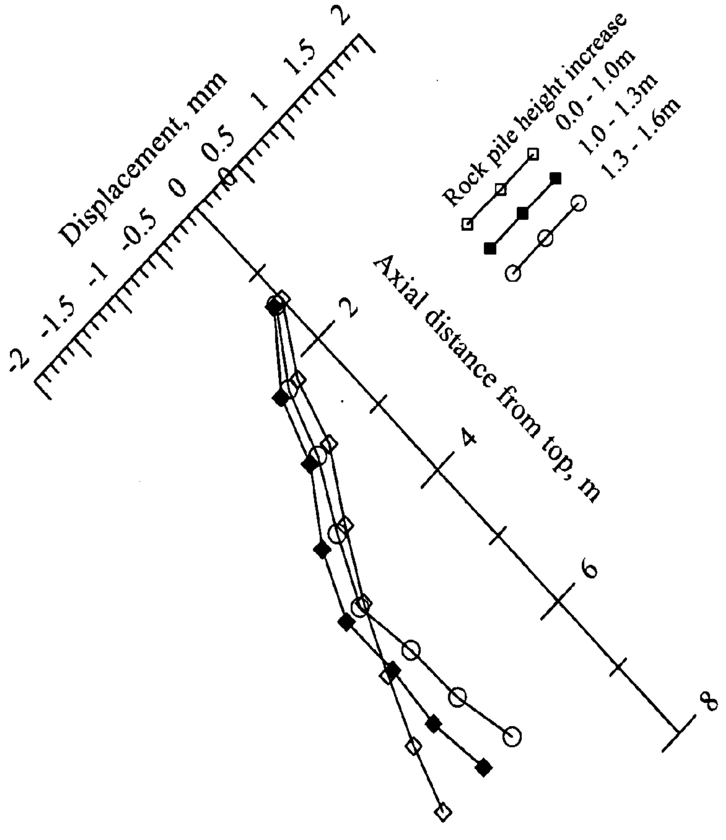

Displacement, mm
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
Axial distance from top, m
2
4
6
8
Rock pile height increase
0.0 - 1.0m
1.0 - 1.3m
1.3 - 1.6m

Fig.12

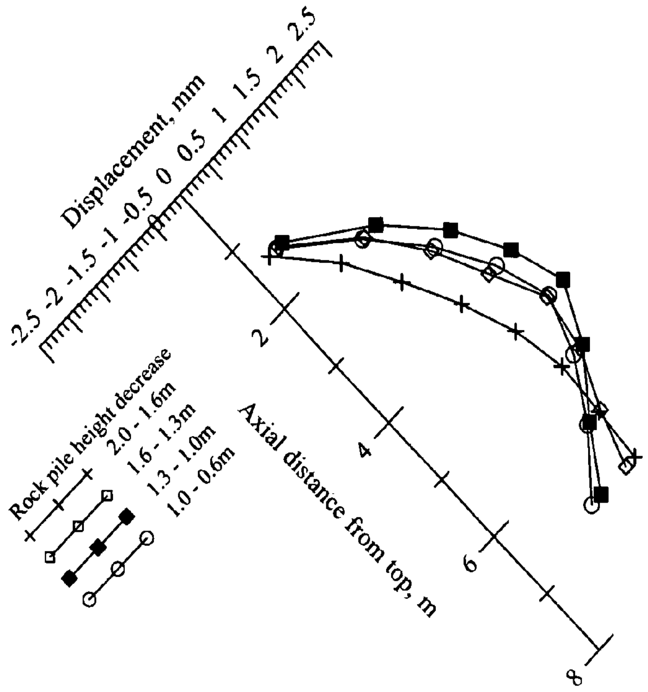

Displacement, mm
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
Axial distance from top, m
2
4
6
8
Rock pile height decrease
2.0 - 1.6m
1.6 - 1.3m
1.3 - 1.0m
1.0 - 0.6m

Fig.13

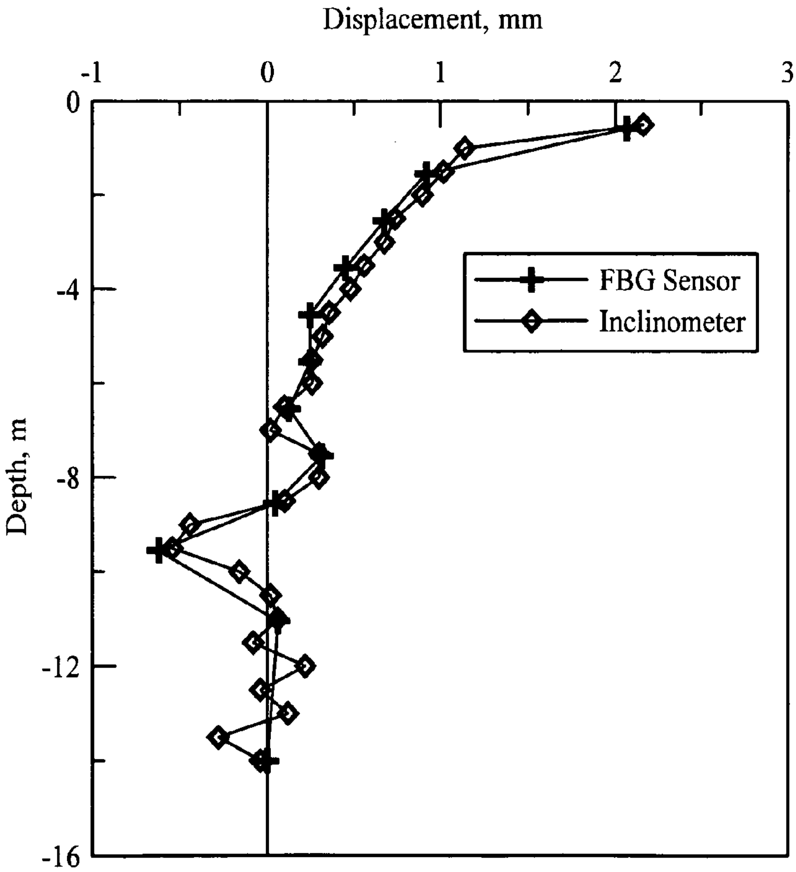

Displacement, mm
-1
0
1
2
3
Depth, m
0
-4
-8
-12
-16
FBG Sensor
Inclinometer

Fig.14

FIBER BRAGG GRATING SENSORED SEGMENTED DEFLECTOMETER FOR GROUND DISPLACEMENT MONITORING

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] Generally, this invention relates to a device for monitoring deformation of natural or man-made slopes, supporting structures of ground excavation, or of long structures such as the pipeline for transferring oil, gases or water, or beams and columns of buildings, bridges or ships; wherein, the deformation is monitored by means of an automated displacement monitoring probe with high sensitivity, durability and stability. To achieve optimum performance, the diameter of the monitoring probe and its distributed density subject to the characteristics of the target can be adjusted.

[0003] 2. Description of the Prior Art

[0004] According to Green, G. E., and Mickkelsen, P. E., "Deformation Measurements with Inclinometers", Transportation Research Record 1169, TRB, National Research Council, Washington, D. C. (1988), S. D. Wilson of Harvard University developed the concept of a probe inclinometer system in 1952. Today, the inclinometer system is probably the most widely used technique in the detection of ground movements. An inclinometer casing made of plastic or aluminum is installed in a near vertical position in the ground. For monitoring the stability of an earth slope, an inclinometer probe (IP) equipped with wheels that fit tightly with the grooves in the inclinometer casing is typically used to serve as the sensor unit. An electric cable raises and lowers the IP in the casing and transmits electric signals to the ground surface. The IP measures the inclination of the inclinometer casing in reference to verticality. Readings from the sensor unit are taken typically at a fixed interval of 500 mm as the probe is raised or lowered in the casing. The displacement at any depth of the casing is determined according to the IP inclination measurements. The aforementioned method is usually carried out manually which is time consuming. An in-place-inclinometer (IPI) probe is available that places the sensor probes in the ground on a long term basis and allows automated data logging. The above-described ground displacement monitoring devices use an electrical system for sensing and signal transmission. The electrical systems are prone to short circuit when exposed in a humid environment such as underground and below ground water. Most of the electrical sensors are non-distributive in nature where one transmission line is dedicated to a specific sensor. When a large number of sensors are used, the equally large number of transmission lines can make the system impractical. The electrical signals are subject to electromagnetic interference. These drawbacks make the electrical ground movement monitoring systems complicated or expensive to use.

[0005] The pipe strain gauge, which has been disclosed in Annual Report of Study for Hazard Prevention in Tokyo, the papers of Takada, Y.; Kyodai B. and Kenkyu N., "Measurement of international strain on landslide occurring ground" No. 8, P. 586 (1965) and Nakamura, H.; Landslides, "A study of finding landslide surface by the use of buried strain meters" Vol. 6, No. 1, pp. 1-8 (1969), respectively, use the principle of flexural strain caused by bending of a flexible pipe. The pipe strain gauge consists of a series of strain gauges attached to the surface of a flexible pipe. By sensing the flexural strain, the deformation distribution perpendicular to the longitudinal axis (as shown in FIGS. **1** (*a*) and **1** (*b*)) can be monitored. The pipe strain gauge may be used to determine the direction of ground movement **01** and location of the sliding surface **02** in FIGS. **1** (*a*) and **1** (*b*). The strain gauge is a non-distributive, electric sensor and thus shares similar drawbacks as the IPI.

[0006] Shiang et al., "Optical Fiber Sensing Technology, and Introduction of Implanted optical Fiber Bend Meter and Test Application", Proceedings of 12th Non-destructive Detection Technology Symposium (2004), pp. 273-279, described a device (called the optical fiber bend meter (as shown in FIG. **1** (*c*)) that uses a pair of stretched fiber Bragg gratings (FBG) **03** to measure ground displacement in combination with the inclinometer casing. The design of the bend meter was based on the concept reported by Yoshida, Y., Kashiwai, Y., Murakami, E., Ishida, S., and Hashiguchi, N., 2002, "Development of the monitoring system for slope deformations", Proceedings, SPIE Vol. 4694, pp. 296-302. The bearing **04** shown in FIG. **1** (*c*) allows rotation of the rigid column **05**. The bend meter can be inserted inside an inclinometer casing. The ground movement causes bending of the inclinometer casing and that bending forces rotation of the rigid column **05** and simultaneous extension/compression of the two fiber Bragg gratings (FBG) **03**. The amount of relative rotation or rotation of the bottom piece around the hinge **04**, is determined by the differential elongation between the two pre-stressed optic fibers inscribed with FBG's. Because of the flexible nature of the optic fiber, the measurement mechanism is effective only if the optic fibers remain tensioned. For this reason, the FBG optic fibers in the bend meter are pre-stressed. Furthermore, the extension/compression sensed by the FBG's are not resulted only from the deflection of the bend meter. All longitudinal forces including the weight of the bend meter units and friction between the bend meter support and the grooves in the inclinometer casing can all affect the readings for such design of FIG. **1** (*c*). It is possible therefore, that non-repeatable and/or unpredictable errors can occur while using the bend meter to monitor ground displacement.

[0007] Though there have been many types of optic fiber sensors available commercially, these sensors are not always dedicated for ground displacement monitoring. They lack the necessary sensitivity and/or compatibility with the currently available ground displacement monitoring systems.

SUMMARY OF THE INVENTION

[0008] Because of the long history and popularity of inclinometer casings, the fiber Bragg grating sensored segmented deflectometer (FBG-SD) is designed to be used in a conventional inclinometer casing.

[0009] A single unit of FBG-SD consists of a flexible tube **06** in FIG. **2**(*a*) (referred to as the flexible segment) that connects to two aluminum or other type of rigid end pieces **07** (referred to as the_rigid segments). The design is thus referred to as a segmented deflectometer. The flexible segment serves as a carrier of strain sensors. The rigid segments are equipped with spring **08** loaded braces **09** in FIG. **2** (*b*) so that the FBG-SD can be fitted to the grooves in the inclinometer casing. Two FBG's **10** are attached to the opposite sides of the flexible tube **06** in FIG. **2** (*a*) to measure the flexural strain. The diameter and length of the flexible tube can be changed for adjusting the strain resolution of the FBG-SD. The length of the rigid end pieces **07** in FIGS. **2** (*a*) and **3** can be varied for adjusting the space resolution. The two rigid segments are connected with a hinge **11** in FIGS. **2** (*a*) and **2** (*b*) which allows rotation only in the plane that includes the two opposite grooves of the inclinometer casing or the FBG's. A 3-dimensional numerical simulated view of the FBG-SD **12** is shown in FIG. **2** (*c*). Or, the FBG-SD is designed to monitor ground movement only in the plane where the rigid segments are allowed to rotate or deflect. The distortion of the inclinometer casing **13** induced by ground movement causes relative rotation between the rigid segments of the inserted FBG-SD as shown in FIG. **3**. This relative rotation creates bending to the flexible tube which behaves as a cantilever. The bending in turn, causes flexural strains to the FBG's attached to the surface of the flexible tube.

[0010] The FBG-SD may be used as a general purpose tool to monitor the deformation of a linear structure. These structures may include oil or water pipelines, columns or beams of bridges, ships or other types of civil/infrastructures. The monitoring can be implemented by first attaching an inclinometer casing **13** in FIG. **4**, to the structure to be monitored **14** and then inserting the FBG-SD into the casing. For field installation, the FBG-SD units are connected together to form a string as it is inserted into the inclinometer casing.

Advantages of the segmented deflectometer include:

[0011] 1. The monitoring probe is compatible with the conventional inclinometer casings. The technique of inclinometer installation is well established. The design allows the inclinometer to be installed first and then the FBG-SD is inserted.

[0012] 2. The FBG-SD is placed inside the inclinometer casing and thus protected from the potentially harsh environment.

[0013] 3. The FBG-SD can be left in place for long term, automated monitoring.

[0014] 4. The FBG-SD uses strain sensors attached to a flexible tube to measure deflection. Its sensitivity and range can be adjusted by varying the diameter of the flexible tube.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. **1**(*a*) and **1**(*b*) describe the principles of pipe strain gauge in that FIG. **1**(*a*) is a displacement diagram and FIG. **1**(*b*) is a strain diagram; FIG. **1**(*c*) shows the schematic view of the bend meter;

[0016] FIG. **2** (*a*) and **2**(*b*) show the top and side view respectively, of the segmented deflectometer; FIG. **2**(*c*) depicts a numerically simulated 3-dimensional view of the segmented deflectometer;

[0017] FIG. **3** demonstrates the signal amplification effect of the segmented deflectometer when used inside of an inclinometer casing;

[0018] FIG. **4** shows a schematic view of using the FBG-SD to monitor the deformation of a linear structure;

[0019] FIG. **5** shows the field system configuration when using the FBG-SD for automated monitoring;

[0020] FIG. **6** depicts photographs of laboratory set up in calibrating the FBG-SD against the conventional inclinometer probe;

[0021] FIG. **7** compares the results from FBG-SD and inclinometer probe with 2.5 mm maximum deformation;

[0022] FIG. **8** compares the results from FBG-SD and inclinometer probe with 12 mm maximum deformation;

[0023] FIG. **9** describes the field set up in the use of FBG-SD to monitor the stability of a Yellow River dike;

[0024] FIG. **10** shows a side view of the rock pile in the test to verify the effectiveness of FBG-SD to monitor the stability of a Yellow River dike;

[0025] FIG. **11** shows a top view of the rock pile in the test to verify the effectiveness of FBG-SD to monitor the stability of a Yellow River dike;

[0026] FIG. **12** shows the deformation versus depth during the loading stage of the field test according to FBG-SD readings;

[0027] FIG. **13** shows the deformation versus depth during the unloading stage of the field test according to FBG-SD readings; and

[0028] FIG. **14** shows deformation measurements of the diaphragm wall from FBG-SD and conventional inclinometer probe during a braced excavation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0029] The fiber Bragg grating segmented deflectometer (FBG-SD) of the invention is intended to be used together with an inclinometer casing. For monitoring ground displacement, the inclinometer casing is grouted inside of a borehole in the ground. This procedure is similar to the convention method for using an inclinometer casing and the inclinometer probe (IP), except that the distortion of the inclinometer casing due to ground displacement is sensed by using the FBG-SD. The components of the FBG-SD are shown in FIGS. **2** (*a*), **2** (*b*) and **2** (*c*). The monitoring device of the invention uses a flexible tube **06** with a length of 215 mm and 12 mm in diameter, which can be made of plastic, as a carrier of strain sensors. A pair of strain sensors which can be fiber Bragg gratings **09** are attached to the two opposite sides of the flexible tube **06** to measure the flexural strain experienced by the flexible tube. The ends of the flexible tube are connected to rigid segments **07** which can be made of aluminum or other types of rigid material. One end of the flexible tube is fixed to a rigid segment where no sliding or rotation is allowed. The other end of the flexible tube is supported on the neighboring rigid segment with a pin **15** fitted in an elongated slot **16** in FIG. **2** (*b*) where longitudinal sliding and rotation are allowed. Because the pin supported end of the flexible tube is free to slide longitudinally, the weight of FBG-SD elements and friction between the brace and the casing grooves would have no effect on the flexural strains. The FBG-SD allows rotations to occur only at the hinge **11** in FIGS. **2** (*a*) and **2** (*b*), thus creating an effect of signal amplification when placed inside of the inclinometer casing as shown in FIG. **3**.

[0030] The FBG-SD can be applied to monitor deformation for many types of civil engineering systems, such as stability monitoring of dikes, deformation monitoring of the supporting structure during ground excavation, deformation of bridge decks and pipelines. The monitoring can be automated as shown in FIG. **5**. Multiple units of FBG-SD are connected together to form a string **17** and then inserted in the inclinometer casing. The conventional IP can only be used in inclinometer casings in a near vertical position as IP measures inclination angle against verticality and it has a limited range. An important advantage of the FBG-SD is that it can be used horizontally, vertically, or on in any angle of inclination as the FBG-SD measures relative deflections. For the diagram shown in FIG. **5**, the FBG-SD may be deployed for monitoring the stability of earth slopes **18**, braced excavation **19**, and river dikes **20**. The total number and distance interval of the FBG-SD units can be adjusted according to the nature of the subject to be monitored. For the current design, the space interval between the FBG-SD units should be no less than 500 mm. The FBG sensor signals are transmitted through an optical switches **18** and an FBG interrogator **19**, and then distributed using a computer server **20** or a file server **21** and internet **22** or via a wireless system **23** such as the general packet radio service **24**, finally reaching to a network **24** of computers **25** reside in offices where the results are analyzed and reported. The FBG interrogator provides the light source for FBG's and determines the wavelength variations of the reflected light signals from the FBG's. For emergencies, messages may be dispatched from the server to

[0031] The following sections describe the cases of laboratory and field applications of the FBG-SD.

EMBODIMENT 1 (A LABORATORY DEMONSTRATION)

[0032] To demonstrate the effectiveness of the FBG-SD as a means to monitor ground movement, a series of experiments were conducted in the laboratory under controlled conditions. Two, 9-m long inclinometer casings were tied together with steel blocks to assure these casings have the same mount of lateral movements. The inclinometer casings were set up vertically against a stairway that was attached to a 3-m thick concrete reaction wall in a structural testing laboratory. A total of eight FBG-SD units were connected together to form a string and inserted into one of the inclinometer casings. An IP was lowered in the other casing to establish the IP initial readings. The two inclinometer casings were then forced to deform simultaneously by pushing the steel blocks against the stairway. Upon fixing the casings in their deformed position, the FBG-SD and IP readings were taken again. Once inserted, the FBG-SD's were left in place throughout the experiment; readings were taken simply by connecting the optic cables directly to the interrogator. For the IP, the probe was first lowered to the bottom and then raised in 500 mm intervals to take readings.

[0033] A comparison between the results from FBG-SD and IP for various types and magnitudes of deformations are shown in FIGS. **7** and **8**. The maximum difference between the FBG-SD and IP measurements in these indoor experiments did not exceed 10%.

EMBODIMENT 2 (SAFETY MONITORING OF A RIVER DIKE)

[0034] The inventor has applied the newly invented FBG-SD as a means to monitor the integrity of a Yellow river dike. The test site was located at dike No.24 in Wu-Tze County, Honan Province, China. A string of FBG-SD with a total length of 8 m was inserted into an inclinometer casing **34** in FIG. **9**. The inclinometer casing was installed at an angle of 45 degrees, 2 m from the edge and parallel to the surface of the river dike **33** in FIG. **9**.

[0035] Soil erosion from the dike surface should result in an unloading condition and cause deformation to the FBG-SD sensor probe if the monitoring system performs properly. The sensor probe was embedded inside the dike body and thus not likely to be damaged by the dike surface erosion. 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 2-m wide wedge shaped pile of rock was formed along the face of the dike slope first to a maximum height of 2 m and then removed in stages as described in FIGS. **10** and **11**. The sensor readings were taken as the rock pile was formed and removed.

[0036] FBG readings were recorded in terms of the wavelength variations. These changes were converted into the degree of rotation of each FBG-SD following the calibration correlations between the wavelength variation and degree of rotation. Accumulating the rotation angles and summing the displacement in the direction perpendicular to the axis of the inclinometer casing yielded the displacement profile. Ground displacement according to FBG measurements at various stages of loading and unloading are shown in FIGS. **12** and **13**, respectively. The results show substantial agreement quantitatively and in trend of ground movement according to numerical simulations.

EMBODIMENT 3 (DEFORMATION MONITORING OF A DIAPHRAGM WALL DURING A DEEP EXCAVATION)

[0037] The FBG-SD system was to monitor the deformation of a 1.2-m thick, 15-m deep diaphragm wall during an internally braced deep excavation project in Beitou district of Taipei, Taiwan. The 8.1-deep excavation covered a square area of 100 m by 100 m, and was braced by two levels of cross lot struts. Two, 14-m deep inclinometer casings spaced at 1 m were tied to the reinforcement cage and then fixed inside of the diaphragm wall upon tremie concrete. A string of 11 FBG-SD's was inserted into one of the inclinometer casings leaving the other casing for IP measurements.

[0038] FIG. **14** shows the lateral movement induced by pre-loading of the second level struts when the excavation reached 5.8 m. The pre-loading pushed the diaphragm wall outwards by as much as 2 mm. As in the case of indoor experiments, the ground movements according to FBG-SD's were very similar to those of IP readings.

[0039] Though the invention has been described in connection with the preferred embodiments thereof, however, changes and modifications to the details of the above-described embodiments without departing from the underlying principles of the invention may be applied in the future. The scope of the invention should, therefore, be determined only by the following claims.

LIST OF REFERENCE NUMERALS

[0040] **01** sliding direction

[0041] **02** sliding face

[0042] **03** stretched fiber Bragg grating

[0043] **04** bearing

[0044] **05** rigid column

[0045] **06** flexible tube

[0046] **07** end piece

[0047] **08** spring

[0048] **09** brace

[0049] **10** fiber Bragg grating

[0050] **11** hinge

[0051] **12** the FBG segmented deflectometer (FBG-SD)

[0052] **13** inclinometer casing

[0053] **14** structure to be monitored

[0054] **15** pin

[0055] **16** elongated slot

[0056] **17** string of FBG-SD

[0057] **18** earth slope

[0058] **19** braced excavation

[0059] **20** river dikes

[0060] **21** optical switch

[0061] **22** FBG interrogator

[0062] **23** server

[0063] **24** file server

[0064] **25** internet

[0065] **26** universal packet radio service

[0066] **27** wireless system

[0067] **28** computer

[0068] **29** mobile phone

[0069] **30** river dike body

[0070] **31** dike surface

[0071] **32** inclinometer casing with FBG-SD

What is claimed is:

1. A monitoring device using a segmented design, referred to as the FBG segmented deflectometer (FBG-SD) mainly for observing deformation in soil or rock mass, comprising:

a flexible tube (referred to as the flexible segment) that connects to two aluminum end pieces of (referred to as the rigid segments); and

the rigid segments which are equipped with spring loaded braces so that the FBG-SD can be fitted to the grooves in the inclinometer casing.

2. The monitoring device according to claim 1, wherein the rigid segments are connected with a hinge which allows rotation only in the plane that includes the two opposite grooves of the inclinometer casing.

3. The monitoring device according to claim 1, wherein the flexible tube can be made of plastic, or other elastic composite material or metal, and the cross section of which can be round or polygonal shape having one or more symmetrical sides.

4. The monitoring device according to claim 1, wherein the flexural deformation of the flexible tube can be measured by fiber Bragg grating, other types of fiber optic strain sensors or strain gauges.

5. The monitoring device according to claim 1, wherein one end of the flexible tube is fixed to a rigid segment where no sliding or rotation is allowed, the other end of the flexible tube is supported on the neighboring rigid segment with a pin fitted in an elongated slot where longitudinal sliding and rotation are allowed.

6. The monitoring device according to claim 1, wherein the rigid segments can be made of aluminum or metal plates or other stiff material.

7. The monitoring device according to claim 1, wherein the FBG-SD can be fitted to the grooves in the inclinometer casing with the help of the spring loaded braces or the FBG-SD can be directly grouted in a borehole.

8. The monitoring device according to claim 1, wherein the FBG-SD can be used horizontally, vertically, or on in any angle of inclination.

9. The monitoring device according to claim 1, wherein the FBG-SD are suitable for monitoring deformation of many types of civil engineering systems including stability of dikes, deformation of the supporting structure during ground excavation and deformation of bridge decks, pipelines and other types of long structures.

10. The monitoring device according to claim 9, wherein the FBG-SD can be fitted inside of an inclinometer casing when used to monitor above ground structures comprising oil tanks, pipelines or bridge decks, furthermore, the inclinometer casings can be mounted on the structure to be monitored first and then the FBG-SD's are inserted.

11. The monitoring device according to claim 9, wherein the total number and distance interval of the FBG-SD units can be adjusted according to the nature of the subject to be monitored.

12. A process of field installation of the monitoring device according to claim 1, comprising:

connecting multiple units of FBG-SD together to form a string; and

inserting the assembled string into the inclinometer casing, wherein the relative rotation creates bending to the flexible tube which behaves as a cantilever; the bending in turn, causes flexural strains to the FBG's attached to the surface of the flexible tube; and the distribution of ground displacement is then computed based on the rotation measurements.

13. A displacement monitoring system, which consists of:

a string of multiple units of DBG-SD's inserted in ground or mounted on the structure to be monitored;

an interrogation system having an optical switching device, arranged on ground surface, for data logging, analysis and distribution; and

a bank of computers where the data are presented and stored.

* * * * *