Monitoring subsurface ground movement using fibre optic inclinometer sensor

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Abstract. The monitoring of subsurface ground movement is important for the prevention and control of geological disaster including land subsidence, ground fissure, surface collapse, and landslides. Inclinometer and extensometer are examples of the conventional geotechnical instruments for monitoring the subsurface ground movement. However, most conventional geotechnical instruments for subsurface monitoring are limited to discrete sensing, high cost, and susceptible to various reading errors. This paper presents the advancement of technology mechanism to monitor horizontal ground movements as well as the data processing technique involved. Distributed optical fibre inclinometer is developed through laboratory pipe bending tests whereas the data is corroborated with conventional instruments. This system was installed on site, measuring the performance of the sensors as well as to monitor the associated ground movements. A simple cost comparative study between fibre optic inclinometer and conventional geotechnical instrumentation indicates the new technology is cost-effective for applications in ground monitoring particularly when monitoring a large number of borehole points and measurement arrays.

1. Introduction

Uncontrolled ground deformation including land subsidence, ground fissure, and surface collapse is a serious geological disaster. The monitoring of ground deformation is therefore important for its prevention and control. This is also an effective way of reducing the risk due to the ground deformation by developing an early warning system. Variety of data are supplied to study the engineering parameters such as pore water pressures, horizontal and vertical deformations, temperature, stresses and strains induced in soils, rock and geotechnical structures.

The effective use of field instrumentation requires a thorough understanding of geotechnical principles, careful planning of instrumentation projects, and capabilities of the instruments and the operators [1]. The technological advances made in instrumentation equipment such as optical fibre sensors will increase the level of confidence in civil engineering construction activities. This is because of the added capabilities such as immune to electromagnetic interference, moisture and corrosion, highly accurate, and distributed sensing in nature [2].

In this paper, distributed optical fibre inclinometer is developed through laboratory pipe bending tests where the data is corroborated with conventional instruments. A cost comparative study between Distributed Optical Fibre Strain Sensing (DOFSS) and conventional geotechnical instrumentation is presented for applications in ground monitoring.

In general, there are few common systems and instrumentation techniques to monitor ground displacements. However, current systems may inherit a few disadvantages for ground monitoring. As
example, extensometer has poor anti-interference and poor durability which can easily damage and lost its precision as a monitoring tool. Besides, for real-time measurements such as in-place inclinometer, it is relatively expensive particularly and very difficult to install for a long array for deep depths.

2. Background
Distributed Optical Fibre Strain Sensing (DOFSS) technology on the basis of Brillouin Optical Time Domain Analysis (BOTDA) offers new possibilities of detecting deformation of large ground mass and able to pinpoint accurately the location of ground movement. This technological advancement made for instrumentation equipment such as optical fibre sensors will increase the level of confidence in civil engineering construction activities because of the added capabilities such as immune to electromagnetic interference, moisture and corrosion, highly accurate, and distributed sensing in nature.

2.1. Brillouin Optical Time-Domain Analysis (BOTDA)
Brillouin Optical Time-Domain Analysis (BOTDA) is an example of DOFSS technology that measures strain and temperature in a continuous (distributed) manner using a standard optical fibre telecommunication cable. The BOTDA measurement principle is based on the transmission of light signals (utilizing stimulated Brillouin scattering) launch into the optical cables and detects the frequency changes and travel time in order to resolve the measurements into strains at every point along the cable. Typically, the measurement accuracy is about ±10 macrostrain and sensing distance for up to 50 km long depending on how the cable is installed. Table 1 shows the specification of BOTDA interrogator used in this study.

The accuracy of the strain measurement depends on instrument laser setup, such as spatial resolution, number of averaging, and frequency steps [3]. In this study, a 5ns laser pulse is used which is equivalent to the spatial resolution of 50cm (i.e. an averaged strain reading over 50cm).

Table 1. Specification of BOTDA interrogator by OZ Optics Ltd.

| Parameter                  | Description                                                                 |
|----------------------------|-----------------------------------------------------------------------------|
| Measured Variables         | Strain and/or temperature, Brillouin spectrum Maximum                       |
| - Fibre Length             | -160 km                                                                     |
| - Sensing Range            | 100 km                                                                      |
| - Spatial Accuracy         | - as low as 5 cm                                                           |
| - Spatial Step             | - as low as 5 cm                                                           |
| Strain Resolution          | 0.1 µε                                                                      |
| Strain Range               | -3% (compression) to +4% (elongation) (depending on cable material)         |
| Strain Accuracy (2σ)       | ± 2 µε (Whole sensing range for BOTDA)                                      |
| Temperature Resolution     | 0.005°C                                                                     |
| Temperature Range          | -270°C to +2100°C (depending on cable material)                             |
| Temperature Accuracy       | ± 0.1°C (Whole sensing range for BOTDA)                                     |

2.2. Optical cable
A standard telecommunication optical cable used in this study is shown in Figure 1. It is 2 mm thick and width of 3.1 mm with two single-mode core fibres. The cable has a linear strain calibration factor (~20 µε/MHz) obtained in the laboratory and performed satisfactorily as strain sensing cables (i.e. the cable jacket provides enough tightness to the fibre core so as to avoid slippage). This cable can be attached on a pipe casing as part of fibre-optic inclinometer which will be discussed more in Section 3.
Inclinometers are geotechnical instruments used to measure horizontal displacements along various points on a borehole. For this reason, sometimes they are also called borehole inclinometers or simply inclinometers. These are ideally suited to long-term, precise monitoring of the position of a borehole over its entire length. Standard inclinometer (ABS) and Distributed fibre optic inclinometer will be discussed in this paper.

2.3. Standard Inclinometer (ABS)
For landslides and lateral movement detection, a set of acrylonitrile butadiene styrene (ABS) inclinometer pipe casing with accelerometer probe is typically used in geotechnical instrumentation to measure the horizontal soil deformation profile along the vertical axis. Any changes in the deflection of the pipe are recorded as equivalent movements in the ground. The inclinometer casing is used to guide the inclinometer probe within the casing with four longitudinal wheel-grooves spaced 90° apart. The casing is installed into the ground, usually within drilled holes, and the annular space grouted. The casing connections are specially made to seal out soil, grout, and other materials in order to maintain the cleanliness of the grooves and prevent the unwanted material mentioned to fill of the casing. Refer to Figure 2 for example of machine-grooved casing and connection.

Vertical inclinometers are relatively low maintenance system (since there are no hydraulic lines or pressure sources) but inherited a number of limitations such as required manual operations and hence not real time, access to the ends of inclinometer casing, and the pipe must not bend too much or be blocked to allow access for the probe. For automatic and real-time measurements, fixed-in MEMs inclinometers can be installed inside the pipe, but they are expensive and are limited to a certain number of accelerometers in the pipe. Information regarding inclinometer components, installations, acquiring and interpreting test results are described in more details in the literature [4][5].

2.4. Distributed Fibre Optic Inclinometer
Similar to the measurement principle of a traversing inclinometer system with two perpendicular axes, the deformable pipe with optical fibre sensor must be designed to conform with the surrounding ground deformation and hence correctly measures the traversing displacements. Figure 3 shows the machine-grooved inclinometer casing with 60 mm outer diameter with 5mm thick made from Polyvinyl Chloride (PVC). Optical fibre cables are attached along the grooves onto the four sides of the pipe using rapid hardening glue. Each casing is 3 m long and can be extended with another pipe using specially designed
connectors. PVC is selected as opposed to Acrylonitrile Butadiene Styrene (ABS) (used in the standard inclinometer casing) because the material is cheap and behaves more elastic. ABS pipes, on the other hand, tend to deform plastically (lower yielding point).

Figure 3 shows the looping configuration of the optical fibre strain sensing cables upon completion of the attachment. A pair of the cables were attached along each axis and joined (spliced) externally at the top to form one continuous optical circuit with four reading directions. In terms of the installation procedure of borehole inclinometer, only the bottom pipe is attached with optical fibres and prepared in the laboratory, whereas the remaining casings and fibre attachment are assembled during field installation. All necessary measures include handling with care, ensuring no sharp bending, and applying protection sleeves on the cables at the ingress/egress points are taken to protect the cables and minimize the signal loss.

Figure 3. Attachment of optical fibre sensors along the machined grooved PVC casing (a) cross-section with axes X-X and Y-Y, (b) typical looping configuration

3. Data Processing Technique
The principle of converting bending strains into traversing displacements have been reported by [6]. The lateral displacement, $y$ of the PVC pipe shall be determined based on strain readings along each axis as shown below.

$$y = \frac{1}{D} \int_a^b (\varepsilon_a - \varepsilon_b) \, dx$$  \hspace{1cm} (1)

Where,

$y$ = lateral displacement plotted along the longitudinal $x$

$\varepsilon_a$ = strain at the side $a$

$\varepsilon_b$ = strain at the side $b$

$D$ = distance between two fibre or diameter of the pipe

The integration of Equation (1) can be done numerically or using a closed-form solution (by fitting a suitable function). What is important is to properly define the two boundary conditions of the pipe, usually at the tip or the top of the inclinometer casing. For a vertical casing installed in a landslide, and when the casing tip is installed in a stable zone (reference datum).

In automating the data processing of fibre optic inclinometer, a software program with Graphical User Interface (GUI) is developed using MATLAB program. The program is developed to analyse the deflection of the Fibre Optic (FO) inclinometer pipe base on the strain that generates from BOTDA. File data from BOTDA can be loaded to this software and user may select any data on the list of files penal to show the strain graph. The strain data can be trimmed base on the location of the FO sensor that attached to the FO inclinometer casing. Figure 4 shows an example of BOTDA trace of strain distribution along the pipe plotted using this program and the way of trimming the strain data is shown. On Analysis interface, there are 2 panels, Data Fitting and Boundary Condition. For Data Fitting panel,
the user must select a data file and assign it to the polynomial order. Then, compares the data fitting with original strain value such in Figure 5. The program requires the user to key-in the traversing displacements by applying the correct boundary conditions such in Figure 6. After assigning all value, a displacement graph will be plotted on the main interface. The user also can combine the result on the analysis interface.

**Figure 4.** Strain Graph using with Graphical User Interface (GUI) that developed using MATLAB Program

**Figure 5.** Strain reading along the optical fibre attached to the pipe (cantilever type of deformation)
4. Experimental Test Results

The testing is vertical inclinometer with cantilever loading configuration (compression or tension at only one side of the casing). Bending test was performed to test the performance of fibre optic using the standard ABS inclinometer casing and the prototype PVC casing.

4.1. Vertical Inclinometer

The sections should be numbered with a dot following the number and then separated by a single space. The testing is vertical inclinometer with cantilever loading configuration (compression or tension at only one side of the casing). Bending test was performed to test the performance of fibre optic using the standard ABS inclinometer casing and the prototype PVC casing. A simple test procedure to measure the pipe bending test is through a cantilever loading configuration. Cantilever deformation is commonly observed in the field such as unbraced excavation, laterally loaded piles, and landslides. Figure 7 shows the experimental setup for the vertical inclinometer. A standard ABS inclinometer casing with external fibre optic grooves was used for direct comparative readings between Fibre Optic (FO) and inclinometer probe. The experiment was conducted by pushing the pipe incrementally in the horizontal direction. An external reference point is measured using a dial gauge at 2m height. In this test, the boundary conditions for FO inclinometer when calculating deflection is zero displacement at the tip and displacement reading from the dial gauge.

Figure 8(a) compares the deflection readings between inclinometer, dial gauge and BOTDA upon pipe deflections of 20 mm, 80 mm, and 140 mm measured at 2 m height respectively. It can be seen that, excellent agreement between all measurement systems. However, BOTDA shows a continuous profile with measurement readings plotted at every 5 cm in comparison to inclinometer of 50 cm interval. Moreover, the FO data can provide a direct reading of the curvature, which is useful when deriving bending moment of the pipe or structure.

The vertical inclinometer testing was repeated using fibre optic with PVC casing together with an extended length of 6 m (Figure 8b). For the second experiment, the results only compare to the dial gauges (since there are no internal grooves inside the PVC pipe). As shown in Figure 8(b), the derivation of the FO lateral displacements was excellent and the difference between the dial gauge and the FO reading is ±2% (i.e. matches well with other dial gauges). The ABS and PVC inclinometer pipe show the same result, and this condition shows that the FO with PVC inclinometer pipe can be used in landslide monitoring.
5. Field Instrumentation
Several FO inclinometer casings were installed at two sites in Perak, Malaysia for measuring the performance of the sensors as well as to monitor the associated ground movements. The first site was at a failed slope near to Block 13 in UTP campus and the second site was in Lahat, Ipoh. Figure 9(a) shows the installation of vertical inclinometer at the crest of a failed slope for the first site and Figure 9(b)
shows the installation of vertical inclinometer to monitor the soil movement caused by pipe-jacking tunneling which will cross a railway track in the second site.

In the slope site, the monitoring work is still ongoing and relevant data shall be reported in the future publication. While, for the second site, the inclinometer pipe was installed next to a micro-tunnel to measure the horizontal ground displacements as shown in Figure 10.

![Figure 9](image1.png)

(a) Field installation of FO Inclinometer for landslide monitoring, (b) subsurface horizontal settlement measurement

5.1. **Vertical Inclinometer for Soil Monitoring**

Figure 11 shows the reading of BOTDA for deflection of FO inclinometer pipe which indicates soil movements caused by pipe-jacking tunneling. For the calculation process, the boundary conditions are referenced to the optical prism measurement installed at the ground surface and using the assumptions of zero displacements at the tip of the pipe.

Figure 12 shows the location of pipe-jacking on the date. Based on the result, it can be seen that the deflection for FO inclinometer on day 6 contrary to the location of pipe-jacking direction because on that day the pipe-jacking are near to the FO inclinometer pipe. The deflection of the FO inclinometer at day 6 cause by the pressure from pipe-jacking. During the execution of the process, the hydraulic jack makes use of thrust power to move the pipe forward into the ground and at the same time, a bentonite injection is applied to increase the pipe-jacking efficiency. However, on the 7th day it is shown that the deflection of FO inclinometer pipe was move towards the pipe-jacking location direction.
Figure 10. Installation method for vertical FO inclinometer

Figure 11. Horizontal ground displacements

Figure 12. Location of pipe-jacking on the date
6. Cost-Benefit Analysis
Although standard inclinometer has been widely used in various geotechnical monitoring work, the needs for advancement in deformation measurements such as DOFSS is highly desirable. Some of the advantages of distributed inclinometer as compared to the conventional method are highlighted in Table 2.

In Table 2 it compares the measurement capabilities between standard inclinometer, fixed-in inclinometer and FO inclinometer. It can be seen that DOFSS having the advantages such as longer measurement distance, more data points and real-time monitoring, as compared to the conventional inclinometer. The fibre optic sensor also can be used to detect the axial strains (compression or extension) of the pipe caused by the ground heaving or subsidence [7].

In terms of cost, a single borehole reading (per visit) using standard inclinometer probe will likely be cheaper than DOFSS because this method only uses the portable probe. In automatic measurements, particularly when monitoring in a large area with many points, it may be preferable to use DOFSS since the BOTDA interrogator can be linked with several boreholes for simultaneous reading. In addition, it is more cost-efficient compares to the in-place inclinometer. The cost for automatically measurement is increasing depending on the cost of the monitoring station and power supply only. Nonetheless, for standard inclinometer method, the cost will be increased depending on the condition of site and location of the borehole.

|                          | Inclinometer | Fixed-in inclinometer | DOFSS     |
|--------------------------|--------------|-----------------------|-----------|
| Maximum measurement distance | depends on cable length | ~ 20 m                | unlimited |
| Reading resolution       | 50 cm        | 50 cm                 | 5 cm      |
| Accuracy                 | ±7.6 mm per 30 m | ±7.6 mm per 30 m      | ±20 με    |
| Automation/real time     | No           | Yes                   | Yes       |
| Measurement cost per trip| Cheaper      | -                     | Higher    |
| Integrated as standpipe piezometer | No          | No                    | Yes       |
| Axial displacement measurement | No          | No                    | Yes       |

Source: (Slope Indicator Company, 2006)

7. Conclusion
In this research, a prefabricated FO inclinometer pipe was designed to monitor ground movements. Data processing, as well as installation procedure, were described and validated through laboratory tests. In general, the performances of FO sensing were consistent with the commercial system in the monitoring of landslide. Besides, the optical fibre used can be relevantly cheap and practical. Moreover, DOFSS can serves as any subsurface ground monitoring system too as it provides real-time monitoring regardless of site conditions.
8. References

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