Development of distributed fibre optic inclinometer for landslide and geotechnical application

Muhammad Farid Ghazali[1], H. Mohamad[2], and K.A. Ang[3]

[1] Researcher, Civil & Environmental Engineering Department, Universiti Teknologi PETRONAS, Malaysia
[2] Associate Professor, Civil & Environmental Engineering Department, Universiti Teknologi PETRONAS, Malaysia
[3] GDS Instruments Sdn. Bhd., 40400 Shah Alam, Malaysia.

ABSTRACT

Geotechnical instrumentation and monitoring works are essential for the successful completion of geotechnical projects particularly for critical ones such as tunnels, slopes, embankment and ground excavations next to sensitive structures. However, most conventional geotechnical instruments are limited to discrete sensing (they may miss the critical location of soil movement), high cost, and susceptible to various reading errors (*e.g.* electromagnetic interference). These problems can be overcame using a novel Distributed Optical Fibre Strain Sensor (DOFSS). As investigated and presented in this paper, the DOFSS is incorporated using a Brillouin Optical Time Domain Analysis (BOTDA) interrogator that measures strain and temperature at every 5 cm along the whole length of an optical cable for kilometers long. The paper presents how this technology can be used to monitor vertical and horizontal ground movements as well as the data processing technique involved. Distributed optical fibre inclinometer is developed through laboratory pipe bending tests where the data is corroborated with conventional instruments. A simplified cost comparative study between DOFSS and conventional geotechnical instrumentation indicates the new technology is cost-effective for applications in slope and embankment monitoring particularly when monitoring large number of borehole points and measurement arrays.

Keywords: BOTDA; landslide; ground settlement; inclinometer; geotechnical instrumentation, monitoring

1 INTRODUCTION

Instrumentation is an integral part of geotechnical engineering since it is an essential tool for monitoring safety and performance during the construction and maintenance phases of many infrastructure projects (*e.g.* embankment on soft ground, underground excavations, tunnelling, and earth dams). The effective use of field instrumentation requires a thorough understanding of geotechnical principles, careful planning of instrumentation projects, and capabilities of the instruments and their operators (Marks, 2011). The technological advances made in 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 (*e.g.* Mohamad *et al.,* 2009, 2017).

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 slope and embankment monitoring.

2 BRILLOUIN OPTICAL TIME-DOMAIN ANALYSIS (BOTDA)

Brillouin Optical Time-Domain Analysis (BOTDA) is an example of DOFSS technology that measures strain and temperature in continuous (distributed) manner using a standard optical fibre telecommunication cable. The BOTDA measurement principle is based on transmission of light signals (utilising stimulated Brillouin scattering) launched 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 microstrain and sensing distance for up to 50 km long depending how the cable is installed.

The accuracy of the strain measurement among others depends on the instrument laser setup, such as spatial resolution, number of averaging, and frequency steps (Mohamad, 2012). In this study, a 5 ns laser pulse is used which is equivalent to spatial resolution of 50 cm (*i.e.* an averaged reading of over 50 cm spatial distance).

3 INCLINOMETER

3.1 Standard Inclinometer

For landslides and lateral movement detection, a set of inclinometer pipe casing with accelerometer probe is typically used in geotechnical instrumentation to measure 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 in the ground, usually within drilled holes, and the annular space grouted. Casing connections are specially made to seal out soil, grout, and other materials in order to maintain clean grooves and prevent filling of the casing. Refer to Fig. 2 for example of machine-grooved casing and connection.

Horizontal inclinometer on the other hand is used to obtain distribution profile settlement or heave typically associated with embankments and landfill areas. In the former case, the casing is installed into a trench before the construction of earthen embankments to obtain the differential settlements along a given line. A pulley unit is needed at one end to pull the probe along the full length of the casing and readings are recorded at every 0.5m interval.

Vertical and horizontal inclinometers are relatively low maintenance system (since there are no hydraulic lines or pressure sources) but inherited a number of limitations such as requiring manual operations and hence not real time, access to the ends of inclinometer casing, and the pipe must not bend too much or being 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 to inclinometer components, installations, acquiring and interpreting test results are described in more details in the literature (Machan and Victoria, 2008; Dunnicliff, 1993).

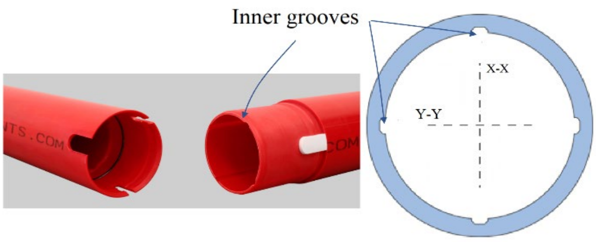
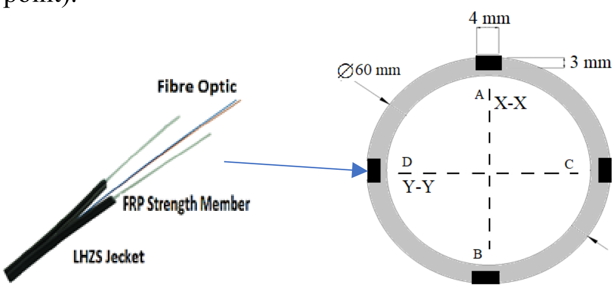


Fig. 2. Standard Inclinometer casing with inner grooves

3.2 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. Fig. 3 shows the machined grooved inclinometer casing with 60 mm outer diameter and 5mm thick made from Polyvinyl Chloride (PVC). Optical fibres are attached along the grooves on 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 cheaper and behaves more elastic. ABS pipes on the other hand tend to deform plastically (lower yielding point).



(a) (b)

Fig. 3. Attachment of optical fibre sensors along the machined grooved PVC casing

4 DATA PROCESSING TECHNIQUE

The principle of converting bending strains into traversing displacements have been reported by Mohamad *et al.* (2011). The lateral displacement, y of the PVC pipe shall be determined based on strain readings along each axis as shown below.

$$y = \frac{1}{D}\iint \varepsilon_a - \varepsilon_b \, dx \tag{1}$$

Where,

y = lateral displacement plotted along the longitudinal x

ε_a = strain at side a

ε_b = strain at side b

D = distance between two fibres or diameter of pipe

The integration of Eq. 1 can be done numerically or using closed-form solutions (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 inclinometer casing. For a vertical casing installed in a landslide, and when the casing tip is installed in a stable zone (reference datum), the horizontal and rotational movements are assumed as zero. However, where the tip of the casing is not in stable ground (such as for casings installed horizontally at the base of embankments), data readings are referenced to the top of the casing, which are optically surveyed with each monitoring visit.

To automate data processing of fibre optic inclinometer, a software program with Graphical User Interface (GUI) is developed using MATLAB program

5 EXPERIMENTAL TEST RESULTS

Two types of load bending test was performed for testing the performance of fibre optic inclinometer. The first is vertical inclinometer with cantilever loading configuration (compression or tension at only one side of the casing). The second test is horizontal inclinometer with two traversing loading points (multiple compression/ tension deformation on each side of fibre).

5.1 Vertical Inclinometer

A simple test procedure to measure a 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. Fig. 4 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 2 m height. In this test, the boundary conditions for FO inclinometer when calculating deflection are zero displacement at the tip and displacement reading from the dial gauge.

Fig. 5(a) compares the deflection readings between inclinometer, dial gauge and BOTDA upon pipe deflections of 20 mm, 80 mm, and 140 mm measured at 2m 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, FO data can provide 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 PVC casing with extended length of 6m (Fig. 5b). For the second experiment, the results are only compared with dial gauges (since there is no internal grooves inside the PVC pipe). As shown in Fig. 5(b), the derivation of FO lateral displacements was also excellent (*i.e.* matches well with other dial gauges).

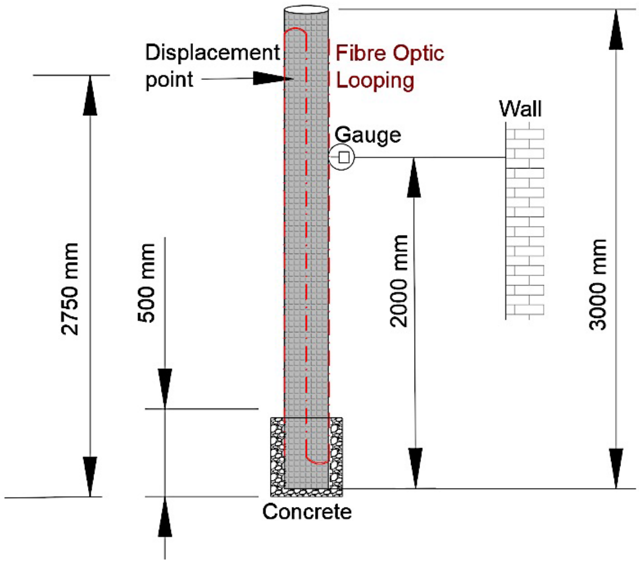


Fig. 4. Inclinometer casing test in vertical condition

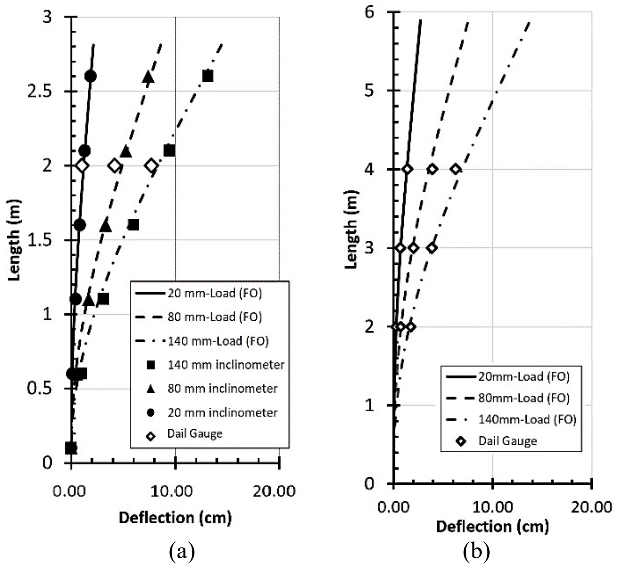


Fig. 5. Deflection of a (a) 3 m ABS inclinometer casing, (b) 6 m PVC FO inclinometer

5.2 Horizontal inclinometer

Horizontal inclinometer is a useful instrument for measuring the differential settlement profile at the base of earth embankment such as in highway and railway constructions. In the horizontally laid pipe experiment, the PVC assembled pipe is loaded at two mid-points between three supports as shown in Fig. 6. The supports comprising of a pin and two rollers. The reason of such loading configuration is to test the ability of deriving the traversing displacements when the pipe curvature is subjected to multiple sagging and hogging deformations (such as in retaining structure with braced excavation and twin embankments over the monitoring line).

Fig. 7 shows calculated the deflection of the pipe at three loading increments of 5 kg, 10 kg and 15 kg. The FO data generally agrees with displacement gauges (dial gauges and LVDT transducers). The maximum readings from FO is slightly lower than the local dial gauges (*e.g.* at left span; FO recorded 21.5 mm and dial gauge measured 22mm). This slight difference is attributed to a slight disorientation of the pipe axis and twisting effect upon hooking the hanging weights at the midpoints. The twisting may likely to be higher in the right span (5mm maximum difference after 15 kg loading). The rotation of the axis measured at one end-pin support increased with loading increment (not shown in this paper).

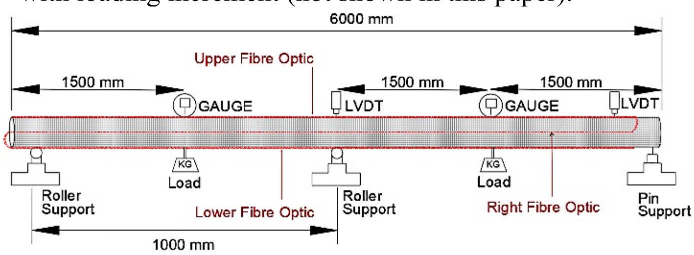


Fig. 6. Two span traversals loading on FO inclinometer casing

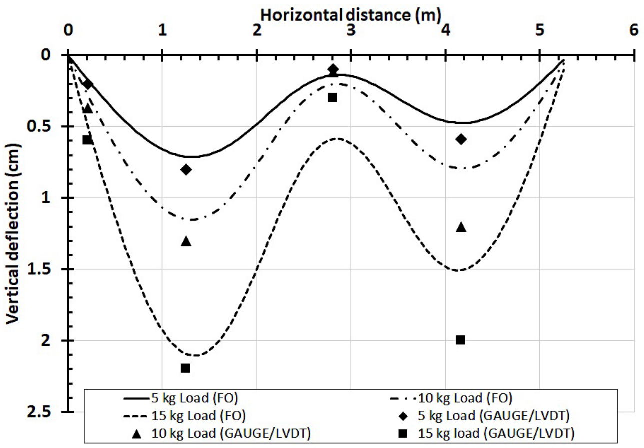


Fig. 7. Deflection of pipe along XX-Axis

Table 2. Comparison between inclinometer sensors

	Inclinometer	*Fixed-in inclinometer*	*DOFSS*
Maximum measurement distance	depends on cable length	< 25 m	unlimited
Best readout resolution/ Data spacing	50 cm	50 cm	5 cm
Measurement mode	Manual	Automatic	Manual or Automatic
Data logger cost	USD 17,600 (with probe sensor)	USD 20,700 (with telemetry)	USD 90,000 (with telemetry)
Cost per 21m borehole drilling + casing	USD 3,500	USD 35,300 (with 14 IPI MEMs)	USD 3,700

6 COST BENEFIT ANALYSIS

Although standard inclinometer has been widely used in various geotechnical monitoring work, the need for advancements in deformation measurements such as DOFSS are highly desirable. Some of the advantages of distributed FO inclinometer as compared to the conventional method are highlighted in Table 2.

Table 2 compares the measurement capabilities and instrumentation costs between the standard inclinometer, fixed-in inclinometer and FO inclinometer. It can be seen that DOFSS have many advantages such as longer measurement distance, more data points, real-time monitoring, as compared to the conventional ones.

Manual measurement using conventional inclinometer probe is often preferred for routine and periodic readings. However, for critical projects and remote locations where real-time monitoring are required, telemetry fixed-in inclinometer is proposed. The cost for a single borehole, say 21 m, installed with 14 IPI MEMs sensors (i.e. spaced at every 1.5 m) is about USD 56k. This is cheaper than DOFSS. In case of monitoring a large area with many borehole points, DOFSS is cheaper because the interrogator can be linked to several boreholes for simultaneous reading and the cost per borehole is very low. Other advantages of DOFSS are (i) the FO casings can be designed as a standpipe piezometer with perforations, (ii) it can be used to detect axial strains (compression or extension) of the pipe caused by the ground heaving or subsidence (Mohamad, 2016).

7 CONCLUSIONS

In this research, a prefabricated fibre optic inclinometer pipe was designed to monitor ground movements such as landslides and differential settlement profiler. Data processing as well as installation procedure were described and validated through laboratory tests. In general, the performances of fibre optic sensing was consistent with the commercial system. However, DOFSS has several distinct advantages such as provide more data points, can be remotely monitored and the casing can also be used as a standpipe piezometer.

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