Estimation of the buried pipeline displacement using distributed fibre optic sensing: An experimental study

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Abstract. Pipe displacement (bending) is one of the most prominent risks caused by the soil movements in the landslide areas. The lateral soil movement causes damages to the buried pipelines, which might explode due to leakage of flammable materials. Employing fibre optic sensors to monitor the buried pipes can maintain the integrity of piping systems and the surrounding environment. The fibre optic sensor has already demonstrated its capabilities to provide a continuous monitoring system for the structures. This paper aims to evaluate the buried pipeline displacement caused by the lateral soil movement. Brillouin Optical Time Domain Analysis (BOTDA) is used to measure the strain values from the fibre optic cable. A small physical model is used to demonstrate the bending of High-density polyethylene (HDPE) pipe under the ground movement. This paper concludes that the fibre optic sensor could be employed to evaluate the horizontal and vertical displacements of the buried pipeline.

Keywords: Buried pipeline, displacement, landslide, physical model, fibre optic sensors, BOTDA.

1. Introduction

Over the world, civil Infrastructures such as bridges, buildings, and pipelines are subject to different kinds of geohazards (earthquakes, landslides, etc.). Some of these infrastructures might completely collapse and leave environmental disasters. The pipeline is a primary entity for the civil infrastructures which is used to transport fluids (oils, water, and gas) over countries and between cities. Sometimes, the pipeline needs to cross the rugged areas that might be subject to natural hazards such as landslides. Buried pipes may damage due to external loads resulted from lateral earth pressure increment. Many countries have spent billions of dollars on maintenance and repair of the buried pipelines due to the lack of monitoring and early warning systems for hazard detection [1].

The most important factors that must be emphasised during the buried pipeline design stage are soil displacement effect on the pipes and estimation of the maximum strains in the pipeline [2, 3]. A continuous monitoring method to pipeline systems should be applied to avoid the risk of pipeline failure, especially those buried underground. However, using separate conventional sensors is an expensive solution for monitoring the pipeline systems because it requires placing thousands of sensors and cables on the pipes. Optical Fiber Sensor (OFS) is one of the current and standard sensors that provide low cost, continuous long-distance monitoring [4].

The optical fibre sensor is a technology that uses a light wave to obtain the deformation of the measurement change. This sensor is already applied in many fields of civil engineering. Distributed optical fibre strain sensor (DOFSS) is one of the latest technologies being used in Geotechnical engineering to provide real-time monitoring. The basis of this technique is a continuous strain measurement using an optical fibre distributor sensor known as Brillouin Optical Time-Domain Reflectometer (BOTDR) or Brillouin Optical Time-Domain Analysis (BOTDA) [5].
Both BOTDA and BOTDR can record the strain measurements by using various cables of fibre optic such as telecommunication fibre optic cable. The fibre optic sensors can provide strain measurement along the cable (up to 50 km long) by achieving a high-resolution which reaches up 10 macrostrains. Moreover, the strains of various pipes materials can be measured by the fibre optic sensor with a similar accuracy of strain gauge measurements [6]. Fibre optic monitoring system based on distributed measurements can provide continuous strain measurement when it is applied along the entire length of a pipeline [7].

Several studies and researches performed on the use of optical fibre sensors to monitor the buried pipelines are subjected to different loads. Moore and Take carried out experiments on various pipes to monitor them under the effect of a normal fault [8]. The strain values along the pipes were obtained by both fibre optic strain sensors and strain gauges sensors at the same moment. Their findings indicated that fibre optic strain sensors have an advantage of providing more data provision than the conventional strain gauge. In addition, Ravet used a distributed Brillouin sensor system to measure the tensile and compressive strains and monitor the buckling of a steel pipe [9].

Glisic and Yao completed a large-scale experiment to monitor the health of buried concrete pipes based on Brillouin light scattering (fibre optic sensor). They discovered that the fibre optic sensor could be used as an early warning system for pipes bends. Additionally, it can be utilised to determine the location of pipe damage caused by soil movement [10]. When the pipeline crosses active landslide areas, the soil movement can lead to developing strains and displacements in the pipes. The challenge is how to employ the fibre optic sensors to estimate the displacement of the buried pipelines. In this study, a new method to detect and estimate pipe displacement is presented based on fibre optic sensors.

2. Materials and Equipment

In this study, a small physical model is used to monitor pipe behaviour using fibre optic sensors. This model was developed by Alarifi, to study the behaviour of a buried pipeline under the landslide effect using strain gauge sensors [11]. Plastic acrylic sheets are used to fabricate the model of a box of 500 mm long, 250 mm wide, and 100 mm deep. Movable plates are fixed in the middle of the box by four linear bearing blocks which help the plates move smoothly. A High-Density polyethylene pipe (480 mm long and 20 mm diameter) is installed by simple support at both ends. A manual pulley and rope used to pull the movable plates out of the box, as shown in figure 1.

A fibre optic telecommunication cable of 8 m long is used to measure the strain along the pipe at four positions (bottom, top, front and backside). A linear variable differential transformer (LVDT) with the capacity of 100 mm is used to measure the displacement of the movable plate. Fully dry sand is utilised as the backfill material for this experiment. The materials properties are listed in table 1.

3. Method Description

The fibre optic cable was installed along the HDPE pipe at four locations, as shown in figure 2. The cable is well-attached to the pipe using an adhesive tape and instant adhesive which is made of cyanoacrylate sold as "Super Glue". The fibre optic cable was tested by a laser light inspector to check if there was a breakpoint before starting the experiment.
Figure 1. The physical model.

Table 1. The materials properties.

|               | Soil                          | HDPE pipe       |
|---------------|------------------------------|-----------------|
| class         | poorly graded sand           | (HDPE) class    |
| D<sub>10</sub>| 0.37 mm                      | PN 16           |
| D<sub>50</sub>| 0.72 mm                      | Tensile strain  |
| D<sub>60</sub>| 1.04 mm                      | (break)         |
| Unit weight   | 15.49 kN/m<sup>3</sup>       | Density         |
| Friction angle| 30.8°                        | -               |
The HDPE pipe is conveniently placed in the middle of the model after filling the box with sandy soil at the bottom level of the pipe (invert level), as shown in figure 3 (a). A second layer of the soil (250 mm in depth) is added above the pipe, and the soil layers are compacted by using a small manual rammer. The LVDT was installed in front of the movable plate and connected to a data logger to record the plate displacement immediately. Moreover, the optical fibre cable connected to the BOTDA analyser channel and the baseline of the strain measurements is recorded.

The movable plate was pulled out (5 mm) by a manual pulley and the first measurement of the strain was recorded. Moving plate displacement increased gradually by 10 mm to 75 mm, and strain measurements were recorded at each stage of movement to monitor strain changes. figure 3 (b) & (c) illustrate the initial stage and lateral soil movement induced by pulling the movable plate at the fifth stage (45 mm), respectively. In figure 3 (c), the blue dashed line shows the active soil zone while the red dashed line represents the boundary of the passive soil zone.

**Figure 2.** The fiber optic cable attached to HDPE pipe.

**Figure 3.** (a) Placing the pipe in the model (b) Initial stage (c) Lateral soil movement (45 mm).
4. Results & Data Analysis

The fibre optic sensors are used to monitor the buried (HDPE) pipe which is subjected to lateral ground movement in the small-scale model. The strains values were obtained by using BOTDA analyser via fibre optic cable. Figure 4 demonstrates the recorded strain values along the cable which include parts that are placed at various paths on the pipe at different stages of soil movement resulting from pulling out the movable plate. The movable plate displacement was controlled and it started with 5 mm and increased by 10 mm at each step until it reached 75 mm.

![Figure 4](image_url)  
*Figure 4. The strain values along the fibre optic cable at different plate displacement.*

*The front side is located in active soil while the backside located in passive zone*

In general, the strain values grew-up steadily along the buried pipe as the soil displacement increased. The highest strain values for all sides (top, bottom, backside, and front side) were recorded in the middle of the pipe. However, the strain values of the top and bottom sides were very close with different signals of positive and negative, respectively. It also happened to the strain values obtained from the front and backside sensors, as shown in figure 5.

Both top and backside fibre optic sensors were in the positive zone, and they had almost the same behaviour, while the bottom and front sides were in the negative area, and they had similar behaviour. Positive strains values indicate the deformation of tensile force in the upper and backward parts of the tube as a result of the movement of soil towards the front side of the pipe. In contrast, negative values indicate the compressive force at the bottom and front side of the pipe.
Figure 5. Strain values in the middle of the pipe.

The strain values increased as a result of increased pressure on the pipe, and pipe displacement is developed in both horizontal and vertical directions. Figure 6 illustrates the pipe position before and after running the experiment and the analysis is based on the strain values obtained from attached sensors along the pipe. After pulling the movable plate, the buried pipe was exposed to active lateral pressure due to the soil movement toward the front side of the pipe.

Figure 6. The Pipe position before and after running the test.

Due to the lateral soil movement towards the pipe, a curved surface was developed similar to what happened to the simple support beam when it was exposed to the external loads (figure 7). This curvature is equal to the total strain values of the two opposite directions (e.g. top and bottom) and is divided by the pipe diameter. The horizontal displacement was determined by analysing the front and backside strains while the bottom and top strains calculated the vertical displacement. Both horizontal and vertical pipe displacements (in the middle of the pipe) are calculated by integrating the curvature twice. The derivation of pipe deformation from distributed fibre optic sensors was done by analysing the strain on
Two fibres that placed symmetrically concerning the axis. The analysis was done by comparing the strain data between two opposing fibres (strain $\varepsilon_1$ and strain $\varepsilon_2$) (figure 7), which resulted in bending curvature. The horizontal and vertical displacement ($y$) of the pipe was determined based on equation (1).

$$y = \iiint \frac{\varepsilon_1 - \varepsilon_2}{D} d^2x$$  \hspace{1cm} (1)

$y$ = pipe displacement (Horizontal or vertical)
$\varepsilon_1$ = strain value (Bottom or front side)
$\varepsilon_2$ = strain value (Top or back side)
$D$ = diameter of the pipe

Figure 7. The plane view of the pipe.

Figure 8 illustrates the maximum horizontal and vertical pipe displacement at each stage of the plate motion. The maximum displacement values of the pipe at each stage of plate displacement were calculated and listed in table 2.
Table 2. Values of horizontal and vertical displacement.

| Plate | Bottom Strain (με) | Top Strain (με) | Backside Strain (με) | Front side Strain (με) | Pipe Vertical Displacement (mm) | Pipe Horizontal Displacement (mm) | pipe motion angle (ϕ) |
|-------|--------------------|----------------|--------------------|-----------------------|--------------------------------|----------------------------------|-------------------|
| 5     | -18.77             | 97.10          | 110.50             | -44.50                | 0.167                          | 0.223                           | 36.83             |
| 15    | -176.03            | 231.53         | 294.33             | -256.33               | 0.587                          | 0.793                           | 35.5              |
| 25    | -218.67            | 296.36         | 371.77             | -325.18               | 0.742                          | 1.004                           | 36.46             |
| 35    | -284.84            | 443.89         | 493.89             | -376.65               | 1.049                          | 1.254                           | 39.93             |
| 45    | -343.29            | 438.51         | 538.97             | -481.47               | 1.126                          | 1.469                           | 37.45             |
| 55    | -387.86            | 529.59         | 641.62             | -566.66               | 1.321                          | 1.740                           | 37.2              |
| 65    | -550.13            | 642.41         | 776.03             | -751.55               | 1.717                          | 2.200                           | 38                |
| 75    | -828.49            | 865.47         | 1032.24            | -1059.31              | 2.439                          | 3.012                           | 39.01             |

The movable plate was pulled-out starting at 5 mm and gradually grew 10 mm up to 75 mm each. The maximum horizontal displacement of 3.01 mm was reached at 75 mm while the maximum vertical displacement of 2.44 mm achieved at the same stage of plate movement (75 mm). In a nutshell, horizontal displacements of the pipe were higher than vertical displacements at all the stages of the plate motion. In addition, noted that the vertical displacement did not exceed 84% of horizontal displacement. The displacement angle of the buried pipe ranges from 35° to 40° to the horizontal axis.

5. Conclusion
In this study, a lab experiment uses the fibre optic sensor to estimate the horizontal and vertical displacements of the buried pipeline. The findings indicate the possibility of employing the fibre optic sensor as an early warning system. The conclusions of this study are as follow:

- A comprehensive monitoring solution can be implemented by using the fibre-optic sensor to monitor the displacement of buried pipelines.
- Fibre optic sensors can help the operator to minimise the time spent in site inspection, as it pinpoints the specific locations where the pipe is moving.
- Fibre optic sensors provide continuous monitoring of pipelines deformation in real-time.
- The computation of pipeline displacement could be measured by the fibre optic sensor based on the analysis of strain measurements.
- The sensitivity of this sensor to detect the pipe displacement at a very early stage when the soil movement cannot be visually assessed.

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