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On the use of high-resolution distributed fibre optic sensing for small-scale geotechnical experiments at 1g

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ABSTRACT: The use of distributed fibre optic sensing (DFOS) is becoming increasingly popular for strain measuring and monitoring. While the technology is efficient in the field, its use for strain measurement in geotechnical model-scale experiments is currently limited, mostly because of a lack of spatial resolution in the DFOS technologies. However, recent developments now enable high spatial resolution measurements, for example, with the use of Rayleigh Scattering technology for the fibre and the Luna ODiSI 6100 DFOS analyser. This technology is becoming increasingly popular for use in small-scale experiments, mainly for structural monitoring. For geotechnical applications, there are a few technological barriers that presently limit their use in the laboratory. However, there are great advantages in using this technology, mainly to measure strain deformation continuously along the fibre at the core of a soil sample. This paper explores the possibility of using high-resolution distributed fibre optic sensing for small-scale geotechnical experiments at 1g, using a trapdoor rig that mimics the formation of a sinkhole. The fibre optic is embedded in the soil above the trapdoor to measure subsidence, and different laying techniques are explored, aiming at enhancing the coupling between the fibre optic cable and the surrounding soil at low confining pressures. This work aims at widening the range of instrumentation available to measure strain in small-scale geotechnical experiments, offering a complementary technique to conventional instrumentations.

Keywords: sinkhole, 1g experiments, fibre optic sensing.

1 INTRODUCTION

Small-scale physical modelling at 1*g* is commonly used in soil mechanics to investigate soil behaviour and geotechnical failure mechanisms (Muir Wood, 2006). The measurement of ground displacements is central to most experiments and is also used to further validate and refine analytical and numerical models. Conventional instrumentation, such as linear variable displacement transducers (LVDTs), only capture the displacement at limited discrete locations and directions, while more recent techniques, such as Particle Image Velocimetry (PIV), can only capture strain profiles at a soil sample boundary (ground surface, or transparent boundary).

Distributed fibre optic sensing (DFOS) has emerged as a powerful tool for continuous, high temporal and spatial resolution mapping of subsurface ground movement, and enable measurement of temperature, strain, and acoustic energy distributions along the entire length of a fibre optic sensing cable (Kechavarzi *et al.* 2016; Xu *et al.* 2021). To date, this technology has mostly been used and deployed in the field, with DFOS cables embedded in trenches on the ground surface and back-filled by in-situ soil to monitor ground cracks, horizontal displacements and ground settlements (Klar *et al.* 2014; Zhang *et al.* 2016). This is because the incorporation of DFOS cables into the ground could provide significantly improved information on the location and magnitude of subsurface ground movement and subsidence.

However, for small-scale geotechnical experiments, conventional DFOS offers limited advantages, mostly because of the restrictions on spatial resolution (typically 1 m for Brillouin optical time-domain reflectometry (BOTDR)) and also the sampling frequency (acquisition time of several minutes per measurement). Beemer *et al.* (2018) investigated the use of the Sensuron Summit Elite optical frequency domain reflectometry (OFDR) system, combined with Fibre Braggs Gratings (FBG) for use in small scale geotechnical experiments at 1*g*, achieving a spatial resolution of 6.35 mm. The tests showed promising results for strain levels above 80 με and proved successful in measuring deformation for soil-structure interaction experiments. However, the fibre had not been used to directly measure strain in the soil.

The recent developments of the OFDR Luna ODiSI 6100 DFOS analyser enable better use of DFOS in small-scale experiments, using cost-effective cables, a spatial resolution of 0.65 mm to 2.6 mm and an acquisition rate of 25 Hz to 250 Hz.

Nevertheless, for strain measurement directly within a soil sample, the accuracy from DFOS relies on sufficient soil-cable coupling, especially for 1*g* tests, which typically have very low overburden pressure (Zhang *et al.* 2016).

This paper explores the impact of different cable installation techniques in improving the data quality of measured ground movements induced by underground subsidence at 1*g*. Both the soil-cable interface properties and cable fixities are investigated and recommendations on the best laying techniques are provided through comparison with PIV data.

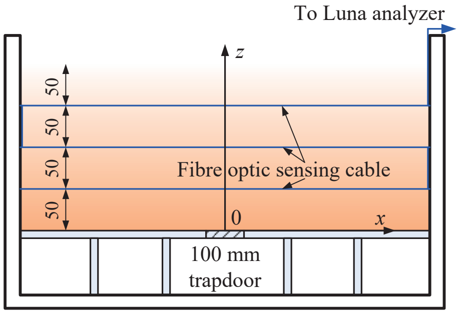
2 SINKHOLE SMALL-SCALE EXPERIMENTS

The experiments replicated the formation of a sinkhole using a 2D plane-strain trapdoor rig, actuated with a hydraulic piston and equipped with an acrylic window (Fig. 1). The box has internal dimensions of 790 mm × 200 mm × 560 mm, with a trapdoor width of 100 mm. Detail on the experimental setup is provided by Möller et al. (2022).

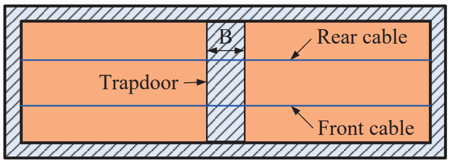
A 200 mm high soil sample was carefully prepared using Hostun HN31 sand at selected relative densities using a sand pourer (Madabhushi *et al.,* 2006). Scaling of soil sample properties at 1*g* meant that a relative density of ~50% corresponds to a relative density of ~80% in the field (Möller *et al.* 2022). The soil strain field was assessed using PIV (Stanier *et al*. 2015).

Linear variable differential transformers (LVDTs) were employed to verify the trapdoor displacement δ, and experiments were terminated at $\delta = 20\ mm$. However, only the first 3.5 mm are of interest in this paper, with a focus on $\delta = 2\ mm$, which corresponds to the early stages of the sinkhole formation (Möller et al. 2022) when it is the most essential to detect subsidence-induced strain in the soil.

The high-resolution Rayleigh-based distributed fibre optic sensing system Luna ODiSI 6100 was used to log DFOS cable strain. This analyzer is based on the optical frequency domain reflectometry (OFDR) technique, and a spatial resolution of a 2.6-mm was adopted for the experiments, with a frequency of 25 Hz. A 2-mm diameter tight-buffed polyurethane-coated DFOS cable (C07, Nanzee Sensing, Suzhou, China) was used. Zhang *et al.* (2016) showed that it is suitable for monitoring soil deformation, thanks to its excellent strain transfer capability and low Young's modulus (200 MPa). The DFOS cable is capable of withstanding moderate impacts during installation, and can easily be pre-strained and directly integrated into loose granular soils. DFOS cables were embedded at 50 mm intervals throughout the entire height of the soil sample to capture and compare the strain profiles with that from the PIV (Fig. 1(a)). At each layer, two separate DFOS cables, rear and front cables were installed independently to enable direct comparison (Fig. 1(b)).



(a) Elevation view



(b) Plan view

Fig.1 Layout of FO strain sensing cables in plane-strain trapdoor test: (a) Elevation view; (b) Plan view.

3. CABLE INSTALLATION TECHNIQUES

3.1 Soil-cable interface

To enhance the soil-cable coupling, one DFOS cable was uniformly coated with a layer of sand (Fig. 2). This was achieved by applying a very thin layer of glue on the cable and rolling it in the sand. This increases the soil-cable friction angle, with negligible impact on other cable properties (e.g. Young's modulus).

3.2 Cable fixities at each layer end

Each cable layer was typically pinned at both edges of the box to replicate the effect of overburden pressure in an infinitely long cable; excess slack between the two ends was removed before the cable was fixed in position. Three other cable fixing methods were also explored to investigate the effect of releasing the pre-tension in the cable on the measurement: (1) leaving the cable in a loose state; (2) guiding the cable through a tube (Fig. 3(a)); and (3) introducing a slack loop into the DFOS cable in the vicinity of the trapdoor (Fig. 3(b)). Table 1 summarizes the test programme reported in this paper.

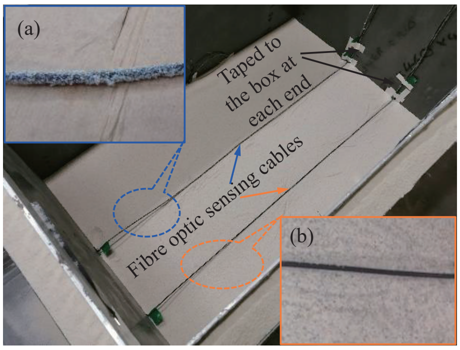


Fig.2 DFOS cables in trapdoor experiments: (a) Sand-coated cable; (b) Standard DFOS cable.

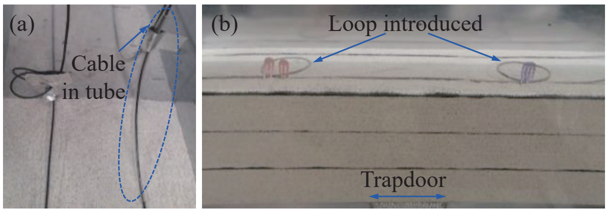


Fig.3 Fixing conditions of DFOS cables in the trapdoor test: (a) Cable guided through a tube; (b) Loop introduced to provide cable slack.

Table 1. Cable installation techniques attempted

Test ID	Dr (%)	Soil-cable interface	Fixing condition
DR-96	96	Polyurethane & Sand-coated	Tape-fixing
DR-48	48	Polyurethane (×2)	Loose & Tubed
DR-52	52	Sand-coated (×2)	Loose & Slack

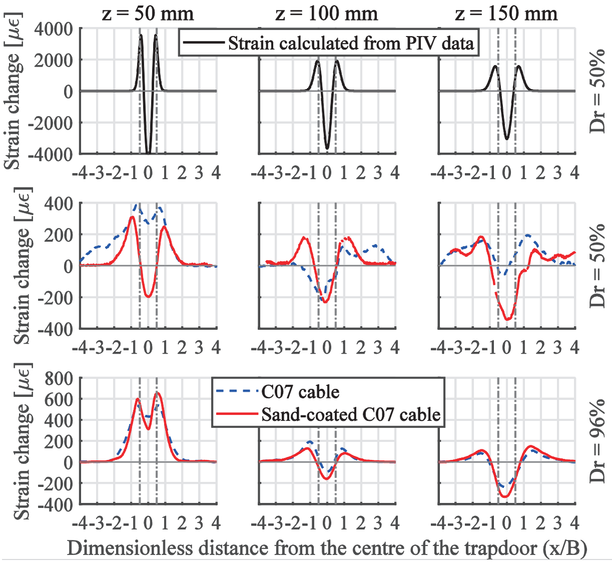


Fig.4 Comparison of strain signature profiles (δ = 2 mm).

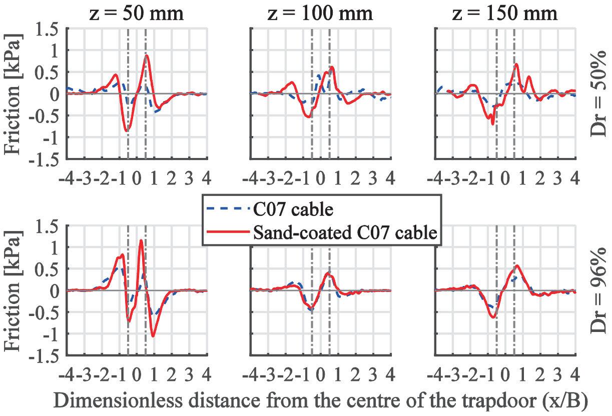


Fig.5 Comparison of friction profiles (δ = 2 mm).

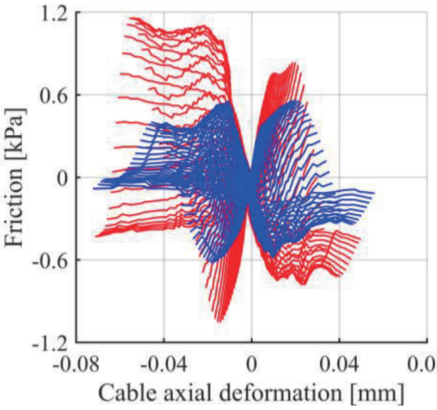


Fig.6 Comparison of friction-displacement relationships between C07 (blue) and sand-coated C07 cables (red) (δ = 2 mm; z = 50 mm, D_R=50%).

4 RESULTS AND OBSERVATIONS.

4.1 Effect of soil-cable interface

Fig.4 shows typical strain profiles obtained with the C07 cable for targeted densities of D_R=50% and D_R=95% and compared with PIV data for D_R=50%. All profiles display a double-peak with a central dip, which corresponds to the location of the sinkhole. A very similar signature strain profile can be obtained with the sand-coated cable, yet with more pronounced peaks and dips, as well as greater inclination, providing more acute data for post-processing. In addition, sand-coating enables to restore a near-zero strain at the edge of the sample for D_R=50%, which was targeted to mimic an infinitely long cable. Nevertheless, an order of magnitude difference is observed with the PIV data, which is in line with the observations from Zhang *et al.* (2016).

The soil-cable friction was derived from the strain gradient along the DFOS cable:

$$\tau = -\frac{ED}{4}\frac{d\varepsilon}{dx} \qquad (1)$$

where D is cable diameter and E is Young's modulus. Fig. 5 shows that the sand-coated cable offers much higher friction (max 1.56 kPa) compared to that of the standard cable (max 0.82 kPa).

The distributed strain profiles could also be integrated along the DFOS cable to obtain the cable axial deformation. Thus, the friction-displacement curves for both standard and sand-coated cable at every 2.6 mm could be derived. Fig. 6 shows that the standard C07 cable exhibits softening behaviour at larger trapdoor displacements than the sand-coated cable, providing insight into the results of Fig. 4 and Fig. 5.

4.2 Effects of cable fixities

Fig.7 compares the strain signature profiles for the four different fixities. First, in the case of the standard C07 cables, the loose cable picks up boundary effects, with non-zero strain experienced at x/B = -4. The tube-guided cable similarly picks up strain at the boundaries, but engages more strain around the trapdoor zone, thanks to its freedom at the end. However, none produce a very satisfactory signal to locate the peaks, which the loose sand-coated C07 cable displays best. Fig. 7 also shows that fixities have a lesser impact on the strain profiles of the sand-coated cables. Finally, Fig. 8 shows that all four cables experienced similar soil-cable interface friction, with limited influence of fixities.

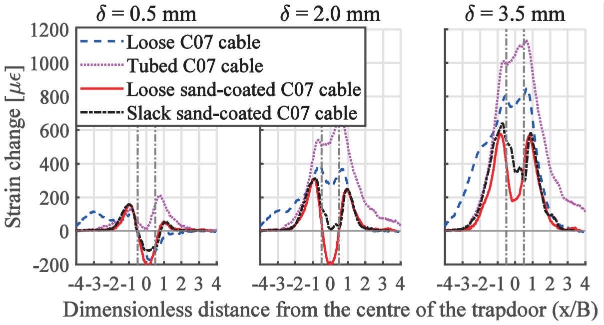


Fig.7 Effects of cable fixities on strain signature profiles (z = 50 mm, DR-48 & DR-52).

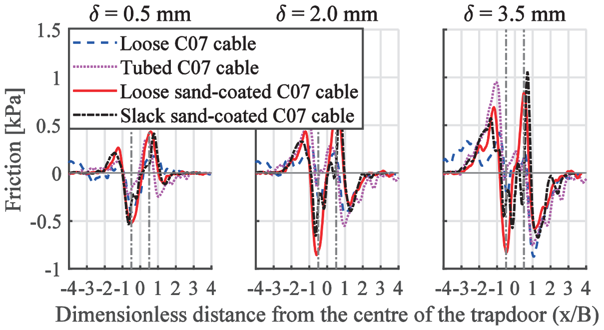


Fig.8 Effects of cable fixities on friction profiles (z = 50 mm, DR-48 & DR-52).

5 CONCLUSIONS

Small-scale sinkhole tests in granular soils were performed with a 2D plane-strain trapdoor rig to explore the application of high-resolution distributed fibre optic strain sensing for sinkhole early warning detection, by examining different cable laying techniques. The results show that a continuous loose sand-coated cable, pinned at the end of each soil layer provides a good quality measurement of soil strain profile and enabled the most accurate location of the sinkhole. The only (and main) difference compared with PIV data is the order of magnitude of the measured strains, which will be further explored through numerical modelling by the authors. Nevertheless, this paper demonstrates the value of using DFOS technology for subsurface strain profile measurement in small scale experiments at 1g.

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