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Fiber Optic Sensing for Sinkhole Detection in Cohesionless Soil

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Abstract. Sinkholes are geo-hazards which can form suddenly without humanly visible pre-indication from soil surface settlement. An early warning system located below ground would enable to detect sinkhole-induced settlement before it reaches the surface, preventing possible damage to infrastructure and protecting lives. This paper focuses on the use of Distributed Fiber Optic Sensing (DFOS) as a solution for early detection of sinkhole formation. A series of small-scale experiments in controlled conditions are used to simulate the formation of a sinkhole. Fiber optics cables are laid in the soil specimen, and strains are collected using the LUNA ODiSi 6100 analyzer. The soil movements are observed through a Perspex window, collected with a camera and analyzed using Particle Image Velocimetry (PIV). Results indicate the ability of DFOS in detecting soil movements and underline the typical signature strain profile expected during sinkhole formation, indicating that at an early stage in the sinkhole formation, horizontal movements govern the strain profile within the cable. In conclusion, our study suggested that the DFOS technology can be used to detect, locate and estimate the size of a sinkhole, even though it has not possible to monitor the real strain level in the soil, due to a lack of shear transfer at the interface between the soil and the cable.

Keywords: Sinkhole · Trapdoor Test · Fiber Optic Sensing

1 Introduction

A sinkhole is created by subsidence of a depression or hole in the ground, eventually creating catastrophic failure at the soil surface. This can be the result of (i) progressive sagging of the overlying deposit above the void, (ii) sudden collapse of brittle formations along failure planes [1]. The genesis of a sinkhole depends on the complex geological structure and the hydrogeological setting of the soil. Nevertheless, the formation of a sinkhole implies that a void must develop at a certain depth and that a disturbing agent must arise to cause the soil to collapse within the void. The areas primarily exposed to these phenomena are karst terrains, which comprises limestone, dolomite, evaporites

and gypsum. These are prone to being dissolved with underground water flow, due to their chemical composition, thus allowing the formation of a cavity which may collapse and cause a sinkhole.

Sinkholes can cause severe damage to the existing infrastructures and buildings [2–4], and in rare occasions can lead to fatalities [5, 6]. Monitoring systems are needed to prevent or reduce the risk of any damage. Existing monitoring techniques, such as satellite-monitoring (DInSAR), laser scanner, photogrammetry, total stations and high precision levelling, are focused on the measurement of movements at surface level. These techniques must allow some settlements and deformations in the soil body, before being able to detect the formation of a sinkhole. Therefore subsurface methods such as embedded Distributed Fiber Optic Sensors (DFOS) could detect sinkhole-induced strains and movements earlier, since they can be installed at depth in the ground.

This paper shows an experimental campaign carried out as part of the SINEW project [7] to investigate the efficacy of this latter monitoring technique in detecting strain changes within the soil, induced by the formation of a sinkhole.

2 Methodology

2.1 Experimental Setup

Sinkholes can be simulated in the laboratory by means of trapdoor tests, both at $1g$ [8] or in the geotechnical centrifuge [9, 10]. In this paper, the experimental study was performed at $1g$ using a 790×200 mm rectangular rig, equipped with a trapdoor of width, $B = 100$ mm that can mimic the formation of a sinkhole, as shown in Fig. 1.

Samples were prepared using Hostun sand, with an average particle size, $d_{50} = 0.356$ mm [10]. Tests were prepared at increasing relative densities ($D_R = 20\%$, 52% and 88%) to allow comparison of sinkhole formation at different soil conditions. The sand was poured manually for $D_R = 20\%$, and using an automatic sand pouter for the higher densities. The sample height was $H = 200$ mm ($H/B = 2$).

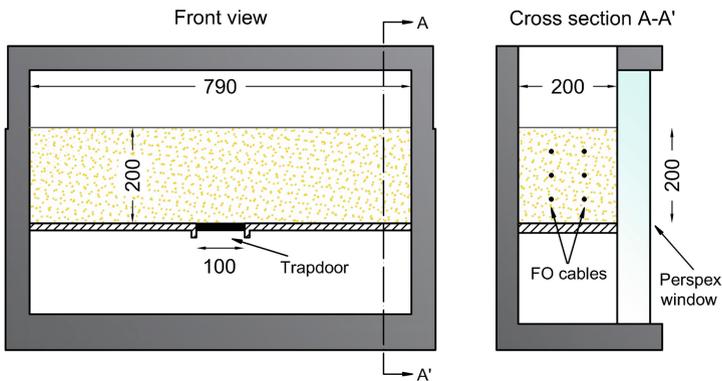


Fig. 1. Experimental rig with plane strain trapdoor

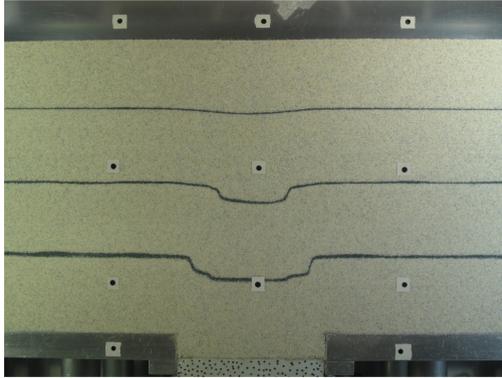


Fig. 2. Image acquired from the Canon Powershot G10, used for PIV analysis

The DFOS cables were installed at heights of $z = 50, 100,$ and 150 mm above the trapdoor and these layers were highlighted using dyed black sand to highlight the shear band during failure (Fig. 2). The cables were pinned at the edge of the box, and coated in sand to increase soil-cable interface coupling in selected experiments [11].

The DFOS analyzer used to collect strain within the cable is the Luna ODiSI 6100 [12]. It is well adapted for small scale experiments in the laboratory due to the small spatial resolution and precise gauge length (2.6 mm used in this case). With a sample width of $L = 790$ mm, this provides ~ 300 sampling points in the FO cable at each level, enabling the establishment of a precise continuous distributed strain profile.

Images for the PIV analysis were acquired using a Canon Powershot G10 camera and the analysis was carried out using GeoPIV_RG [13].

3 Results

For a trapdoor displacement δ lower or equal to 1–2% of the trapdoor width, the soil is able to adjust and redistribute the stresses on an adjacent support [14]. This behavior is known as arching [15] and is regarded as the *early* phase of the sinkhole formation. This phase is the main focus of the work presented in this paper. Despite measuring the strain profile at three heights within the soil sample, the cable of most interest in this study is the one located at $z = 150$ mm, which represents a realistic embedded height that could be achieved during earthwork (~ 1 m depth from original soil surface at full scale).

3.1 Particle Image Velocimetry Analysis

The main results from PIV analyses consist in the settlement profiles at different heights above the trapdoor, which have been fitted using a modified Gaussian distribution [16] according to the following equations:

$$S_v(x) = S_{\max} \cdot n / \left\{ (n + 1) + \exp \left[\alpha \cdot (x/i)^2 \right] \right\} \quad (1)$$

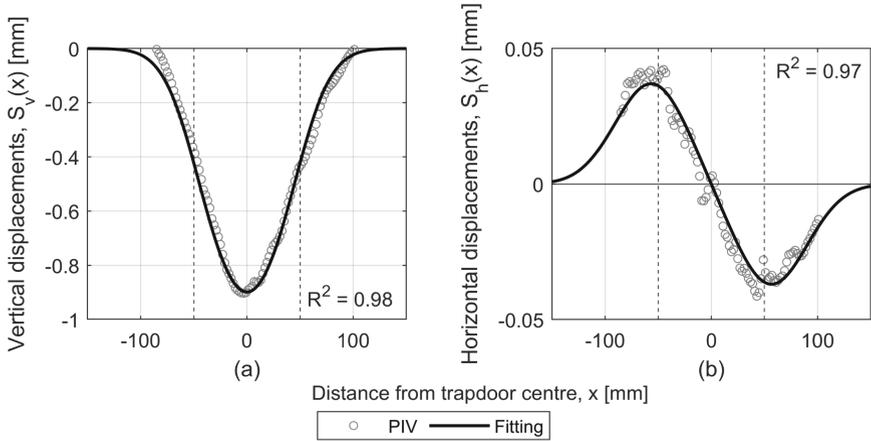


Fig. 3. (a) Vertical displacements, (b) Horizontal displacements from PIV for $D_R = 52\%$ $\delta = 2$ mm and $z = 150$ mm

$$n = 1 + \exp(\alpha) \cdot (2\alpha - 1) / (2\alpha + 1) \tag{2}$$

where S_{max} is the maximum settlement at the trapdoor centerline, i is the distance from the trapdoor centerline of the inflection point, α is a shape factor to alter the location of the inflection point. Horizontal soil displacements from PIV are interpolated using a double Gaussian distribution, according to the following equation:

$$S_h(x) = S_{hmax} \cdot \{ \exp[-(x-b)/c] - \exp[-(x+b)/c] \} \tag{3}$$

where S_{hmax} is the maximum horizontal displacement while b and c are fitting parameters. Displacement profiles from PIV are shown in Fig. 3, demonstrating the adequateness of Eq. (1) and (3).

From the displacement profiles, it is then possible to evaluate the strain which are representative of those experienced by the fibre optic cable using:

$$\varepsilon = \left\{ \left[(x_{i+1} - x_i + S_{h,i+1} - S_{h,i})^2 + (S_{v,i+1} - S_{v,i})^2 \right]^{0.5} \right\} / (x_{i+1} - x_i) \tag{4}$$

This is needed for comparison with DFOS data, where horizontal and vertical displacement cannot be accessed.

3.2 Strain Profiles from DFOS

The experimental soil strain evaluated from fitted displacement profiles (Eq. (4)) are then compared with the experimental strain experienced by the fiber optic cables, obtained from the Luna ODiSI 6100 interrogator. Figure 4 shows a difference in strain magnitude between the fiber optic cable and the corresponding strain in the soil. This discrepancy might be related to a lack of shear transfer between the soil and the cable, induced by a lack of coupling and the low stress level at 1g. To further understand this behavior,

detailed inspection of the fiber optic cable was performed numerically to enable better visualization of the cable deformation and strain profile [17]. Figure 5 shows a comparison between the experimental output from the interrogator and the numerical results for validation. The results concur with the experimental observations and demonstrate the impact of testing at 1g, and of the low stress level, on the cable's ability to follow soil movement, a difficulty that disappears at higher stress levels [7, 17].

This does not invalidate the use of 1g small scale experiments to further understand the use of DFOS for geo-hazard monitoring, as this is currently the most practical and cheapest way of generating experimental results using Rayleigh backscatter light analyzer.

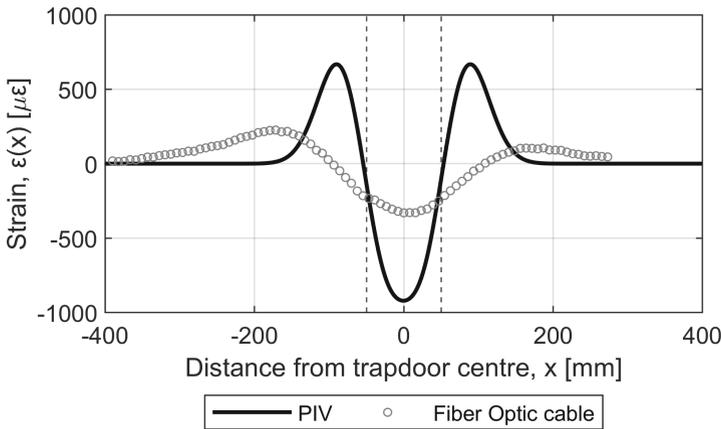


Fig. 4. Soil strain from PIV and strain within the fiber optic cable for $DR = 20\%$ $\delta = 1$ mm and $z = 150$ mm

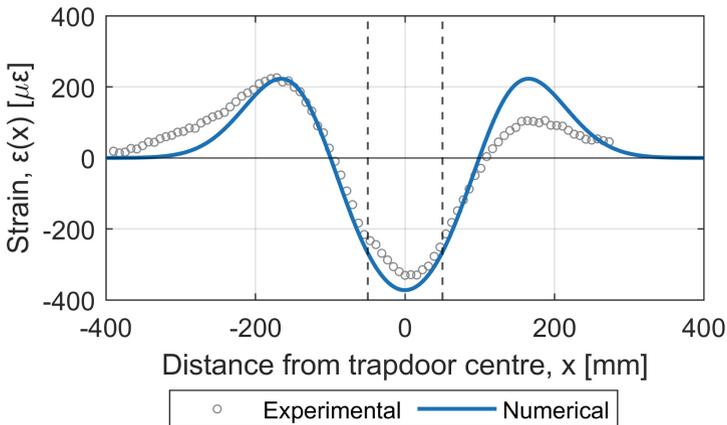


Fig. 5. Strain within the cable for $DR = 52\%$ $\delta = 1$ mm and $z = 150$ mm. Experimental strain obtained from the interrogator vs Numerical strain from FE analysis (modified after [17])

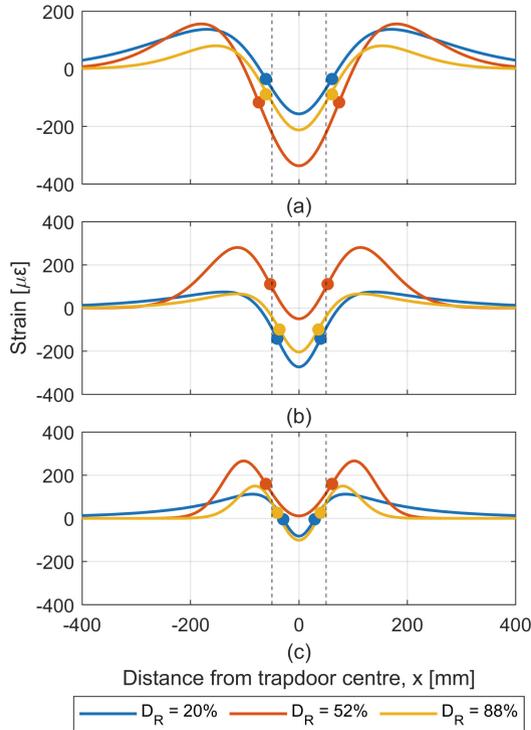


Fig. 6. Inflection point position on the experimental cable's strain profiles for $\delta = 1$ mm: (a) $z = 150$ mm, (b) $z = 100$ mm, (c) $z = 50$ mm above the trapdoor

Moreover, the singular shape of the strain profile indicates the expected signature that one would expect from a sinkhole detection. The strain profiles obtained can reveal the position and the size prediction of the sinkhole, by looking at the position of the inflection point, as shown in Fig. 6, which pertains to experimental results.

4 Conclusions

Sinkholes are highly dangerous events for the health of infrastructures. Hence, to minimize or avoid the possible damages induced by a sinkhole, it is important to monitor soil deformations. A way to address this, is the use of an inexpensive fiber optic cable, buried at shallow depths, in the soil mass, that 'senses' the change in strain in the soil before its effects reaches the surface.

Different from civil structural applications (e.g. concrete structures, steel structures, etc.), where the fiber can be simply glued onto the surface, the effectiveness of DFOS in following soil movements is strongly dependent from the soil-cable interface and this limit has been considered as the main barrier to the use of this technology for geotechnical applications.

This paper illustrated the effectiveness of a relatively new technology (i.e. DFOS with Raileigh backscattering) in detecting soil movements.

Our study focused its attention on small scale trapdoor test, performed in controlled conditions at 1g. Results from PIV have been processed so that can be compared with data obtained by the fiber optic interrogator.

Despite DFOS technology is not able to follow the soil strain as expected, it is able to pick up an unequivocal profile of strain, induced by the trapdoor lowering, since the beginning of the test (i.e. $\delta \leq 0.01 - 0.02 \cdot B$). In conclusion, our study suggested that the DFOS technology can be used to detect, locate and estimate the size of a sinkhole, even though it has not possible to monitor the real strain level in the soil, due to a lack of shear transfer at the interface between the soil and the cable.

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