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## Fibre Optic Sensing and Satellite Imaging for Early Warning of Catastrophic Ground Subsidence

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1 **Fibre Optic Sensing and Satellite Imaging for Early Warning of**  
2 **Catastrophic Ground Subsidence**

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57 **Abstract (200 words)**

58 Sinkholes pose significant risks to infrastructure and safety, emphasizing the need for early detection  
59 methods as their occurrence rises due to climate change. The ongoing SINEW project aims to provide  
60 early warning of sinkhole expansion using combined fibre optic sensing and radar satellite imaging to  
61 protect critical linear infrastructure. This paper presents key findings from experimental and numerical  
62 campaigns validating the use of distributed fibre optic sensing (DFOS) for early subsidence detection.  
63 1g laboratory experiments demonstrate distinct signature strain profiles during sinkhole formation, with  
64 finite element analyses providing insight into soil-cable behaviour. Numerical scaling confirms the  
65 technique's feasibility under realistic stress levels and 3D sinkhole conditions. DFOS proves capable of  
66 detecting active sinkholes at an early stage, even when cables are situated away from the subsidence  
67 centreline, albeit a weak signal that requires complementary monitoring investigations. In this instance  
68 when uncertainty arises regarding potential cavity formation in a specific area, combined Multi-Temporal  
69 Interferometric Synthetic Aperture Radar (MT-InSAR) serves as an effective complement to pinpoint the  
70 location of the subsidence. Analysis of a car park collapse demonstrates MT-InSAR potential, detecting  
71 settlement profiles of a few millimetres years before collapse, and promising significant advancements  
72 in remote sensing technology.

73

74 **Keywords (6)**

75 Ground movements, Monitoring, Fibre optic Sensing, InSAR, Geohazards, Sinkhole

## 76 1. Introduction

77 Sinkhole collapses are one of the most common and disruptive geohazards. A sinkhole first develops  
78 underground with the formation of a cavity, which progressively collapses towards the surface layer. A  
79 sinkhole can also form due to the collapse of underground mines. Failure can be triggered by heavy  
80 rain, surface flooding, or pipe leakage, initiating the collapse of an otherwise stable cavity, with  
81 progressive expansion of the underground void and sagging of the upper soil layer until catastrophic  
82 collapse occurs. Ongoing climate change raises the likelihood of extreme weather, including torrential  
83 rain and flooding, and therefore sinkhole formation is becoming increasingly common.

84

85 Building on an active sinkhole presents risks of progressive ground instability, with post-collapse repairs  
86 costing from £10,000 to a few million pounds. Revealing subsidence expansion offers the opportunity  
87 for remedial work, typically grouting of the cavity (e.g. Kamal et al., 2011; Petersen et al., 2003; Qubain  
88 et al., 1995; Warner, 2004), before damage to infrastructure. However, there is, to date, no known  
89 effective method to predict active sinkholes. The technology exists, although current mature techniques  
90 (top five rows of Table 1) often require the manual and periodic monitoring of all the fissures and cavities  
91 across a large area, and/or have poor resolution.

92

93 Radar satellite-based monitoring (Interferometric Synthetic Aperture Radar, InSAR) is emerging as a  
94 powerful tool for monitoring of subsidence-induced surface settlement, with the advantage of covering  
95 extremely large areas (e.g. Baer et al., 2018; Intrieri et al., 2015; Kim et al., 2016). However, InSAR  
96 relies on the satellite's repeat-orbit cycle for its temporal frequency (typically between 4 to 35 days, see  
97 later **Table 2**), does not provide information of ground deformation at depth, and is currently  
98 computationally expensive to run without targeting a specific zone of interest. This technology might  
99 therefore be best used in conjunction with another, more frequent, localised subsurface monitoring  
100 technique. Additionally, existing studies on InSAR monitoring of sinkhole formation (e.g., Baer et al.,  
101 2018; Intrieri et al., 2015; Kim et al., 2016) primarily focus on sinkholes that emerge in inhabited regions,  
102 necessitating potentially distinct processing techniques. Further research is imperative to adapt this  
103 methodology to urban environments, where safeguarding critical infrastructures is paramount.

104



**Table 1.** Typical detection techniques for ground subsidence compared with combined DFOS and MT-InSAR (adapted from information from Moller et al. 2022, Abadie et al. 2024, Gutiérrez et al., 2019)

Technique	Temporal Frequency	Area Coverage	Resolution	Cost	Sub-surface
Seismic Wave Propagation	V. Low	V. Low	Low	High	P
Time Domain Reflectometry	<b>V. High</b>	Medium	V. Low	Medium	P
Ground Penetrating Radar	V. Low	Low	Low	Medium	P
High-precision levelling	Low	V. Low	<b>High</b>	Medium	
Airborne laser scanning	V. Low	Medium	Medium	<b>V. High</b>	
Ground-based Interferometric Synthetic Aperture Radar	<b>High</b>	Medium	Low	Medium	
Multitemporal Interferometric Synthetic Aperture Radar (MT-InSAR)	Medium	<b>V. High</b>	Low	<b>Low</b>	
Distributed Fibre Optic Strain Sensing (DFOS)	<b>V. High</b>	Medium	<b>V. High</b>	Medium	P

105 Published work on innovative methods to continuously monitor sinkhole formation below ground is  
 106 limited, and the use of distributed fibre optic sensing (DFOS) has only been employed in very few field  
 107 applications (Lanticq et al., 2009; Buchoud et al., 2016). There is a need to further understand this  
 108 technology through systematic testing of the signature strain profile in controlled laboratory experiments  
 109 (Möller et al., 2022), in the field (Guan et al. 2013; Inaudi, 2017; Xu et al., 2022b), or via numerical  
 110 analyses (Linker and Klar, 2017; Della Ragione et al., 2023).

111  
 112 Nonetheless, active subsidence collapse affects a spatially restricted zone of a few meters to tens of  
 113 meters and develops over several days, weeks or even years before sudden catastrophic failure (Baer  
 114 et al., 2018). Current literature outlines that surface displacement is dominated by vertical strain  
 115 (Gutiérrez et al., 2019), with sinkhole collapse generating measurable ground deformation (Chang and  
 116 Hanssen, 2014). Distributed fibre optic sensing (DFOS) technologies are very sensitive to strain, can be  
 117 included easily in the construction of newly built infrastructure at a limited cost, and can provide  
 118 subsurface deformation measurements. This gives credence to the use of distributed fibre optic sensing  
 119 for sinkhole detection.

120  
 121 However, is this technology able to detect sinkholes sufficiently early? Does it exhibit a clear signature  
 122 strain profile that can predict the location of an active sinkhole? Are the common limitations of DFOS,  
 123 such as soil-cable interface coupling, obstructing the use of the results? How can this be used in  
 124 association with satellite monitoring techniques? This paper summarizes the methodology and results  
 125 of the SINKhole Early Warning (SINEW) project, providing elements of responses to these questions.

## 126 **1.1. The SINEW Project**

127 The SINEW project, started in 2019, aims to identify whether the use of combined distributed fibre optic  
128 sensing (DFOS) and Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) can be an  
129 efficient method to detect active sinkholes in expansion at a sufficiently early stage for ground remedial  
130 work to be actioned. These two relatively novel technologies complement each other very well for this  
131 application, as clearly shown in Table 1. Combined, they can offer a very accurate, relatively cheap  
132 method to detect sinkholes sufficiently early and over a very large area.

133

134 The project is particularly concerned with newly built linear infrastructure, such as roads or railways, for  
135 which the use of DFOS is particularly suited. The combined use of MT-InSAR enables expanded  
136 monitoring to (i) continuous detection of sinkholes when the DFOS interrogator is needed somewhere  
137 else and (ii) a larger zone, away from the linear infrastructure, facilitating the identification of sinkholes  
138 that are not forming directly below the DFOS, but still pose a potential threat to the infrastructure.

## 139 **1.2. Distributed Fibre Optic Sensing**

140 DFOS technologies - e.g., Brillouin optical time domain reflectometry (BOTDR) - use a long fibre optic  
141 cable ( $\geq 50$  km), laid in the ground during earthwork or in a trench. A laser pulse is emitted by an  
142 interrogator through the fibre. Brillouin scattering infers the location and amount of axial deformation  
143 within the cable by measuring the proportional relationship between the Brillouin frequency shift of the  
144 backscatter light. This provides valuable information on soil deformation, with a spatial resolution of 0.5  
145 to 1 m (Kechavarzi et al., 2016). Recently, developments in fibre optic sensing have permitted to improve  
146 the precision and range of measurements. Examples are Brillouin optical time domain analyser  
147 (BOTDA) and Brillouin optical frequency-domain analysis (BOFDA), which loop the cable to the  
148 interrogator and pulse a short continuous wave to the other end (Sparrevik et al., 2022), enabling a  
149 spatial resolution of a few cm, for over 50 km long cables (e.g. FibrisTerre, 2019; SMARTEC, 2010).

150

151 DFOS can also be used with different cables and interrogators to achieve even higher spatial resolution  
152 (up to 0.65 mm), but over a much-reduced distance (2.5 – 50 m) (Luna Innovations Inc., 2020). This is  
153 well adapted for laboratory experiments and provides a great opportunity to test this technology in a  
154 controlled environment to systematically understand the strain profiles obtained for specific scenarios.

155 **1.3. Satellite Imaging**

156 Satellite Synthetic Aperture Radar (SAR, Moreira et al., 2013) is a remote sensing technique  
157 increasingly employed in civil engineering, with applications ranging from monitoring buildings and  
158 landslides to dams. Notably, SAR offers the ability to detect small displacements in the line of sight of  
159 the sensor with a relatively high level of precision, typically achieving accuracy on the millimetre scale.  
160 While experiments in the literature have demonstrated sub-millimetre accuracy (Ferretti et al., 2007),  
161 practical use typically yields accuracy levels between 1-2 mm (Selvakumaran et al., 2020). Unlike  
162 optical-based remote sensing methods, SAR is an active system that can penetrate clouds and operate  
163 independently of weather conditions and sun illumination. An additional benefit includes the ability to  
164 historically track a region of interest if it becomes clear that deformation is occurring in an area where  
165 other monitoring instruments are not located.

166  
167 The SAR system is typically mounted on a satellite platform and captures target locations in two-  
168 dimensional images. These images are acquired in two directions: the azimuth direction, corresponding  
169 to the satellite's orbit direction, and the range direction, which is perpendicular to the azimuth direction.  
170 The spatial resolution of SAR images varies among satellites, as detailed in **Table 2**. SAR-equipped  
171 satellites orbit the Earth from pole to pole, either in ascending (south to north) or descending (north to  
172 south) directions, depending on the satellite's orbit relative to Earth's rotation. This orbital pattern,  
173 combined with Earth's rotation, allows for global coverage approximately every 10-12 days. The revisit  
174 period, or the time interval between successive satellite measurements over an area of interest,  
175 determines the temporal frequency of measurements. Commercial high-resolution SAR images can be  
176 expensive; however, this study utilizes open-source data from the European Space Agency satellite  
177 constellation, Sentinel-1 (**Table 2**).

178

**Table 2.** Information about different SAR satellite options

Technique	Spatial Resolution [m x m]	Wavelength [cm]	Revisit Period	Approximate Cost/Scene [EUR]
<b>Sentinel-1</b>	<b>5 x 20</b>	<b>5.6 (C-band)</b>	<b>6 to 12 days</b>	<b>Free</b>
TerraSAR-X	3 x 3	3.1 (X-band)	11 days	650 – 3500
RADARSAT-2	9 x 10	5.6 (C-band)	24 days	2300 – 5000
COSMO-SkyMed	3 x 3	3.1 (X-band)	4 to 16 days	3500 – 4000
ENVISAT	4 x 20	5.6 (C-band)	35 days	1000 - 1500

179 Spatial resolution which determines the level of detail within images (i.e., pixel size), influences the  
180 accuracy of deformation maps and is determined by the satellite's antenna size. Wavelength, the  
181 characteristic length of radar waves emitted, varies among satellite missions operating within specific  
182 wavelengths (and frequencies). X-band and C-band frequency radars are commonly used for monitoring  
183 urban environments.

184

185 Interferometric Synthetic Aperture Radar (InSAR) techniques for deformation monitoring exploit the  
186 information contained in the phase measurement of at least two complex SAR images acquired at the  
187 same imaging geometry (ascending/descending pass direction, incidence angle, polarisation etc.) at  
188 different times over the same area, by forming an interferogram (Bamler and Hartl, 1998; Rosen et al.,  
189 2000). This deformation measurement is in the line-of-sight of the sensor. Persistent Scatterer  
190 Interferometry (PSI) relies on reflectors characterized by consistent radar responses, typically  
191 associated with robust reflecting objects, and remains stable over time. It utilizes conventional Multi-  
192 Temporal Interferometry Synthetic Aperture Radar (MT-InSAR) techniques without imposing restrictions  
193 on the temporal and spatial baselines of the multi-temporal differential interferograms utilized in the  
194 analysis (Ferretti et al., 2000, 2001). The PSI technique relies on analysing scatterers which remain  
195 coherent over a sequence of interferograms. This technique is well adapted to urban environments,  
196 which is most relevant to detecting sinkholes close to critical infrastructures in the city.

## 197 **2. Modelling methods for idealised use of fibre optic sensing**

198 For geotechnical applications, the most appropriate way to model sinkhole expansion and replicate  
199 appropriate soil stress levels would be to use a geotechnical centrifuge. However, at the time of this  
200 study, traditional DFOS analysers were not sufficiently stable to be used on the geotechnical centrifuge  
201 (Eichhorn, 2022) and this experimental method could not be used to investigate the feasibility of using  
202 DFOS for sinkhole early warning.

203

204 Consequently, a series of tests at 1g was first performed to systematically understand the response of  
205 DFOS cable laid over expanding subsidence in an upper cohesionless soil layer. Due to the limitations  
206 of low stress levels, the results are indicative only. The test campaign involved tests with different soil  
207 conditions (Möller et al., 2022) and cable laying techniques (Xu, et al., 2022a), rigorously analysed to  
208 identify the signature strain profile from the DFOS and its interpretation with regards to the

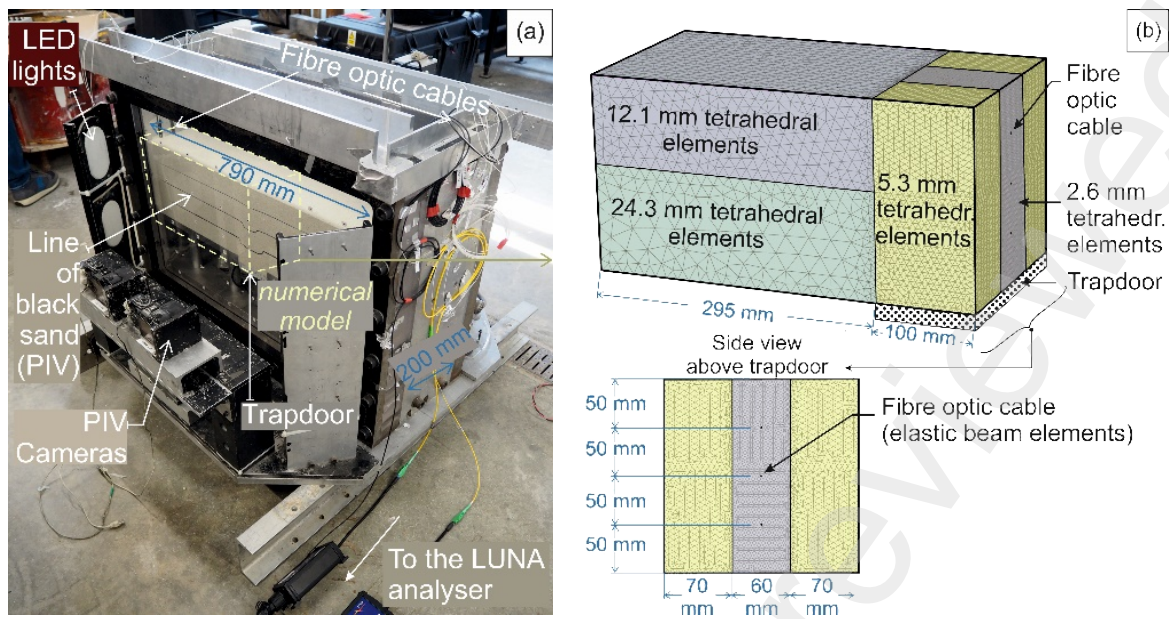
209 geomechanics of the formation of a sinkhole (Möller et al., 2022). This work was successful, but  
210 weakened by uncertainties caused by the lack of coupling at the soil-cable interface at low-stress levels  
211 (1g experiments). To further analyse soil behaviour in the vicinity of the cable, the experimental work  
212 was supplemented with 3D finite element (FE) analyses and then scaled to realistic stress levels for  
213 applications in the field (Della Ragione et al., 2023). The present paper delves deeper into the results  
214 of both campaigns, intricately correlating and analysing how the findings from the experimental and  
215 numerical investigations underscore the efficacy of DFOS in sinkhole detection. Furthermore, it  
216 discusses how leveraging the results from this campaign could optimize the technology's performance  
217 in field applications.

## 218 **2.1. Experimental Set-up**

219 The experimental study was performed using a 790 x 200 mm rectangular rig, equipped with a trapdoor  
220 of width  $B = 100$  mm, that can mimic the formation of a sinkhole (**Figure 1(a)**). Samples were prepared  
221 using dry Hostun sand, with an average particle size  $d_{50} = 0.356$  mm (da Silva, 2017). The tests were  
222 prepared at increasing relative densities ( $D_R = 19\%$ ,  $54\%$  and  $88\%$ ) to allow comparison of sinkhole  
223 formation at different soil conditions (**Table 3**). The sand was poured manually for  $D_R = 19\%$  and an  
224 automatic sand pourer was used for the higher densities (Zhao et al., 2006). The sample height was  $H =$   
225  $200$  mm ( $H/B = 2$ ), and one-third of the sand was dyed with dark blue ink to increase contrast for the  
226 use of Particle Image Velocimetry (PIV) to track sand particles and infer the geomechanics associated  
227 with the formation of a sinkhole. Images for the PIV analysis were acquired using two Canon Powershot  
228 G10 cameras, a ChAruCo board was used for calibration (Eichhorn et al., 2020) and the analysis was  
229 carried out using GeoPIV\_RG (Stanier et al., 2016).

230  
231 The trapdoor rig was actuated using a hydraulic piston. The displacement of the trapdoor, denoted as  
232  $\delta$ , was measured with the aid of two Linear Variable Differential Transformers (LVDTs) positioned  
233 beneath the trapdoor. The experiments were conducted to an ultimate displacement of  $\delta=20$  mm,  
234 corresponding to a late expansion of the sinkhole, close to collapse. Further details on the experimental  
235 set-up can be found in (da Silva, 2017; Möller et al., 2022), and the test programme used in this paper  
236 is provided in **Table 3**.

237



**Figure 1** (a) Experimental test set-up (Exp.) and (b) replicating numerical models (Num).

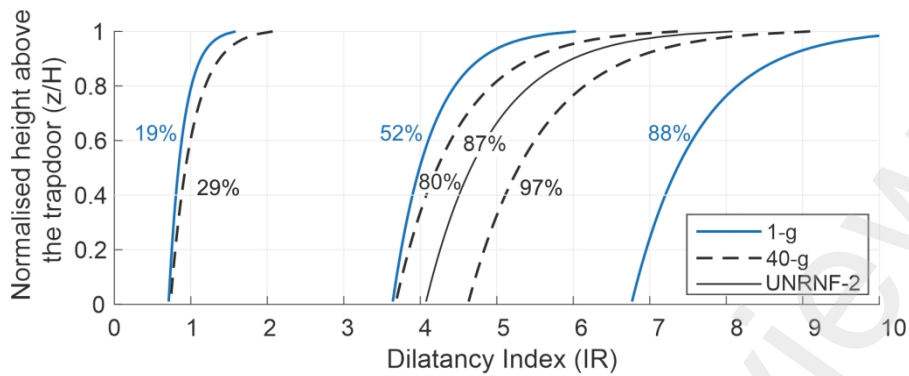
**Table 3.** Test programme

Test	Exp. / Num.	$g$ level	$D_R$ (%)	Effect of $D_R$	Validate use of DFOS	DFOS strain analysis	Scale to field	Expand to 3D
E2D-19	Exp	1	19	P	P			
E2D-52	Exp	1	52	P	P	P		
E2D-88	Exp	1	88	P	P			
UNRNF-2	Exp	40	87				P	
N2D-52	Num	1	52		P	P		
N2D-R	Num	40	87		P	P	P	

238 Repeatability and consistency of the testing procedures were verified by repeating selected tests and  
 239 comparing one test with a centrifuge test from published literature (UNRNF-2, da Silva, 2017), matching  
 240 the displacement fields from the PIV and demonstrating the robustness of the testing procedure (Möller  
 241 et al., 2022). UNRNF-2 was performed in the centrifuge at 40g, with the same experimental rig as in  
 242 **Figure 1(a)**, but without the use of fibre optic sensing. The relative density of the test was 87%, with a  
 243 trapdoor width  $B = 2$  m at prototype scale, and thus with the same soil height to trapdoor width  $H/B$  ratio  
 244 equal to 2 used for tests E2D-19, -52 and -88 listed in **Table 3**. UNRNF-2 was also used to benchmark  
 245 the numerical analyses described later in this paper

#### 246 *Scaling considerations*

247 When conducting tests at 1g, appropriate scaling of the soil properties must be considered. In the case  
 248 of sinkhole experiments, most of the geotechnical mechanism is driven by arching (da Silva, 2017),



**Figure 2.** Comparison of relative dilatancy ( $I_R$ ) for selected relative densities at 1g and 40g.

249 which in turn is highly dependent on soil dilation. It is hence crucial to scale the dilatancy index,  $I_R$   
 250 appropriately for 1g tests.

251

252 This can be achieved using the equation from (Bolton, 1986):

$$I_R = D_R \cdot (10 - \ln p') - 1 \quad (1)$$

253

254 Where  $p'$  is the effective stress. Accordingly, the tests at low relative densities limit dilation of the sample  
 255 and tests at 1g mimic a much higher relative density in the field. This is shown in Figure 2 for tests E2D-  
 256 19, -52 and -88 (at 1g) and UNRN2-2 (at 40g).

### 257 *Fibre Optic Sensing*

258 DFOS is composed of two fundamental elements: (i) the fibre optic cable to measure the strain and (ii)  
 259 an optical spectrum analyser (or interrogator) to characterise the spectrum of the backscattered light  
 260 and infer the axial strain within the cable.

261

262 The cable used for this study was a 2 mm diameter tight-buffed polyurethane-coated fibre optic strain  
 263 sensing cable. This fibre is a common single-mode fibre (SMF) that has been widely used in structural  
 264 health monitoring applications. It has a low Young's modulus of 200 MPa and can therefore be easily  
 265 pre-strained and directly integrated into loose material such as soil. Laboratory calibration tests  
 266 performed at the Cambridge Centre for Smart Infrastructure and Construction (CSIC) demonstrated  
 267 near-perfect strain transfer behaviour within the cable.

268

269 The DFOS cables were installed at heights of 50, 100, and 150 mm above the trapdoor, and away from  
270 the window and back edge of the box. The layers corresponding to the cable heights were highlighted  
271 using dyed black sand (see **Figure 1(a)**). The cables were laid to avoid any pre-stress and were pinned  
272 on the vertical walls of the rig. Other laying techniques were tested to improve soil-cable coupling and  
273 end effects but provided limited improvement to the results (Xu et al., 2022b).

274

275 The cables were connected to the Luna ODiSI 6100 analyser, which provides a 2.6 mm spatial  
276 resolution. The maximum measurement length for this gauge spacing is 10 m, with a sampling frequency  
277 of 25 Hz. The analyser can measure strain within a range of  $\pm 12000 \mu\epsilon$ , with an error margin of  $\pm 30 \mu\epsilon$   
278 (Luna Innovations Incorporated, 2020).

## 279 **2.2. Numerical Model**

280 The numerical models implemented to further analyse the experimental results used symmetry to  
281 replicate half the geometry of the 2D 1g model tests (**Figure 1(b)**). A mesh consisting of 305,000  
282 tetrahedral elements with 425,000 nodes was selected and refined around the trapdoor and the cables,  
283 where larger strains were expected.

284

285 The soil was modelled using the Hardening Soil model with small-strain stiffness (HSsmall, Benz et al.,  
286 2009; Schanz and Vermeer, 1996), which provides a balanced approach for modelling sands under low  
287 confining pressure conditions and scaled-up conditions at realistic stress levels. This method, discussed  
288 in (Della Ragione et al., 2023), offers a comprehensive representation suitable for analysing both the  
289 experimental tests and extending the work to full-scale analysis.

290

291 The fibre optic cable was modelled using an embedded beam element (Sadek and Shahrour, 2004).  
292 Meshing was implemented such that a 3-noded line element from the cable could cross a 10-noded  
293 tetrahedral element from the soil mesh. To accurately simulate the interaction between the soil and  
294 cable, a built-in interface element was employed to define the cable surface properties. Coupling at the  
295 soil-cable interface was then modelled to replicate both extreme scenarios: the optimal condition,  
296 characterized by a rough cable ( $R_{inter} = 1$ ), and the worst-case scenario featuring a smooth cable ( $R_{inter}$



297 = 0.01). This was achieved by defining a slippage condition on the shear force on the cable element  
 298 interface  $t_s$ :

299

$$|t_s| = \sigma_n^{avg} \cdot R_{inter} \cdot \tan \phi' \cdot \pi \cdot D \quad (2)$$

300

301 where  $\sigma_n^{avg}$  is the average soil normal stress,  $\phi'$  the mobilized angle of friction, and  $D$  the cable diameter.

302  $R_{inter}$  is a strength reduction factor.

303

304 The numerical analyses involved replicating the most relevant experimental test (N2D-52, Figure 2) to

305 further understand the behaviour of the cable inside the soil body. The analysis was then scaled to

306 realistic stress levels at 40g (N2D-R), replicating test UNRNF-2 and predicting what the DFOS cable

307 response would have been.

308

309 A final analysis was performed to extend the results to the case of a 3D circular sinkhole, where cables

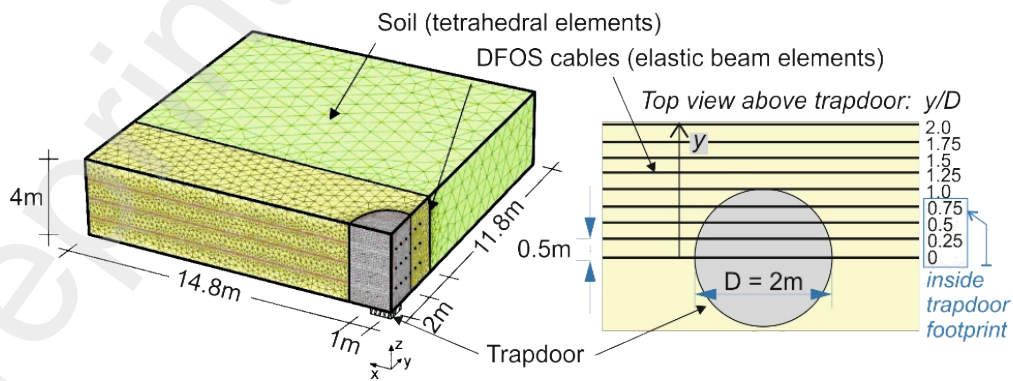
310 were laid in a grid, at a distance  $y$  from the cable centreline (N3D-R, Table 3, Figure 3). Further

311 information on the geometry, and mesh, and a detailed discussion of the soil and cable model is provided

312 in (Della Ragione et al., 2023). This analysis permits extending the findings to a more realistic scenario

313 of cavity collapse in clean fine sand to provide both expected DFOS strain profiles and surface

314 settlement, used later in MT-InSAR analysis.



**Figure 3** Cable layout in the three-dimensional numerical analysis (N3D-R)

### 315 3. DFOS for early detection of sinkhole

#### 316 3.1. Results at 1g

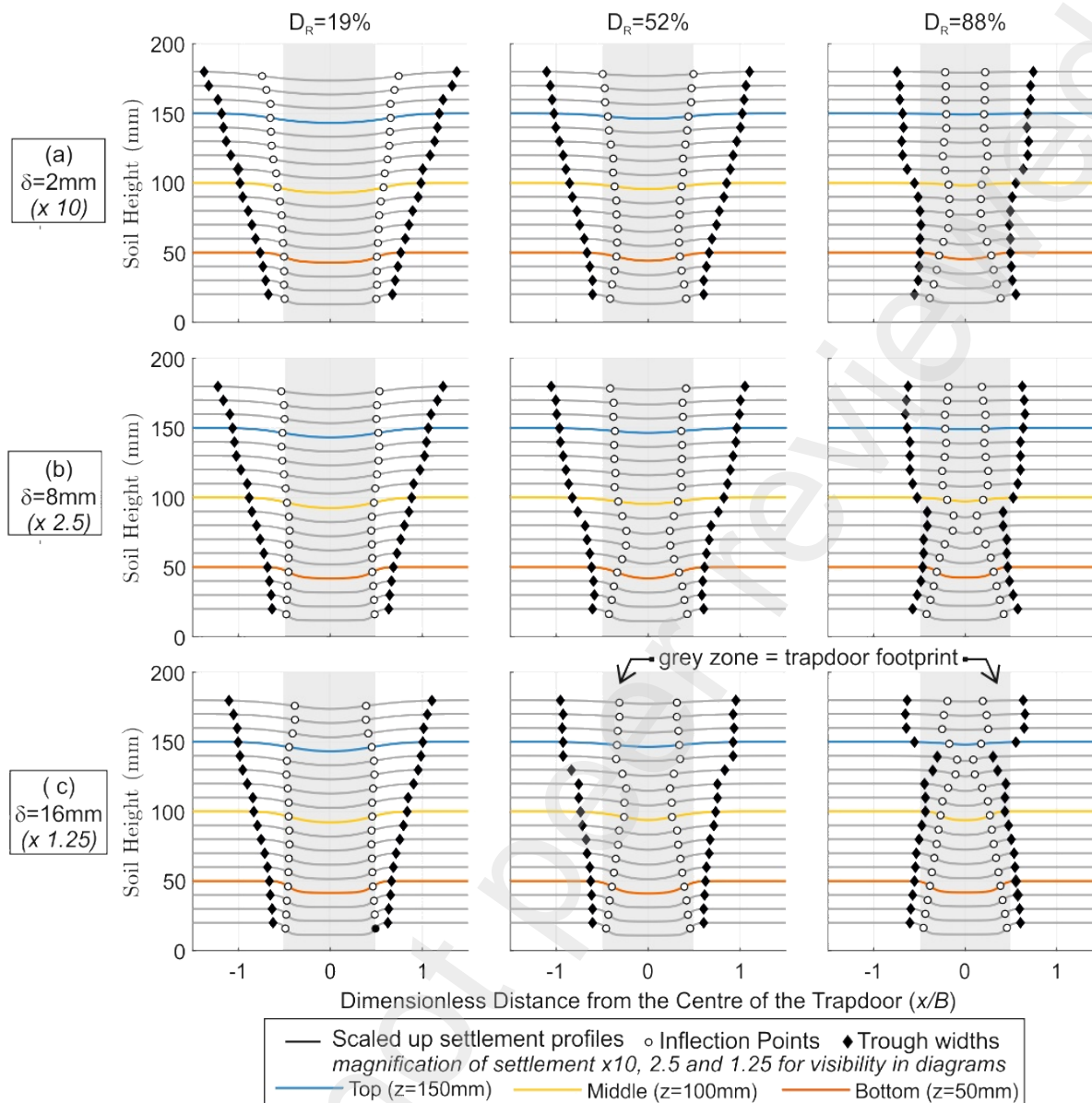
##### 317 *Subsidence*

318 PIV results were used to identify the soil behaviour and the kinematic mechanism of collapse. A modified  
319 Gaussian curve (Vorster et al., 2005) was fitted to the observed settlement profiles; the inflection point,  
320 and width of the settlement profile were determined from the fitted curve as per da Silva (2017). The  
321 results for tests E2D-19, -52 and -88 are shown in **Figure 4**. In this figure, three positions of the trapdoor  
322 were selected, corresponding to early ( $\delta = 2$  mm), medium ( $\delta = 8$  mm) and late ( $\delta = 16$  mm) formation  
323 of the sinkhole (Möller et al., 2022).

324

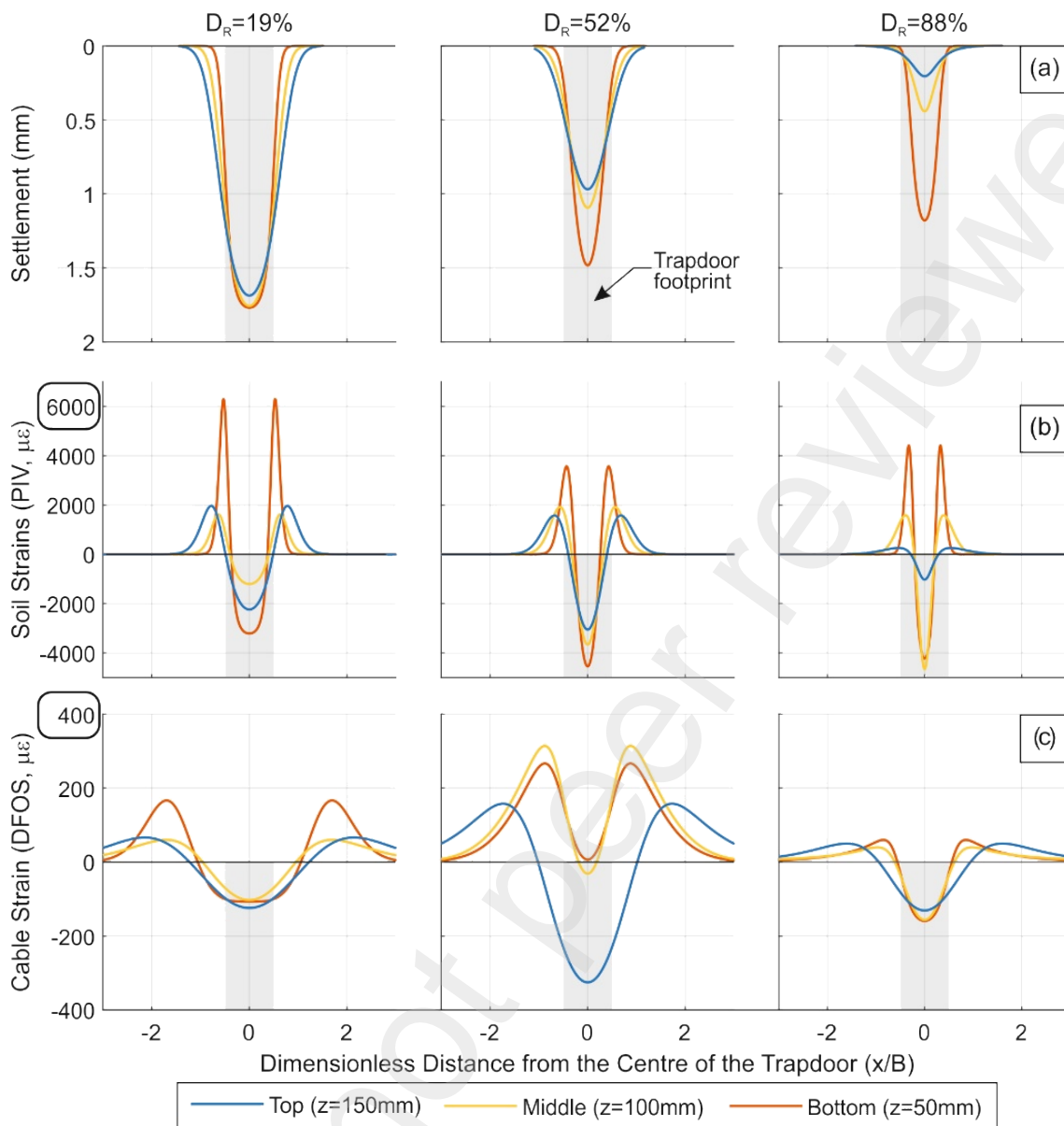
325 The position of the inflection points and the trough width varies as the trapdoor displacement increases,  
326 and this effect is clearer for higher relative densities. The effect of a very high relative density is indeed  
327 evident in the narrower inflection point and trough widths approaching the formation of a chimney  
328 displacement mechanism. For the lowest relative density, the inflection points remain relatively constant  
329 with height and are located along the trapdoor edge. In this diagram, the location of the DFOS cables  
330 has been highlighted using orange (bottom), yellow (middle) and blue (top) lines, and the trapdoor  
331 location in grey, a convention maintained throughout the figures of this paper. This emphasizes the  
332 anticipated deformed shape of each cable, although it remains unobservable during the experiment.  
333 The figure illustrates greater deformation with lower relative density and when the cable is positioned  
334 higher in relation to the cavity.

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**Figure 4.** E2D-19, 52, 88: Inflection points position and settlement trough width derived from PIV for selected trapdoor displacement representing early ( $\delta = 2\text{ mm}$ ), medium ( $\delta = 8\text{ mm}$ ) and late ( $\delta = 16\text{ mm}$ ) formation of the sinkhole. Settlement profiles are magnified for clarity.

336 **Figure 5** (a, b) display the strain recorded from PIV and a zoom of the settlement recorded at the  
 337 corresponding cable depths, extracted from **Figure 4** (top row), for all three relative densities tested  
 338 during the experimental campaign. A trapdoor displacement of  $\delta = 2\text{ mm}$  was selected here. This aligns  
 339 with the initial phase of subsidence development (Möller et al., 2022), where the onset of arching occurs  
 340 following a rapid reduction in load to a minimum level, coinciding with the base movement reaching 2%  
 341 of the trapdoor width, equivalent to 100 mm (da Silva Burke and Elshafie, 2021). This corresponds to  
 342 the approximate point at which the signal should be detected to enable remedial work to take action.



**Figure 5.** E2D-19, 52, 88: Profile of (a) soil settlement, (b) PIV soil strain and (c) DFOS strain at 50 mm, 100 mm and 150 mm height above trapdoor level for trapdoor displacements of 2 mm at 3 different  $D_R$ .

343

344 For clarity of the figures, the data from both PIV and DFOS used to derive the strain profiles throughout  
 345 this paper, for both experimental and numerical data sets, were filtered and fitted using the summation  
 346 of two modified Gaussian distributions following the method described in (Möller et al., 2022).

347

348 The results from **Figure 5(a)** show large settlements at low and medium relative densities, where dilation  
 349 is lower, and the arching mechanism is weaker, in line with the results from **Figure 4**. The results from

350 PIV also show narrower strain profiles for dense soils, in line with the narrower trough widths observed  
351 in the top row of **Figure 4**. All three strain profiles display a larger strain at the bottom layer where the  
352 shear strain is the highest (da Silva, 2018; Möller et al., 2022). The differences between the middle and  
353 top layers then depend on how the funnel mechanism has developed. This is particularly evident when  
354 comparing  $D_R = 19\%$  with  $D_R = 88\%$ : the trough width for  $D_R = 19\%$  (top left diagram of **Figure 4**) is much  
355 wider than that at  $D_R = 88\%$  (top right diagram in **Figure 4**); and for  $D_R = 88\%$ , the top cable is located  
356 above the arch, where not much settlement is observed (top right diagram of **Figure 5(a)**). This results  
357 in a larger and wider strain profile for the top layer of  $D_R = 19\%$  than for  $D_R = 88\%$ .

### 358 *Fibre optic signature strain profile*

359 The results from **Figure 5(c)** demonstrate a clear signature strain profile, with a trough located at the  
360 centre of the sinkhole, that can be used to sense the early expansion of a sinkhole. The results also  
361 prove that the DFOS cables can detect the key features of the strain profiles observed from the soil, far  
362 away from the cable, as outlined in the previous section: differences between cables and differences in  
363 the overall magnitude of the strain due to relative density.

364

365 There are, however, differences in the strain profiles that need to be explored further: (i) the magnitude  
366 of the strain in the cables is much lower compared to that experienced by the soil; (ii) the width of the  
367 strain profiles is much larger, and (iii) the strain does not return to zero at the edges of the box for low  
368 and medium dense samples.

369

370 While point (iii) can be explained from boundary effects at the edges of the box, and is a relatively minor  
371 limitation of this work, points (i) and (ii) are more prohibitive and weaken the confidence in the results  
372 shown in **Figure 5**. Point (i) is likely the product of the lack of coupling between the soil and the cable,  
373 which is largely worsened by the low-stress levels at  $1g$ . Further work to understand the limitations of  
374 the soil-cable interface and its consequences at realistic stress levels is presented in Section 3.2. Point  
375 (ii) is further explored in the next paragraph.

376 *Influence of Horizontal Ground Movement*

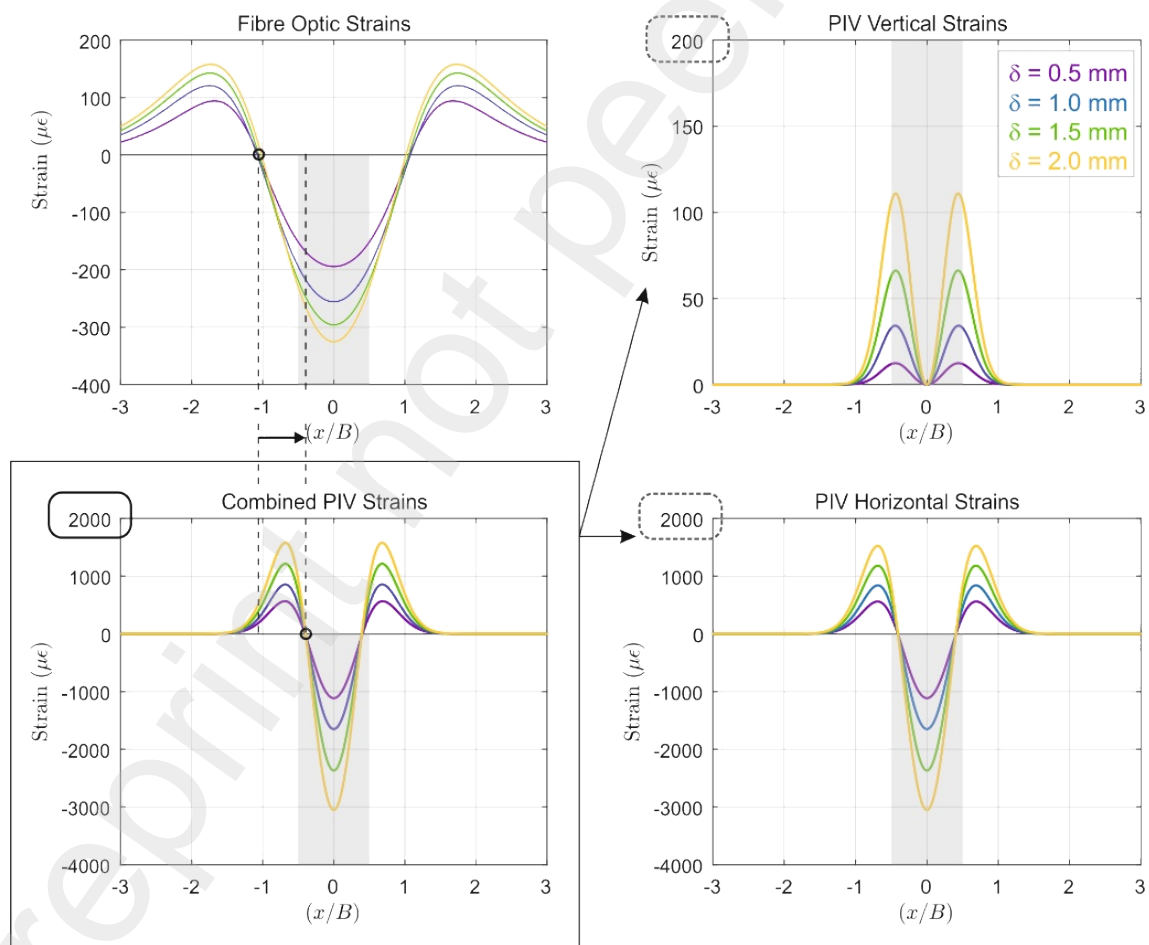
377 Exploiting the high sensitivity of DFOS to small strain, **Figure 6** shows that the results obtained for a  
378 trapdoor displacement equal to 2 mm also hold for even earlier formation of the subsidence. This  
379 concurs with the results observed in the field (Xu et al., 2022b) and provides confidence in the ability of  
380 DFOS to detect sinkholes sufficiently early.

381

382 In addition, the strain from PIV was decomposed in its horizontal and vertical components to further  
383 understand the conformance of the cable strain to the ground deformation. The method to obtain this  
384 decomposition is detailed in (Möller et al., 2022).

385

386 While each profile exhibits a double peak, they diverge significantly, particularly in terms of strain  
387 magnitude. **Figure 6** demonstrates that horizontal soil displacement predominantly influences the



**Figure 6.** E2D-52: Detailed comparison between strain profiles from DFOS and PIV, with horizontal and vertical decomposition of the PIV strain for very early trapdoor displacements  
 $D_R = 52\%$ ,  $z = 150$  mm  $0.5$  mm  $\leq \delta \leq 2.0$  mm, top cable

388 combined PIV strain profile. Accordingly, the DFOS cable is measuring mostly the horizontal ground  
389 deformation. The differences observed between the DFOS strain profile and the combined PIV profile  
390 can then be explained by the cable axial stiffness, which despite being selected as low as possible ( $E =$   
391  $200 \text{ MPa}$ ), is still much higher than that of the soil. This axial stiffness limits the longitudinal movement  
392 of the fibre when stretched, distorting the original longitudinal strain profile, and therefore the horizontal  
393 strain observed from PIV. This explains point (ii) above.

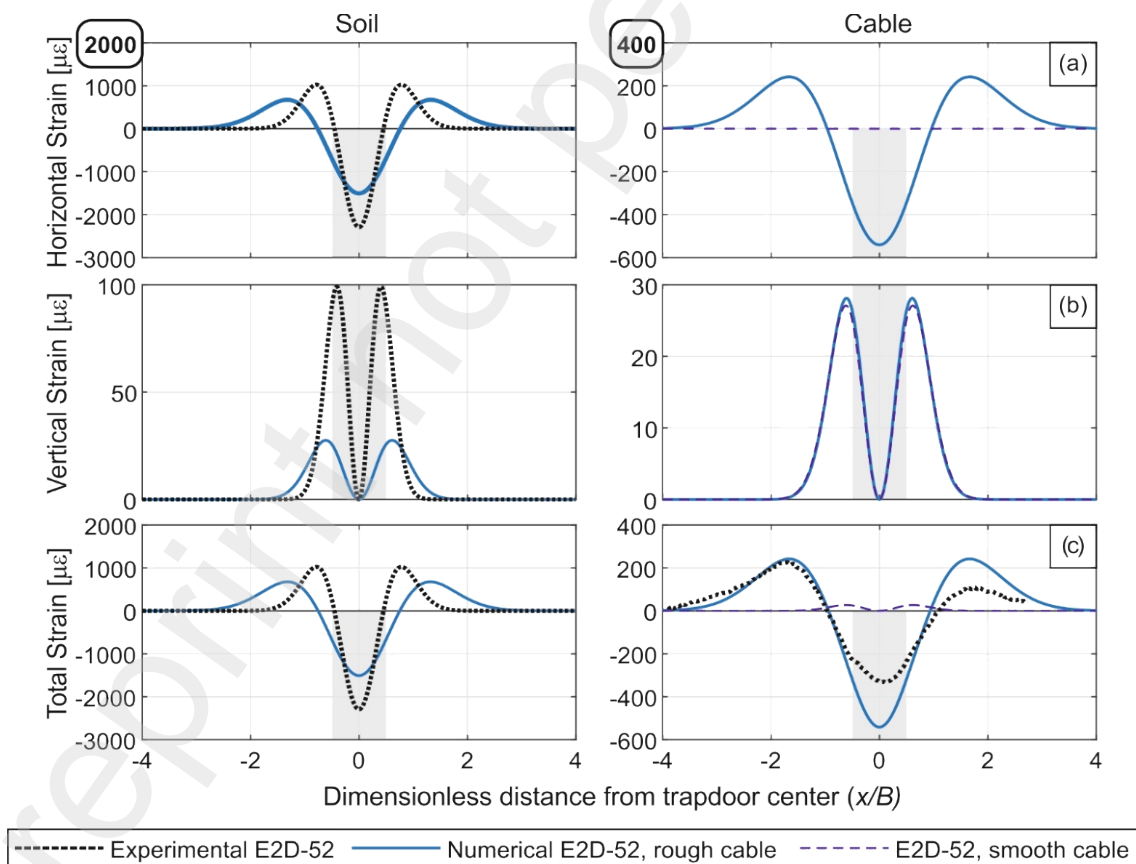


395 The decomposition of the strain such as shown in **Figure 6** is not accessible directly from the  
 396 experimental fibre optic data. To further the analysis, and elucidate point (i) and the limitations of the 1g  
 397 tests, numerical analyses were performed, investigating both the influence of the soil-cable interface  
 398 and the stress level within the soil.

399

400 The results mimicking experiments E2D-52 are shown in **Figure 7**, using the same decomposition of  
 401 the strain as for **Figure 6**. First, the comparison of the total strain with experimental data, both within the  
 402 soil and cable (**Figure 7(c)**), gives confidence in the numerical model, which involves the particularly  
 403 challenging task of modelling soil behaviour at low-stress levels (Della Ragione et al., 2023b). Here,  
 404 both the trend and magnitude of the strain are captured well. The key features observed previously in  
 405 Figure 6 for the decomposition of the strain within the soil also hold in the numerical model.

406

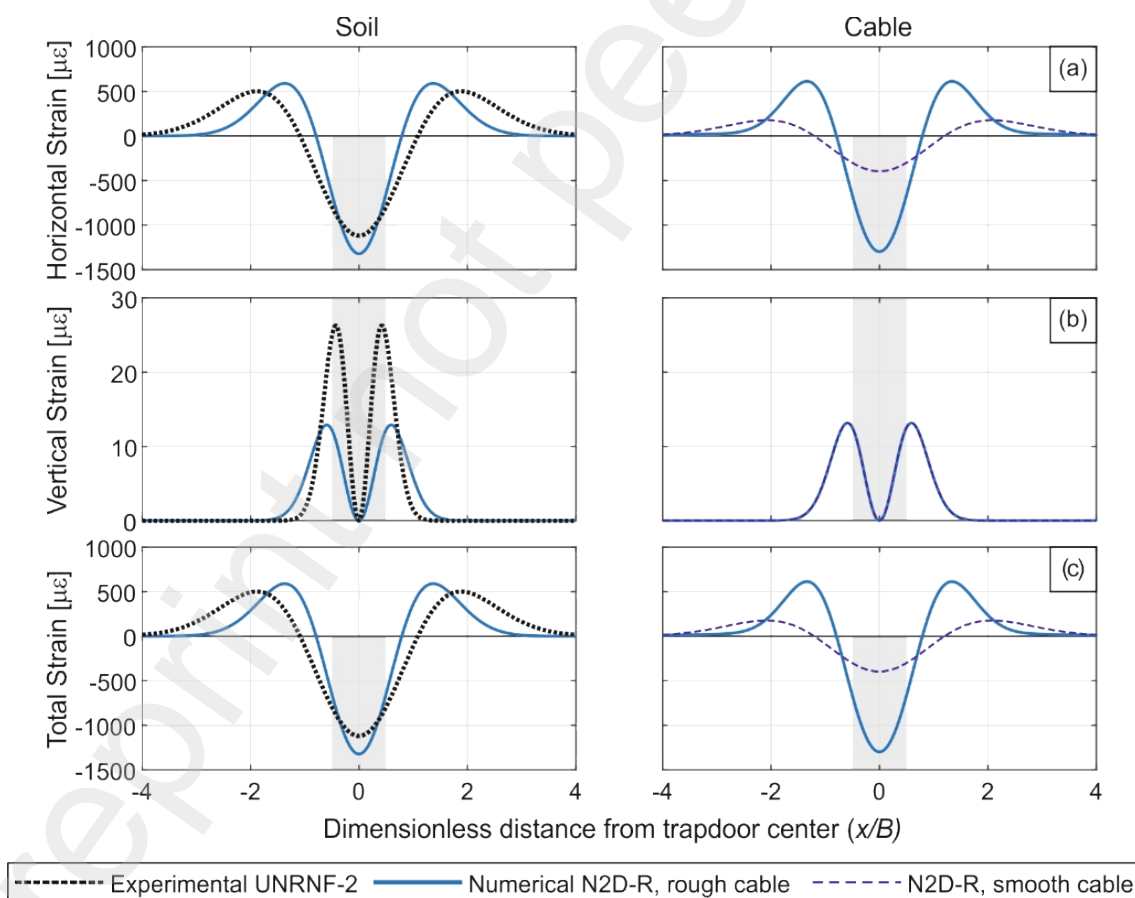


**Figure 7.** Analyses in 2D at 1g (N2D-52): Strain induced by (a) horizontal displacements; (b) vertical settlements; (c) both ground movements in (LHS) the soil and (RHS) a rough and smooth DFOS cable; compared with experimental data from E2D-52.  $\delta = 2$  mm, top layer.

407 The contrast in strain magnitude between the cable and the soil is also observed here, which provides  
 408 further confidence in the experimental techniques for the laying of the fibre optic and coupling between  
 409 the soil and cable. The second column of **Figure 7** compares the case of a rough cable, fully coupled  
 410 with the soil, with the case of a smooth cable. The results clearly show that the lack of coupling between  
 411 the soil and the cable inhibits the cable's capacity to detect strain induced by ground horizontal  
 412 movement, with the cable vertical strain conforming perfectly with the soil vertical strain. This confirms  
 413 the hypothesis of Section 0, point (ii).

### 414 3.2. Applications to realistic stress levels

415 **Figure 8** extends the findings to realistic stress levels at 40g for a trapdoor displacement of  $\delta = 40$  mm  
 416 (i.e. 2% of B), and compares the soil strain obtained from the numerical analysis to the PIV experimental  
 417 data from centrifuge modelling (da Silva, 2017). The results show good agreement with the experiments,  
 418 validating the model.



**Figure 8.** Analyses in 2D at 40g (N2D-R): Strain induced by (a) horizontal displacements; (b) vertical settlements; (c) both ground movements. (LHS) soil, compared with experimental PIV data from UNRNF-2 and (RHS from Della Ragione et al., 2023a) a rough and smooth DFOS cable.  $\delta = 40$  mm, top layer

419 The results of **Figure 8** highlight the effect of stress level on the strain profile, and most importantly,  
420 strain magnitude of the DFOS cable (Point (i), p. 15). The results clearly show that the order of  
421 magnitude difference in strain profile disappears at realistic stress levels, highlighting the applicability of  
422 the technology for field applications but also, the key limitations of the low stress levels at  $1g$  on the  
423 cable's ability to conform with soil deformation, even when improving cable laying techniques (Xu et al.,  
424 2022a).

425

426 **Figure 8** also shows the expected differences between a smooth and rough cable: the lack of coupling  
427 strongly affects the strain induced by horizontal ground movements, however, not as severely as at  $1g$ .  
428 Improving soil-cable coupling, for example by changing the outer shape of the cable using, for example,  
429 grip armoured cable or epsilon composite cables (Sparrevik et al., 2022), has the beneficial outcome of  
430 improving the conformity of the cable deformation with the *horizontal* soil strain. This increases the  
431 magnitude of the signature strain profile, and narrows down the width of the trough, and hence provides  
432 more accurate results on the location and extent of the sinkhole.

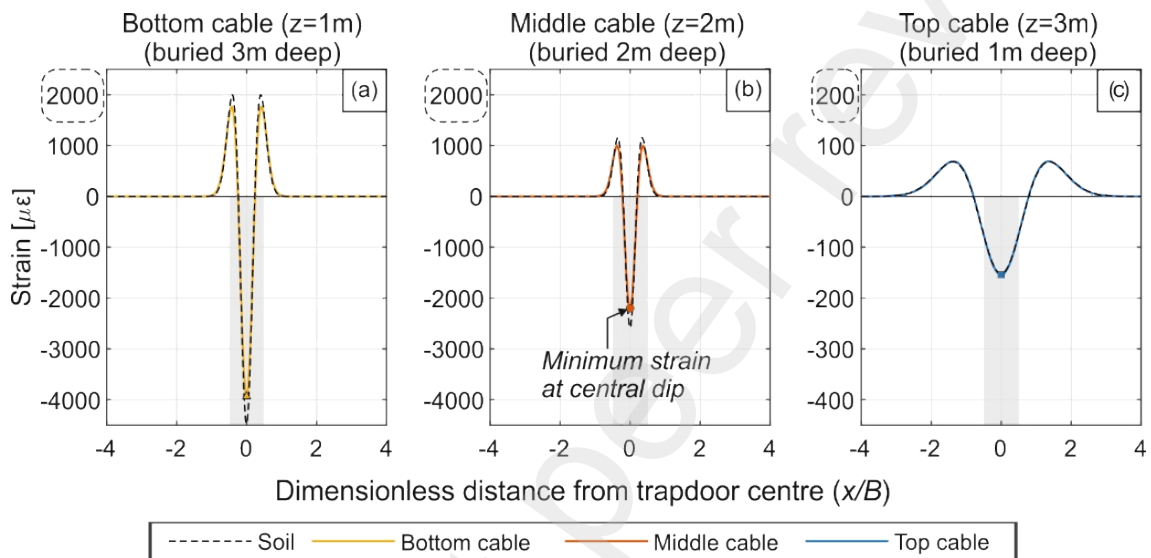
433

434 The results from **Figure 6**, **Figure 7** and **Figure 8** are interesting and partially concur with previous  
435 research exploring sagging subsidence, showing that the ground may experience considerable  
436 horizontal movement (Gutiérrez et al., 2012; Carbonel et al., 2014; Kim et al., 2016). However, the  
437 results from this paper show the prominence of the strain induced by horizontal movement of the ground,  
438 which had not been identified previously, and could potentially change the mindset for monitoring of  
439 sinkholes moving forward.

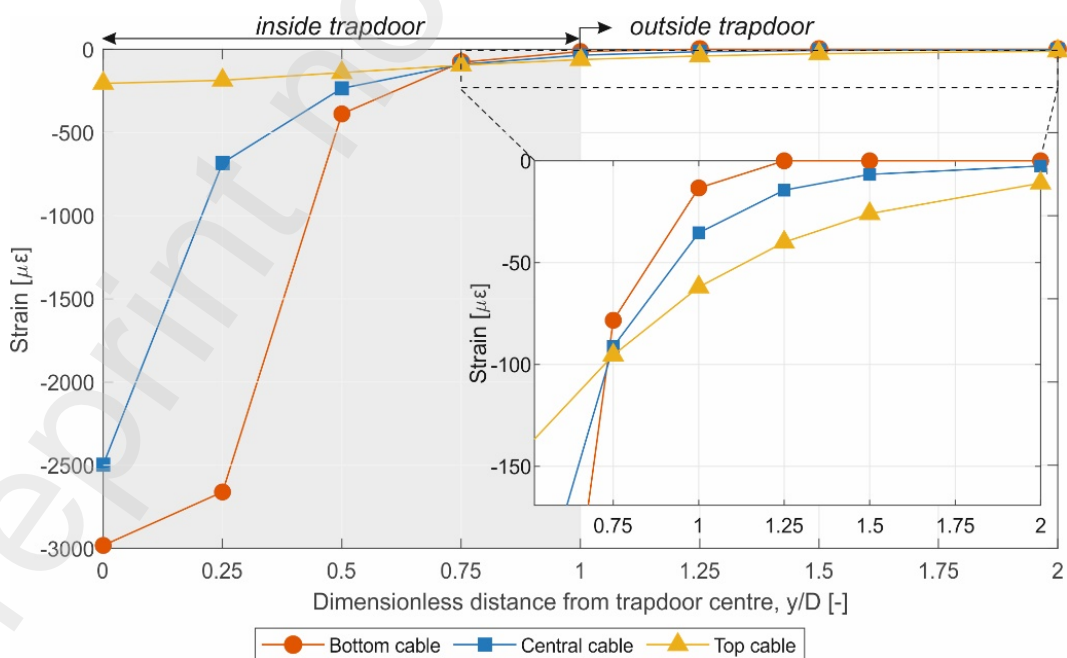
### 440 **3.3. Extension to 3D cavity**

441 The results from the 2D analysis at  $40g$  are here extended to 3D, using the model of **Figure 3**. First, the  
442 results of the central cables, located directly above the centre of the trapdoor, with  $y/D = 0$ , are shown  
443 in **Figure 9**. The cable was modelled with a rough interface surface, capturing an ideal case scenario.  
444 Comparison of Figure 9(c) with **Figure 8** (c, RHS) shows a reduction of the strain magnitude when  
445 considering the full mechanism in 3D. Comparison of the strain profiles between the three elevations of  
446 cables shows a much narrower and stronger profile for cables located close to the trapdoor, compared

447 with the top cable, a conclusion that concurs with the results of **Figure 5(c)** in 2D at 1g. The results of  
 448 this graph also show good conformance of the soil strain with the cable strain, as for the 2D case.  
 449  
 450 **Figure 10** finally looks at the influence of the cable location eccentricity  $y/D$  (see **Figure 3** for definition)  
 451 by plotting the reduction in the minimum strain at the central dip (as shown in **Figure 9**) about  $y/D$ . The  
 452 results show an abrupt reduction in strain magnitude on the edge of the trapdoor footprint ( $y/D \geq 1$ ),  
 453 which mostly affects the bottom and middle cable. The set of top cables, despite having less pronounced



**Figure 9.** Analyses in 3D at 40g (N3D-R): Compared strain from the cable and soil obtained at the centerline of the trapdoor ( $y/D = 0$ , Figure 3) in the bottom, middle and top cables,  $\delta = 40$  mm



**Figure 10.** N3D-R: Evolution of the minimum central peak strain in DFOS cable with eccentric distance to trapdoor centerline  $y/D$  ( $\delta = 40$  mm)

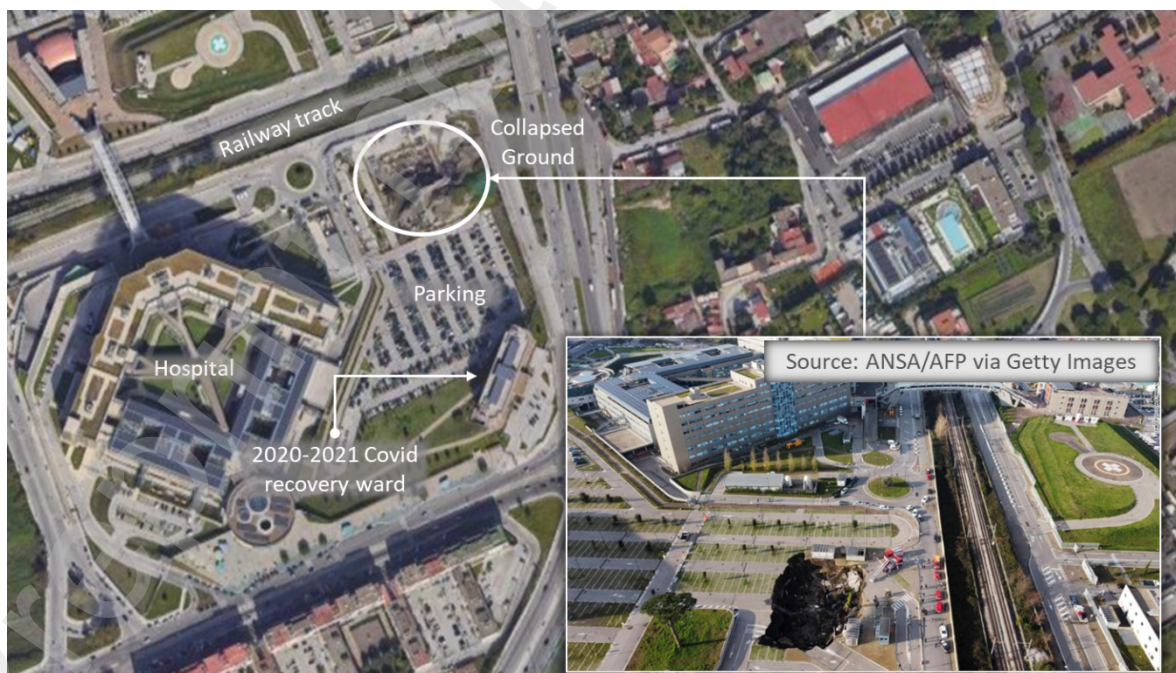
454 strain readings, is much less affected by the position of the cable with regards to the centreline, and  
455 benefits from the funnel-shape failure mechanism highlighted in **Figure 4**. The horizontal ground  
456 movement close to the surface affects a much wider zone, which the cable can sense, even when not  
457 located directly above the sinkhole footprint.

#### 458 **4. Satellite imaging of a real collapse**

459 As shown in **Table 1**, the combined use of satellite and fibre optic monitoring could enhance monitoring  
460 from Distributed Fibre Optic Sensing (DFOS), in particular when the sinkhole is not forming directly  
461 below the instrumented infrastructure and the signature strain profile is weak. To explore the use of  
462 satellite monitoring in the prediction of sinkhole collapse, the collapse that occurred in the car park of  
463 the Naples Hospital on 8 January 2021 was chosen. This occurred around the time when the DFOS  
464 monitoring project was started and provided a contextual relevance to the project.

#### 465 **4.1. The case of Naples' hospital car park collapse**

466 This paper targets the restricted zone of Naples' hospital car park, where a 20 m deep hole suddenly  
467 formed on the 8<sup>th</sup> of January 2021, affecting a 2,000 m<sup>2</sup> zone (**Figure 11**). The collapse occurred following  
468 two weeks of heavy rain, engulfing a few cars and leading to the temporary closure of the Covid-19



**Figure 11.** Aerial Google Map view of the collapsed ground in the car park of Naples' hospital (photo credit: ANSA/AFP via Getty Images)

469 recovery ward. The satellite data available for this zone dates back to 2016, enabling very good tracking  
470 of the ground deformation over time.

471

472 Croce and Pellegrino (1967) and Alberico et al. (2006) report that this area mainly consists of a thin  
473 layer of remoulded fine silty sand deposit, sitting on fine silty sands, with coarse-grained sands and silty  
474 sands layers at depth. Over time, anthropic activities in the area have led to the deposition of shallow,  
475 irregular, and heterogeneous fills, potentially concealing abandoned structures from years past.

#### 476 **4.2. Method: Persistent Scatterer Interferometric Synthetic Aperture Radar**

477 Persistent Scatter Interferometry (PSI) is particularly well-suited for urban areas characterized by a high  
478 density of strong radar signal reflectors such as buildings and rocks. PSI serves as an opportunistic  
479 method for measuring deformation, focusing on specific targets known as Persistent Scatters (PSs),  
480 which exhibit stability and consistent phase delivery.

481

482 Understanding coherence (also referred to as correlation) is essential as it serves as a metric of  
483 accuracy in the interferometric phase. Each pixel in the interferogram is assigned a coherence value  
484 ranging from 0 to 1. During subsequent processing, a default coherence threshold of 0.75 is typically  
485 applied, ensuring that only PSs with a correlation value exceeding 0.75 are retained.

486

487 Satellite data was acquired from Open Copernicus Access Hubs managed by the European Space  
488 Agency. SAR data, in the form of "Single Look Complex (SLC)" files, was downloaded using specific  
489 parameters outlined in **Table 4**. Only the descending data were used in this paper and proved to provide  
490 good results without the need to also process the ascending data. Adhering to these parameters ensures  
491 that the SAR images possess the necessary characteristics (such as direction and polarization) required  
492 for interferometric processing. To permit large image downloads, an automated routine leveraging the  
493 sentinelat package can be used (Wille et al., 2017). This script automated the download process,  
494 ensuring efficient and streamlined retrieval of satellite data.

495

496 The following element of the analysis consists of establishing the Digital Elevation Model (DEM), which  
497 provides a digital representation of the Earth's topographic surface, excluding trees and buildings and



**Table 4.** Sentinel-1 data information for image downloads used in this paper

Sensing period	18 <sup>th</sup> June 2018 to 04 <sup>th</sup> of January 2021
Number of images	78
Satellite Platform	Sentinel-1A
Product type	<b>SLC</b>
Polarisation	VV
Sensor Mode	IW
Orbit Number	124
Wave band	C
Direction	Descending

498 is used during the processing for topographic correction. The DEM was obtained from the United States  
499 Geological Survey.

500

501 Drawing a specific area of interest (AOI) from the obtained satellite images is essential. Processing the  
502 images in their entirety would be computationally impractical. To achieve this, the most recent imagery  
503 of Naples from Google Earth can be utilized. From there, a polygon can be created to delineate the  
504 boundaries of the collapse, ensuring alignment with the actual features observed. The choice is based  
505 on a compromise between computational time and the need to be large enough to be able to adequately  
506 carry out the processing chain and correct for errors.

507

508 The acquired datasets are imported into SARSCAPE software to generate SAR images (Sarmap, 2014).  
509 To ensure data consistency, image acquisitions from different dates are carefully reviewed, with images  
510 being deselected one by one. Subsequently, the selected images undergo cropping to the Area of  
511 Interest (AOI) using a process called sample selection. This step plays a crucial role in reducing the  
512 computational load for subsequent procedures.

513

514 This enables the pre-InSAR processing, encompassing tasks like image downloading, cropping, and  
515 acquiring a Digital Elevation Model (DEM). SARscape is utilized to execute a PSI processing chain,  
516 entailing the generation of interferograms and the subsequent application of diverse corrections. These  
517 corrections include adjustments for topographic, atmospheric, and orbital errors (leveraging data from  
518 Sentinel acquisitions pertaining to precise orbit), along with noise correction.

519

520 The resulting time series can be imported into a geographic information system (GIS) like QGIS for  
521 additional analysis and interpretation. This facilitates a deeper understanding of the observed changes  
522 across the monitored area. In the subsequent section, we will present the findings of these analyses,  
523 including visual representations and interpretations of the subsidence patterns. The final output is a  
524 time-series measurement in the Line of Sight (LOS) of the satellite for each of the PS.

525

526 In this study, 78 images from the European Space Agency (ESA) Sentinel-1 C-band radar satellite from  
527 18<sup>th</sup> June 2018 to 4<sup>th</sup> January 2021 (just before the collapse date) were processed. During interferometric  
528 processing, a digital elevation model (DEM) derived from Shuttle Radar Topography Mission (SRTM)  
529 data with a resolution of 3 arc-seconds (90 meters) was employed. The measurements noted are in the  
530 line-of-sight (LOS) of the satellite, and to estimate the vertical component of this deformation  
531 measurement, the satellite incident angle ( $\theta$ , between the SAR beam and the vertical) can be used by  
532 multiplying the cosine of this angle with the line-of-sight measurement. Based on the assumption that  
533 the motion is predominantly vertical, and horizontal displacements are negligible, settlement profiles of  
534 the targeted zone are derived.

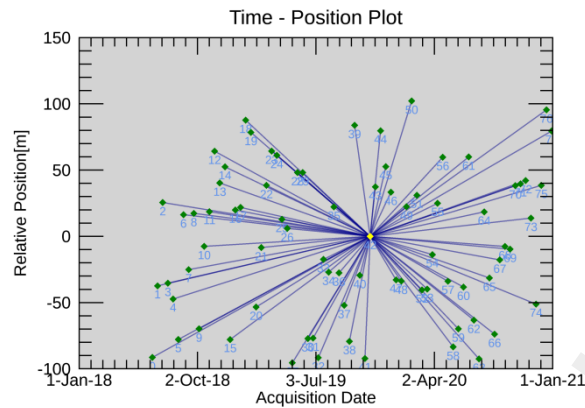
535

536 The data are processed only up to the collapse date, as there are no Persistent Scatterers (PS) available  
537 afterwards. One limitation of this technology is its inability to monitor sudden, drastic changes in the  
538 surface. However, it remains effective in monitoring surrounding infrastructure, which typically  
539 undergoes smaller, gradual changes during a collapse event. This capability has been leveraged in this  
540 study.

#### 541 **4.3. Satellites synchronisation**

542 Connection diagrams illustrate the pairing of SAR images to generate differential interferograms,  
543 ensuring the reliability of the satellite imaging process. Each SAR image is multiplied by the complex  
544 conjugate of the master image to create differential interferograms. Two common representations of  
545 connection diagrams are time-position and time-baseline plots. In the PS processing method depicted  
546 in **Figure 12**, each acquisition is denoted by a diamond shape, with the yellow diamond representing  
547 the Master acquisition and green diamonds representing valid acquisitions. In this method, the Master  
548 image, dated November 5, 2019, serves as the reference image for displacement measurements. The





**Figure 12.** Time-position connection diagrams

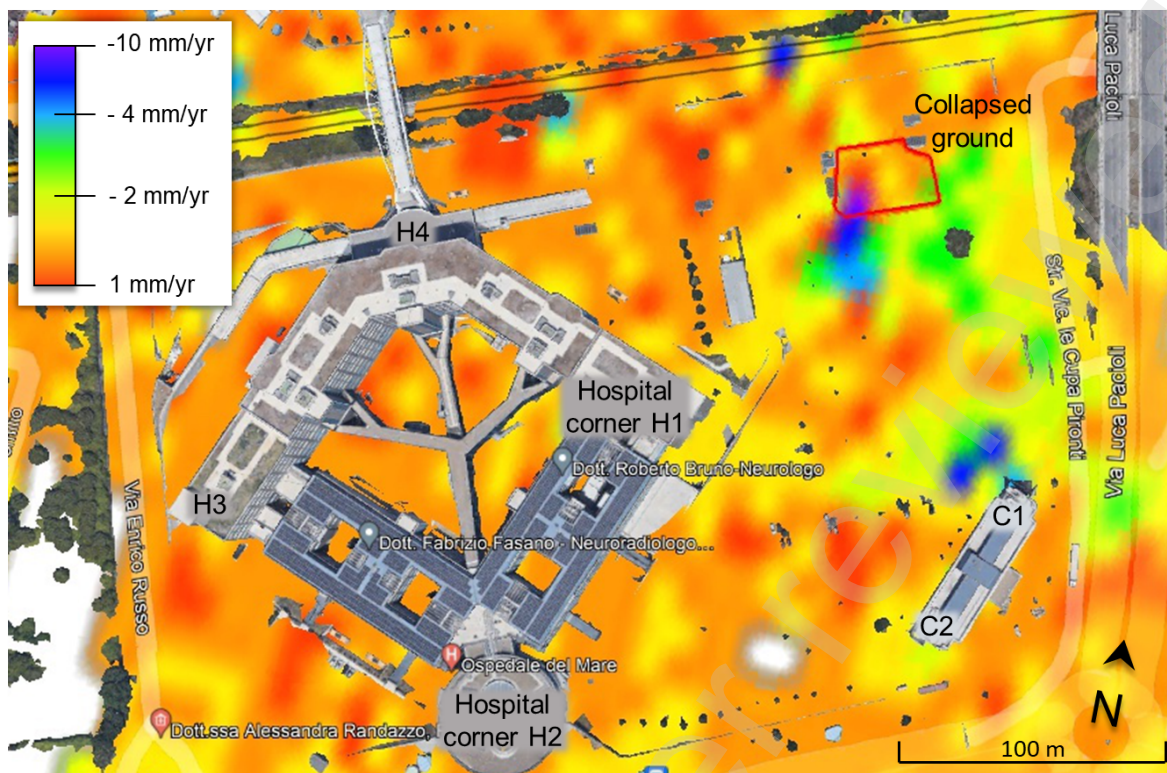
549 master image was selected to ensure that the point is temporally centred and possesses a median  
 550 interferogram size relative to all other points, thereby enhancing accuracy. The diagrams also indicate  
 551 the distances between satellite acquisitions at different times, showing that the SAR images were  
 552 captured from slightly displaced locations. Perpendicular baselines observed in the diagrams range from  
 553 -200 to 50 m, within the typical range for satellite observations. However, if the separation between  
 554 acquisitions exceeds 500 m, it may hinder further processing, and such pairs should be excluded from  
 555 the analysis.

#### 556 4.4. Evolution of ground settlement over time

557 The results of this analysis enable to study the ground movement of the area around Naples' hospital.  
 558 **Figure 13** depicts the velocity map surrounding the collapse, generated using the PS processing  
 559 method. The colour bars indicate the velocity of units in millimetres per year. Noticeably, significant  
 560 subsidence is evident in the lower-left corner of the collapsed ground, likely indicating the triggering of  
 561 collapse, as suggested by the high subsidence velocity. These velocity maps provide a comprehensive  
 562 overview of the potential subsidence profile around the collapsed ground. Additionally, the map appears  
 563 to reveal a chain of subsidence extending from the Covid-19 recovery ward to the railway, which would  
 564 require further investigation.

565

566



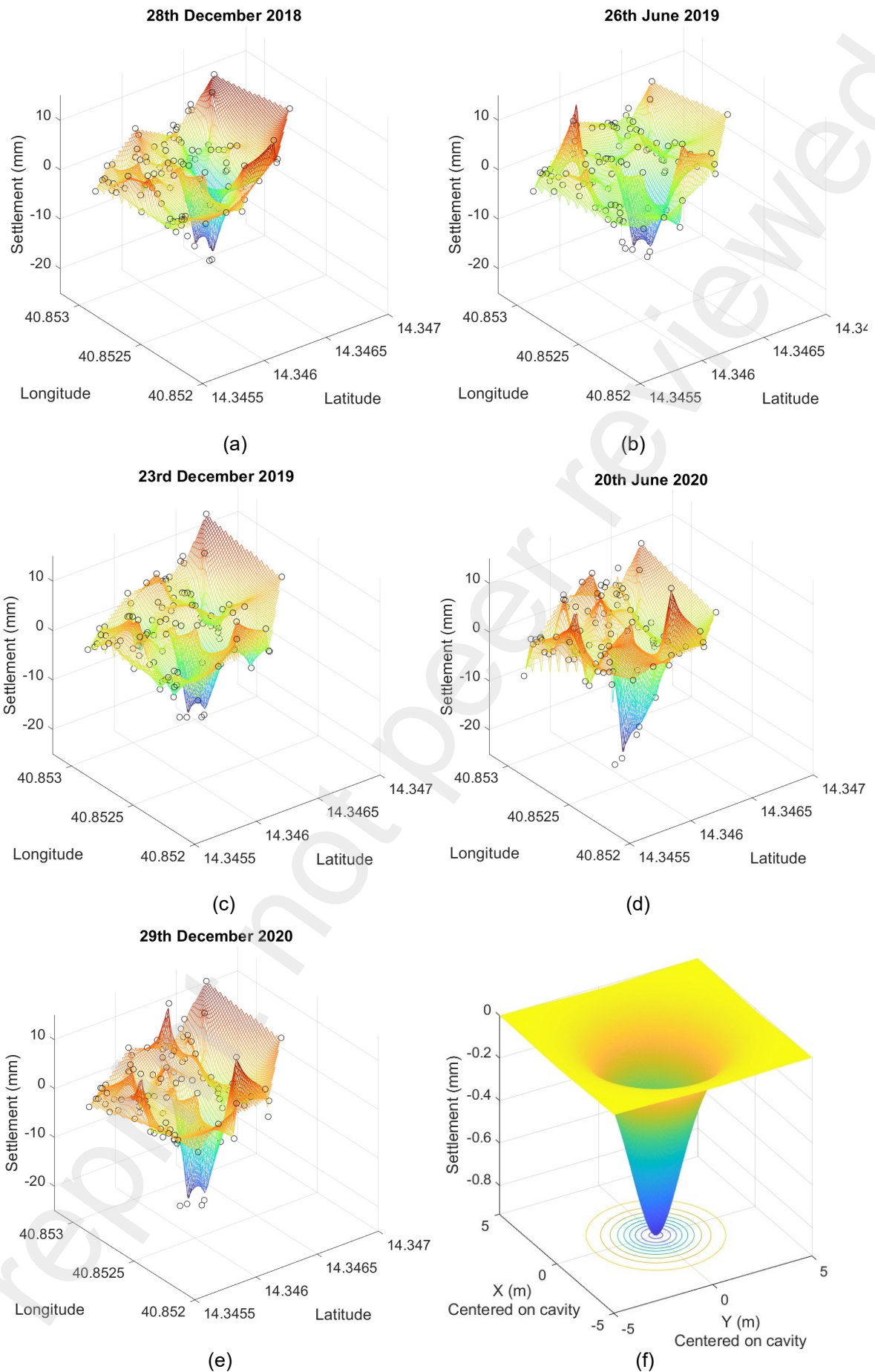
**Figure 13.** Vertical ground velocity map of the zone around the collapse gathering all images from June 2018 to the day before the collapse. All the time series are acquired in descending mode.

567

568 **Figure 14** provides a zoomed analysis of the evolution of ground subsidence over time in the very close  
 569 region surrounding the surface collapse. This figure was obtained by fitting a 3D surface to the  
 570 subsidence points of measurement obtained from the satellite images in the zone immediately  
 571 surrounding the area (shown in black on the graphs). The results of this set of graphs are compared  
 572 with the subsidence profile of a 3D Finite Element analysis published in Della Ragione et al. (2023a,b),  
 573 showing the ideal case of the early collapse of a perfectly circular cavity in clean fine sand. The images  
 574 show that, quite early on, the satellite images permit evidence of a clear signature settlement profile  
 575 corresponding to the formation of a subsidence at depth.

576

577



**Figure 14.** (a-e) Evolution of the settlement with time around the cavity before collapse (ground level is “zeroed” at the beginning of the analysis – i.e. in June 2018); (f) comparison with idealized circular cavity expansion obtained from 3D FE analysis in sand (Della Ragione et al. 2023b)

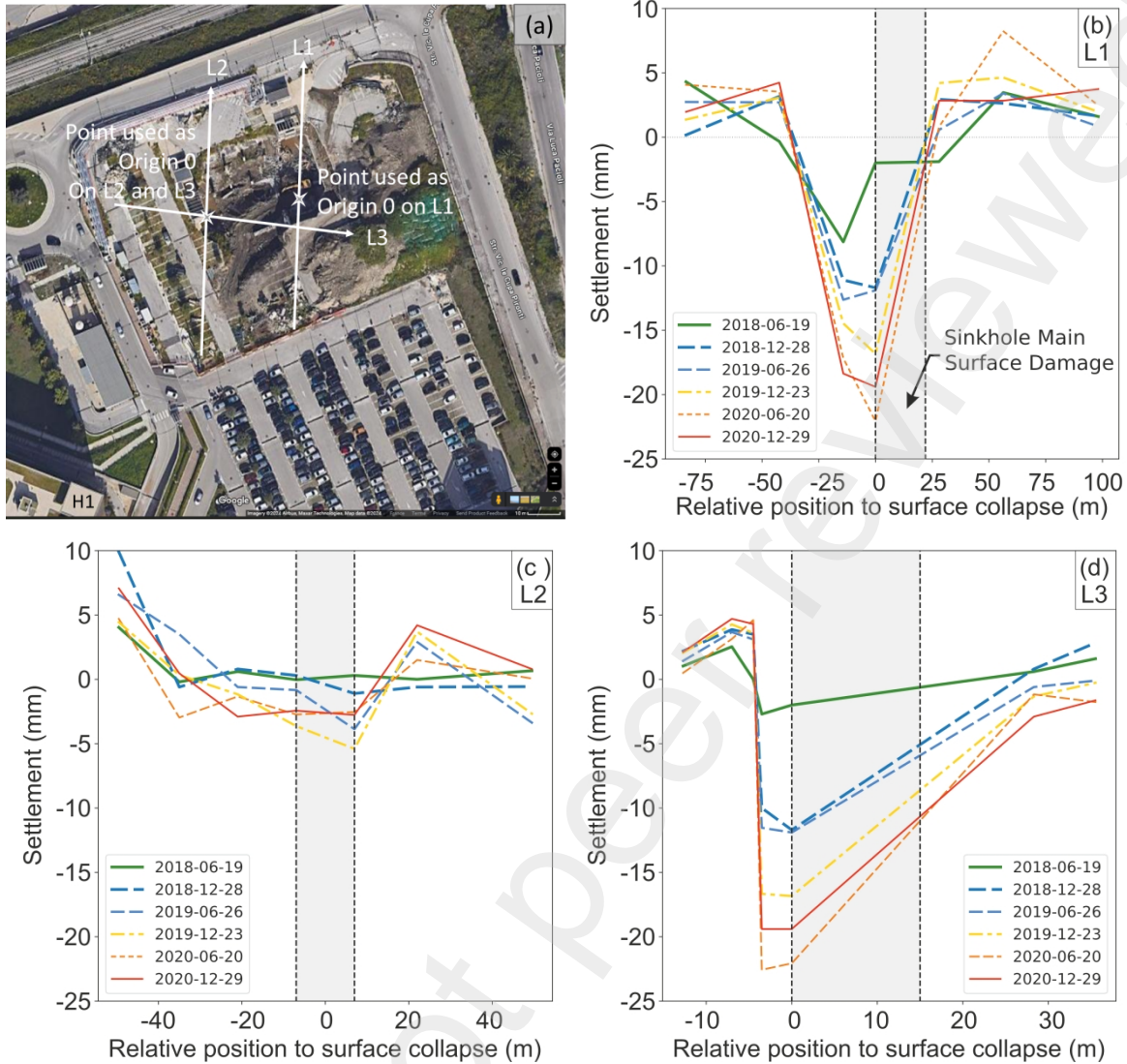
579 This is further analysed by taking a cross-sectional cut through selected lines along the collapsed  
580 surface damage, represented in **Figure 15** (a), and showing the evolution of the settlement profile over  
581 time, super-imposed with an estimation of an ideal sinkhole main surface damage zone.

582

583 Several observations can be drawn from the series of graphs shown in **Figure 15**(a,b c):

- 584 • **Figure 15** (b) displays a distinct subsidence profile closely resembling the ideal formation  
585 illustrated in **Figure 5** (a).
- 586 • The measured displacements are of a few millimetres, likely imperceptible to the naked eye,  
587 underscoring the resolution and capability of satellite imaging, a phenomenon noted by many  
588 in similar contexts.
- 589 • Ground subsidence appears to have been gradual, with clearly delineated profiles dating back  
590 to December 2018, nearly three years prior to collapse, highlighting the potential of remote  
591 sensing techniques for early detection.
- 592 • **Figure 15** (c) and (d) reveal that not all lines provide a clear image of subsidence evolution,  
593 warranting further research into automating monitoring processes, possibly leveraging Artificial  
594 Intelligence (AI) techniques.
- 595 • The settlement profile depicted in **Figure 15** (d) is likely influenced by the proximity of a small  
596 building (as seen in the photograph of **Figure 11**), which remains relatively stable on the  
597 periphery of the collapse. This accounts for the abrupt vertical drop observed in the settlement  
598 collapse. Similar phenomena occurred in built environment, such as the notable example of a  
599 sinkhole that emerged in Fukuoka in 2016, situated in the middle of a road flanked by towering  
600 skyscrapers. Further studies are needed to validate this observation.
- 601 • Surface damage does not necessarily correlate with the peak of subsidence observed in satellite  
602 imaging data. This is logical considering the urban setting of the studied zone: construction and  
603 ground work induce reinforcement and consolidation in some locations, which likely alter surface  
604 settlement profiles around buildings and infrastructures, diverging from the location of the cavity  
605 at depth. Consequently, detection through remote sensing techniques must be followed by  
606 specialized investigations to pinpoint the cavity before remedial action, for example, utilizing  
607 ground-penetrating radar techniques.

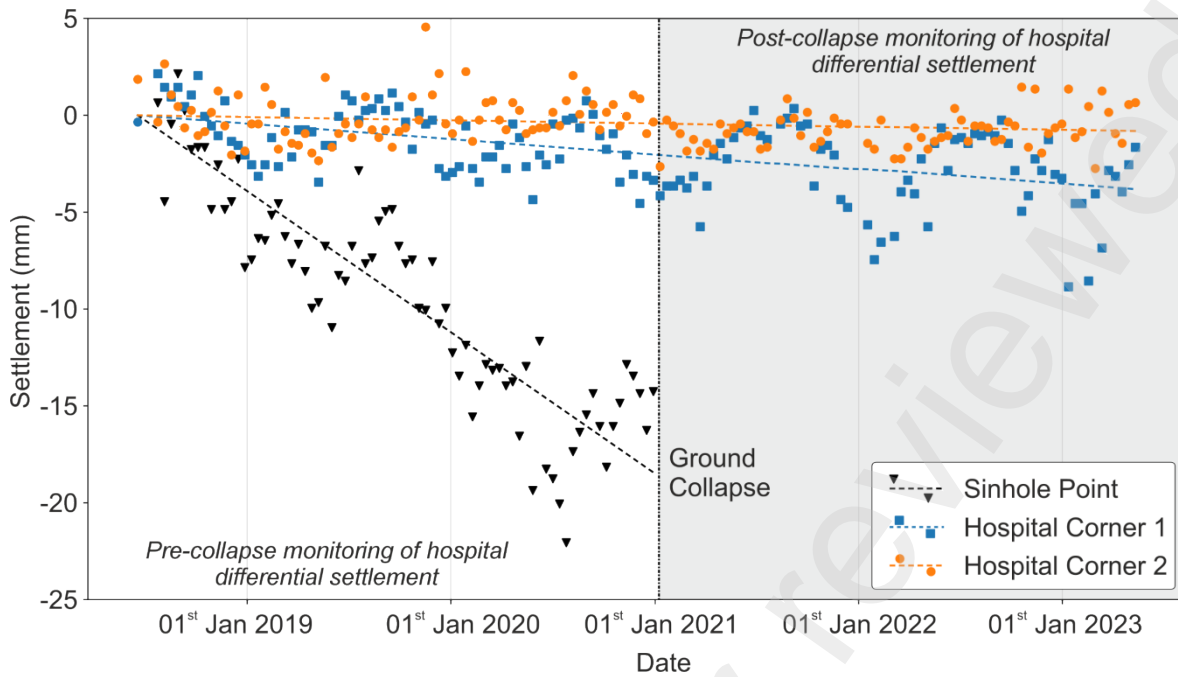




**Figure 15.** Evolution of cross-section settlement along selected lines with time around the cavity before collapse (ground level is “zeroed” at the beginning of the analysis – i.e. in June 2018)

608 **4.5. Monitoring of surrounding critical infrastructure**

609 Lastly, the satellite images used as part of the above study can also serve as a valuable tool for  
 610 monitoring the evolution of surrounding infrastructure, both preceding and following the ground collapse.  
 611 This technique is becoming increasingly prevalent in the surveillance of critical infrastructure, with  
 612 detailed descriptions available in works such as Selvakumaran (2020), Selvakumaran et al. (2020), and  
 613 Della Ragione (2024). An illustrative application is presented in **Figure 16**, which depicts the temporal  
 614 vertical displacement of two hospital corners (see **Figure 13**) juxtaposed with the vertical settlement of  
 615 a pertinent point within the zone later affected by collapse. In this example, the settlement was zeroed  
 616 in 2018, before the occurrence of large ground subsidence (according to **Figure 15**).



**Figure 16.** Evolution of the movement of selected points for monitoring of surrounding buildings: hospital and satellite building, compared with collapsed point on the ground surface

617 The graph exhibits seasonal changes in the building caused by swelling and contracting, which would  
 618 generally be offset in a thorough analysis.

## 619 5. Conclusions

620 This paper, conducted as part of the SINEW (SINKhole Early Warning) project, endeavours to develop  
 621 a remote sensing technique for the early detection of sinkhole collapse. Through a comprehensive  
 622 approach, it demonstrates the effectiveness of leveraging Distributed Fibre Optic Sensing (DFOS) and  
 623 Satellite Imaging for timely identification of sinkhole expansion. The study employs combined  
 624 experimental testing at 1g and finite element analyses to validate the feasibility of DFOS, followed by a  
 625 pertinent case study on a ground collapse in Naples, that well reproduces a “trapdoor” experiment at a  
 626 field scale and permits to explore satellite imagery's potential and limitations.

627

628 The initial focus of the paper is on DFOS utilization. Notably, the paper highlights the prominence of the  
 629 strain induced by horizontal ground movement in the combined strain response of the soil, a critical  
 630 conclusion for the understanding of the DFOS response for sinkhole application. DFOS data indeed  
 631 display a clear signature strain profile that captures the key features from the soil strain profile – and in  
 632 particular, the strain induced by horizontal ground movement - far away from the cable. The cable strain  
 633 tends to display a lower strain magnitude and a wider trough, which worsens with (i) a lower stress level

634 and (ii) a lack of soil-cable coupling. Increasing the stress level via numerical modelling to mimic field  
635 conditions resorbed the difference in strain magnitude. In addition, enhancing soil-cable coupling clearly  
636 improves the ability of the cable to conform to soil horizontal movement and produces a clearer, narrower  
637 and stronger strain profile.

638

639 Loose cohesionless soil exhibits less dilation and therefore generates less arching at depth to support  
640 the surficial soil layer. As a result, loose and medium-dense cohesionless soil “benefit” from early higher  
641 surface settlements and larger trough width, which are easier to detect by the fibre optic. In addition, the  
642 higher the location of the cable above the sinkhole, the weaker the strain signal, but the more likely to  
643 sense the sinkhole, in particular when located far from the centreline of the subsidence. This is because  
644 cables close to the soil surface are more likely to be affected by horizontal soil movements generated  
645 by the large trough width from the funnel-shaped sinkhole mechanism close to the soil surface.

646

647 Brillouin technology is also very sensitive to small changes in material density, and as a result, the signal  
648 is easily polluted by small local changes in strain and temperature (Kechavarzi et al., 2016). Further  
649 work on the use of DFOS for sinkhole detection needs to expand the research to account for frequency  
650 shifts due to temperature, human-induced mechanical disturbances (e.g. loading, train, traffic) and  
651 vegetation growth. Additionally, the paper emphasizes the impact of cable location on signal strength  
652 and sinkhole detection, particularly when positioned away from the subsidence centreline.

653

654 In cases where DFOS signals are weak, the paper proposes the potential use of open-source data from  
655 Multitemporal Interferometry Synthetic Aperture Radar to infer soil surface settlement and velocity,  
656 aiding in narrowing down the sinkhole's position. The examination of a ground collapse that occurred in  
657 2021 in the car park of Naples' hospital highlights that a distinct subsidence profile could have been  
658 discerned up to three years before the collapse should the technology have matured at that time. These  
659 settlement profiles are juxtaposed with idealized subsidence profiles derived from the experimental and  
660 numerical investigations conducted to validate DFOS technology, revealing promising congruence in  
661 trends for cavity collapse affecting cohesionless soil layers.

662

663 The settlement profile obtained through MT-InSAR monitoring reveals ground movements of just a few  
664 millimetres, making visual identification nearly impossible and emphasizing the necessity for high-  
665 resolution, large-area remote sensing techniques. The chosen location, nestled within a hospital car  
666 park, highlights the practicality of integrating DFOS and satellite imagery technologies in the monitoring  
667 of densely populated urban locales.

668

669 However, the study acknowledges the manual nature of its results, necessitating extensive human effort  
670 for data processing and analysis. Ongoing research aims to integrate this technology into an automated  
671 framework, leveraging Artificial Intelligence for sinkhole detection under critical infrastructure.

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681

## 682 **7. Author contribution statement (<https://credit.niso.org/>)**

683 **Christelle Abadie:** Conceptualisation, Formal Analysis, Funding Acquisition, Methodology, Project  
684 Administration, Supervision, Writing – original draft. **Talia da Silva Burke:** Conceptualisation, Formal  
685 Analysis, Methodology, Supervision, Writing – review and editing (DFOS, Experimental and Numerical).  
686 **Sakthy Selvakumaran:** Conceptualization, Investigation, Methodology, Software, Supervision, Writing  
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694

## 695 **8. Declaration of generative AI and AI-assisted technologies in the writing process**

696 During the preparation of this work, the authors used Chat GPT in order to improve language and  
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698 take full responsibility for the content of the publication.

699

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