Fibre optic instrumented geogrid for ground movement detection

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Abstract

The serviceability of transportation infrastructure, and other civil engineering assets, can be adversely affected by post-construction ground movements. Potential sources of these movements include loss of material from dissolution features, differential movements at earthwork/structure transitions and movements associated with mining legacy features. Post-construction ground movements are mitigated through engineering design, which may be supported through the inclusion of monitoring systems within the earthworks at locations of particular interest.

The number of available methods capable of monitoring sufficiently large areas and providing early warning of the onset/development of ground movement is limited. The incorporation of distributed fibre optic sensing (DFOS) systems into earthworks could provide important information on the commencement, location, origin and magnitude of ground movements in near real-time for critical infrastructure over areas at risk.

HS2 is the new high-speed railway connecting London, Birmingham and the north of England. This paper presents field monitoring trials on the HS2 Phase One route using a newly developed sensing solution consisting of a DFOS instrumented geogrid for ground movement detection. Controlled field tests were first performed on two simulated sinkholes using 3x3m pits in which water-filled bags were placed and covered with stabilised chalk and granular soils, respectively. By deflating the bags in varying sequences, the captured strain signature profiles from the instrumented geogrid were compared with displacement measurements from conventional instrumentation, to assess the instrumented geogrid's sensitivity to millimetre-scale settlements. Robustness and resilience were also evaluated through in-situ durability tests. Finally, as a result of these trials, this technology is being deployed over a 100 m-long, 10 m-wide stretch of the mainline alignment on the HS2 site at Tilehouse Lane Cutting to demonstrate its viability within a live construction environment. During the remaining construction period, continuous monitoring, near real-time data processing and visualisation will offer the opportunity to detect any incipient ground movement below the temporary haul road surface.

Keywords: Distributed fibre optic sensing, Ground movement, Geogrid, Sensorgrid, Early warning

1. Introduction

Nearly all of the UK's critical infrastructure is placed on, or situated in soil. Therefore, ground movement can have a significant social, economical and physical impact on infrastructure provision both at present and in future years. Such ground movements are commonly induced from shallow geohazards like sinkholes, subsidence, landslides, etc., often resulting in both long-term degradation and, ultimately, structural failure of particular assets. Climate change projections suggest that these geohazards, which are themselves often driven by antecedent weather conditions, are likely to increase in magnitude and frequency for certain areas of the UK through the 21st century. Implementing early warning systems by measuring and monitoring spatio-temporal movements may be used as part of a coordinated design and risk management approach to mitigate these increasing risks posed to critical infrastructure (Ast et al. 2001). This was also emphasised by the task force appointed by Network Rail to carry out a review of earthworks management following the fatal train derailment at Carmont, Scotland on 12th August 2020 (Network Rail, 2021).

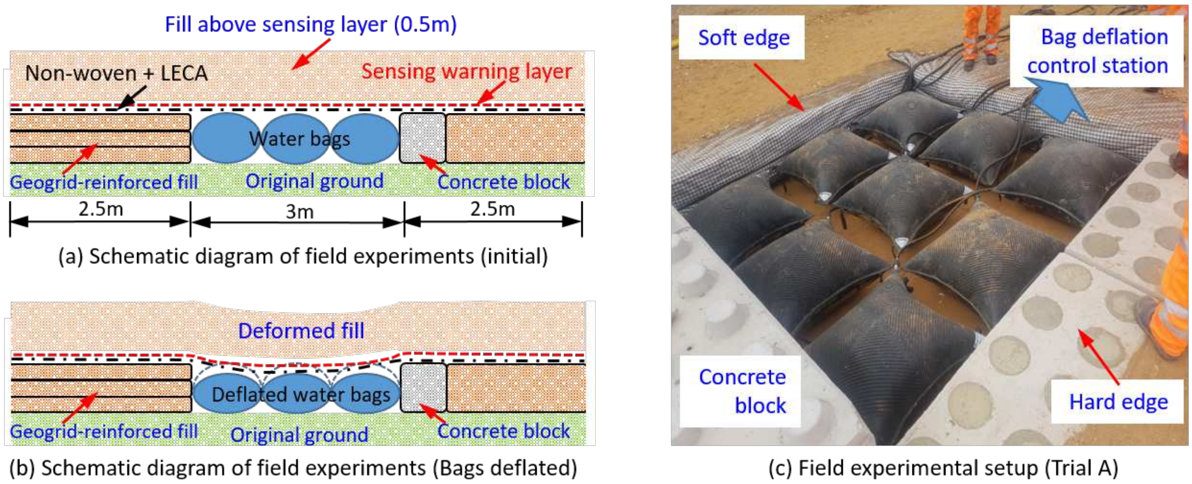
The number of available methods that are capable of monitoring sufficiently large areas and providing early warning of the onset/development of ground movement, is limited. Conventional instrumentation, such as borehole extensometers, are often constrained by discretely instrumented 'measuring points'. Remote sensing technologies like interferometric synthetic aperture radar (InSAR) are commonly used to detect ground surface elevation changes and have proved effective in mapping large-scale ground motions. However, these do not allow for the capture of subsurface deformation, which is often a precursor and early warning of surface ground movement, and their effectiveness in highly vegetated infrastructure corridors is often limited. Distributed fibre optic sensing (DFOS) technology has emerged as a powerful tool for continuous, high temporal and spatial resolution mapping of subsurface ground movement. DFOS enables 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). The incorporation of DFOS cables into the ground could provide significantly improved information on the location and magnitude of subsurface ground movement and subsidence (Möller et al., 2022). To date, this technology has been trialled in some field monitoring campaigns, 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. Many have reported that the quality of fibre optic sensing data is highly reliant on the mechanical coupling between fibre optic cables and their surrounding soils, which is dependent on both the cable construction and its installation (Iten et al., 2011; Klar et al. 2014; Zhang et al. 2016; Winters et al. 2020).

This paper reports on controlled field experiments designed to assess the use of a newly developed geogrid, integrated with DFOS strain cables during the manufacturing process (referred to as a Sensorgrid), for early warning of localised ground movement. This innovative Sensorgird was developed in collaboration between Huesker, the Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge and Epsimon Ltd. The performance and practical implications of the new sensing solution were explored through real-world trials simulating the type, scale and rate of ground movement that could be experienced by earthworks assets in areas of unmitigated ground movements.

2. Field-scale controlled experiments

2.1 Experimental setup

Two 3 x 3m voids constructed at the HS2 site at Tilehouse Lane Cutting (TLC) to simulate the ground movement from shallow geohazards and explore the behaviour and response of the Sensorgrid against two different types of overburden fills commonly found and used on the South Portal at TLC: stabilised chalk (trial A) and granular fill (trial B). As illustrated in Figure 1, nine heavy-duty water-filled bags were laid in the base of each, with a maximum inflation height of 0.5m. On one end of the pit, concrete modular blocks were used to form a hard edge, simulating the transition between earthwork and structure (e.g. bridge abutment). At the other end a soft edge was formed by using a geogrid and a non-woven wrap-around on compacted fill (Figures 1(a) and (c)). On one side of the pit, four modular blocks could be removed at the end of the trial to inspect the condition and profile of the Sensorgrid. When all the bags were fully inflated, a layer of non-woven geotextile was placed loosely on top of them to support a lightweight expanded clay aggregate (LECA) fill. This was then followed by the installation of the Sensorgrid, and a 500mm layer of overburden fill above the sensing layer.



(a) Schematic diagram of field experiments (initial)

(b) Schematic diagram of field experiments (Bags deflated)

(c) Field experimental setup (Trial A)

Figure 1: Field simulation of ground movement: (a) Schematic diagram of field experiments at the initial stage; (b) Schematic diagram of field experiments when bags deflated; (c) Field experimental setup (Trial A).

2.2 Field instrumentation

The strain fibre optic (FO) cable integrated into the Sensorgrid used in these two trials was 2.5 mm in diameter and consisted of single-mode optical fibre with a 0.9mm Hytrel coating embedded in an elastic 2.5 mm polyurethane outer sheath. It was knitted into a geogrid by Huesker by substituting it for yarns of similar size. The Sensorgrid used in these two trials was 0.5m wide and carried three individual FO cables, a central fibre, a redundant fibre positioned next to it and an offset fibre.

Prior to the trials, the performance of the Sensorgrid was evaluated through extensive testing at CSIC. In particular, the strain transfer function was evaluated using a bespoke universal testing machine to carry out tensile tests (Figure 2(a)). As illustrated by one of the test results presented in Figure 2(b), the strain transfer function of this very elastic cable showed good linearity, no hysteresis, good repeatability to high strains and high sensitivity (high strain coefficient or gauge factor, which is the slope of the linear relationships shown).

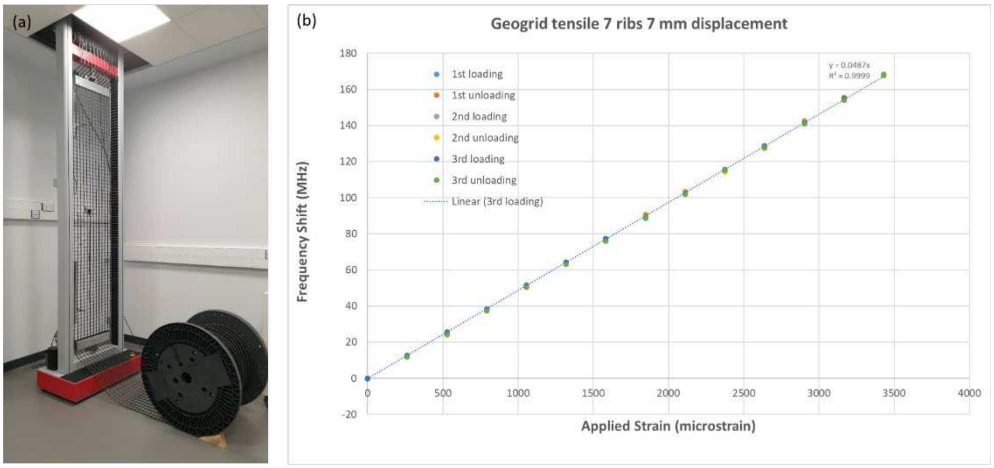


Figure 2: Laboratory tensile tests on the Sensorgrid: (a) Tensile test at CSIC; (b) Testing results.

Figure 3 shows an overview of the field instrumentation set-up. The grid was positioned on top of the bags in a way that the offset fibre was running over the middle of each bag, as illustrated in Figures 3(a) and (b). The anchored length of Sensorgrid was 2.5m on either sides of the pit.

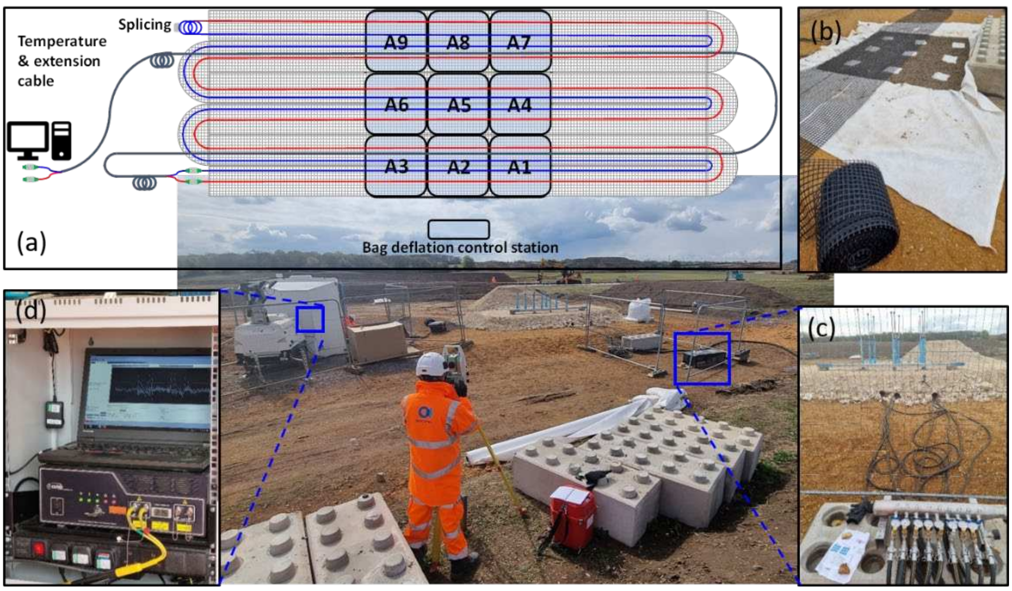


Figure 3: Field experimental setup at trial A: (a) Sensorgrid layout; (b) Sensorgrid installation; (c) Water bag control station; (d) Fibre optic sensing analyser operating in real-time.

A conventional total station monitoring system was employed to capture the displacement on the crown of each bag, created by deflation, as well as the resulting displacement experienced by the Sensorgrid. One circular metallic plate was sitting on the centre of each bag and a second plate was sitting on top of the Sensorgrid above the bags. These two plates were connected to rods and tubes that extended over the overburden fill. Prisms were attached to the rods and tubes and monitored using a total station, as shown in Figure 3. This allowed the movement of the bags (void) and the geogrid to be recorded in real-time, with an accuracy of ±1mm.

To simulate ground movement, water was released from the bags through a control station (as pictured in Figure 2(c)), causing the fill above to move downwards and strain the mesh, which in turn caused a change in the characteristics of the spectrum of the back-scattered light pulsing through the FO sensing cable captured in real-time by a Brillouin Optical Time Domain Analysis (BOTDA) analyser (OZ Optics Ltd, Canada) (Figure 2(d)). After full completion of testing on trial A, the overburden fill, the monitoring tubes and the Sensorgrid were removed to recover the bags from the pit and reuse them for trial B.

3. Results and Observations

3.1 Early warning strain signatures

The strain signature profiles measured in the Sensorgrid at the very early stage of sinkhole formation are illustrated in Figure 4. These represent a change in strain with respect to a baseline measurement taken following the installation and prior to starting the tests. By convention, positive strain change corresponds to an increase in tension while negative strain change represents compression or loss of tension. The strain profiles shown are those obtained with the FO cable centred on the water bags in the row with red numbering, as indicated in the schematic inset in the figures. The grey shading illustrates the bags that have been (grey numbering) or are being (red numbering) deflated at the time of the measurement.

In both trials A and B, the Sensorgrid was sensitive to millimetre scale subsurface vertical settlement (not necessarily the ground surface settlement) over the relatively small spatial scale of 1m (deflated bag width). The strain generated was several times higher than the system's measurement resolution. At this early stage, the strain profile in Trial A exhibited a double-peak shape associated with the central dip across the A2 section and negative strain at the edge of the trial area. The strain profile is wider than that of the deflated water bag as the deformation across A2 generated axial strain in the grid. For Trial B, the strain profile displays a different pattern with a negative strain change in the centre line of the fibre optic trial pit B9, as shown in Figure 4 (b). This artefact is due to the different construction procedures used in Trial B where the soil over the water bags was compacted. This compaction forced the geogrid down in the dips in between the bags, creating tension in the FO cable over the centre of the curved bags. As the bags were deflated this tension was released, resulting in a negative strain change (loss of tension). This would not happen in a site installation when the geogrid is installed over a flat surface. Nevertheless, both trials demonstrate the sensitivity and effectiveness of the Sensorgrid system in detecting relatively small movements over a small spatial scale.

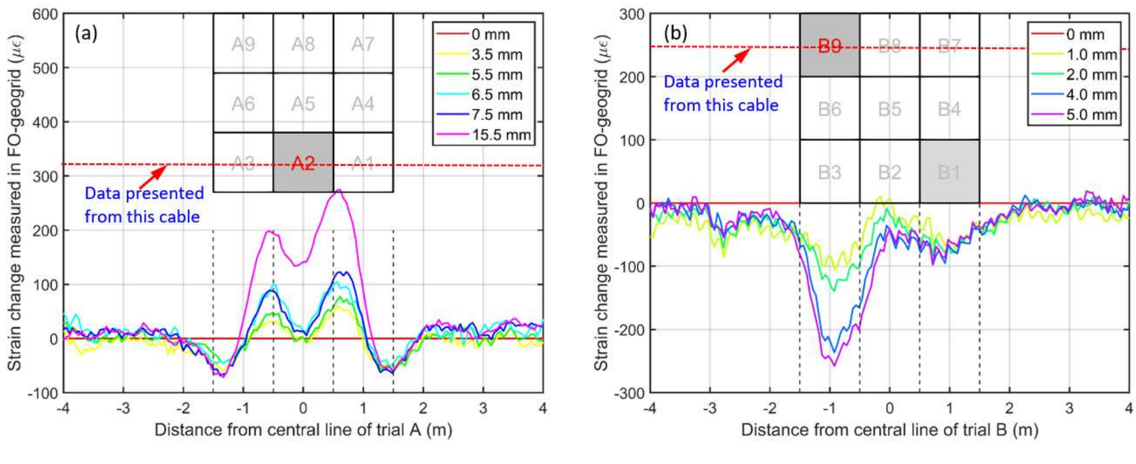


Figure 4: Early warning strain signature profiles: (a) Trial A - deflation of bag A2; (b) Trial B - deflation of bag B9 (following the deflation of B1).

3.2 Strain signatures at large ground deformations

The evolution of the measured strain profiles as sinkholes propagate was investigated by deflating bags in sequence. As displayed in Figure 5(a), the strain profile gradually became wider as the single bag A2 was deflated; i.e. the positive peaks remained around the edges of A2 but strain propagated up to about 1m into the anchorage length on both sides of the trial pit. Similar behaviour was observed in trial B, as shown in Figure 5(b). The propagation of strain, as the bags were deflated, can also be visualised using contour plots, as highlighted in Figure 5(c) and (d). This type of two-dimensional plot on a larger scale installation is essential to allow for rapidly pinpointing the location of problem areas. Following completion of each trial, the lateral modular blocks were removed for inspection, as shown in Figure 6.

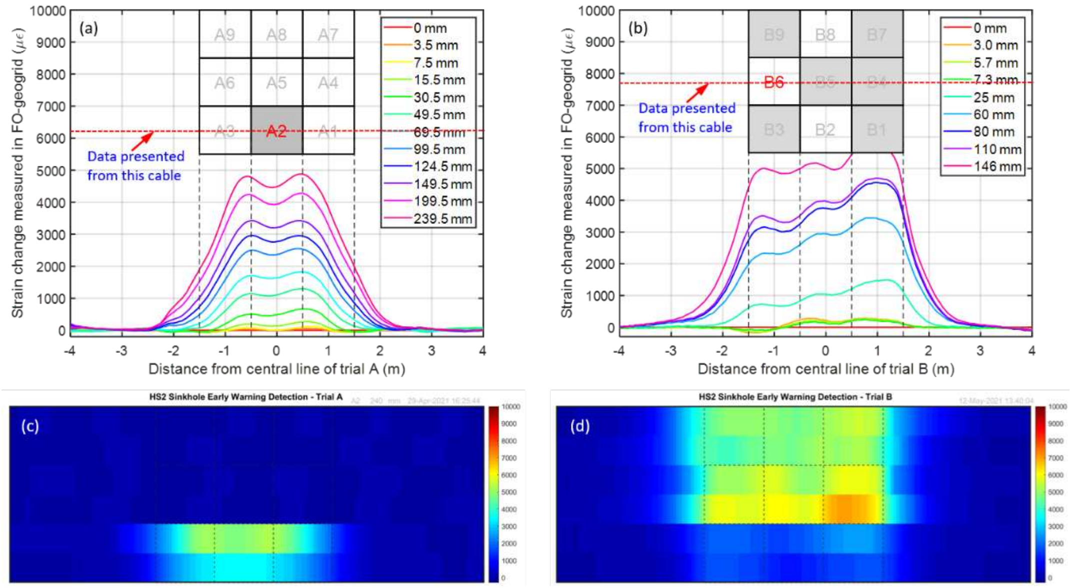


Figure 5: Strain profiles at large ground deformations: (a) Trial A – deflation of bag A2; (b) Trial B - deflation of bag B6 (following the deflation of B1, B9, B3, B7, B5, B4 and B6 in sequence); (c) Strain contour at trial A deflating A2 to 239.5mm; (d) Strain contour at trial B deflating B6 to 146mm.

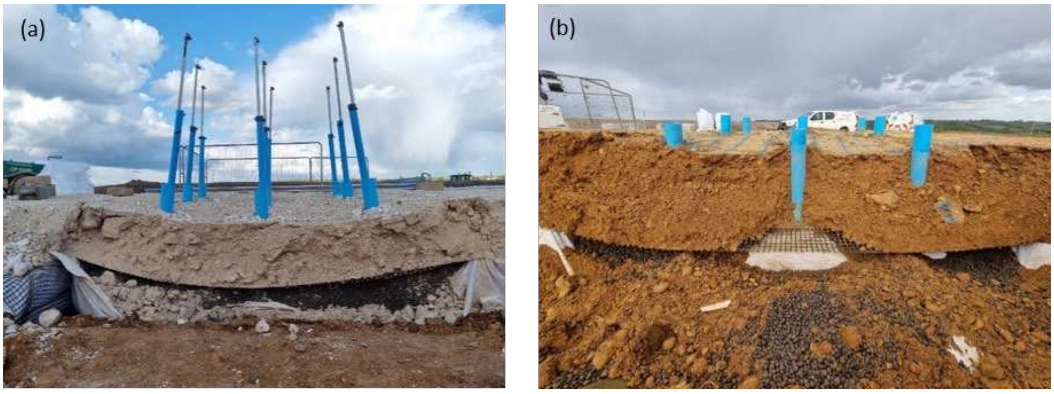


Figure 6: Deformed profiles of Sensorgrid after all bags were fully deflated: (a) Trial A; (b) Trial B.

During the trials, a FO temperature cable was installed above the Sensorgrid to assess potential temperature effects. The largest temperature changes occurred on 29 April 2021 due to sun exposure, with rapid changes and an increase of almost 25°C, which was picked up by part of the cable located outside of the soil. However, in the cable covered by the soil in the trial pit, the changes were not significant and in the order of the precision of the analyser (i.e. ± 1 °C).

4. In-situ durability assessment

Separate tests were conducted in order to assess the robustness of the Sensorgrid used in these preliminary trials, where no significant problems had occurred, under more realistic field conditions representative of the temporary haul road and final pavement construction process at TLC. Two separate Sensorgrid circuits were laid on the ground in a single loop over a length of approximately 50m in order to apply four different treatments: (1) T1 with one protection layer of non-woven geotextile (NW20) above and below the Sensorgrid, (2) T2 with two layers of NW20 above and below the Sensorgrid, (3) T3 with three layers of NW20 above and below the Sensorgrid; (4) T4 with three layers of NW20 above and two layers of NW20 below the Sensorgrid; The non-woven geotextile (NW20) used here had a weight of 235 grams/m^2, and was the same product used to cover the water bags in the trial areas. After placing the Sensorgrid and NW20 protections, a series of construction activities were carried out, including placement and levelling of a stabilised chalk fill over the Sensorgrid, and compaction of that fill with eight passes of a 20-tone vibratory roller. For all treatments, both strain and optical power were measured with a Neubrex NBX-5000 Brillouin Optical Time Domain Reflectometry (BOTDR) analyser all along the FO cables integrated in the Sensorgrid. The data showed that, whereas acceptable localised losses were generated during soil placement, soil levelling and soil compaction resulted in significant losses at several locations along the optical fibres. These were likely due to excessive localised bending in the fibres generated by sharp aggregates, but as the losses are cumulative they eventually exceeded the optical budget available (dynamic range of the analyser), leading to erroneous strain data.

Since the manufacturing of the Sensorgrid by Huesker is realised through a knitting process, different grid designs can be achieved by using FO strain cables of different sizes and stiffness and therefore robustness. As such, a stiffer Sensorgrid (Fortrac® R 220/100-30 GSGTA) was produced with a much more robust cable for the larger scale ground movement monitoring scheme deployed at TLC, as described below.

5. Large-scale trial of ground movement monitoring at Tilehouse Lane Cutting

TLC is approximately 710m long in total and up to 11m deep, and it connects the North Approach Embankment and Colne Valley Viaduct to the south-east with the West Hyde embankment and the 10.6 mile-long twin-bore Chiltern Tunnel passing under the M25 to the north-west, as indicated in Figure 7. The ground investigation (48 CPTs) and cutting excavation has revealed dissolution features ranging from 0.5 to 2m in diameter to be present along the cutting (Figure 7(a)). The condition of the infill material varies, and voids are occasionally present. Engineered mitigation has been constructed at these locations and a geogrid-reinforced mattress will also be installed over the area. This has provided the opportunity to prove the viability of the technology in a live construction environment and 5m-wide Sensorgrid with FO strain sensing cables at a 0.5m spacing is being deployed to monitor potential ground movement beneath a 100m-long, 10m-wide stretch of the mainline alignment on the HS2 site at TLC.

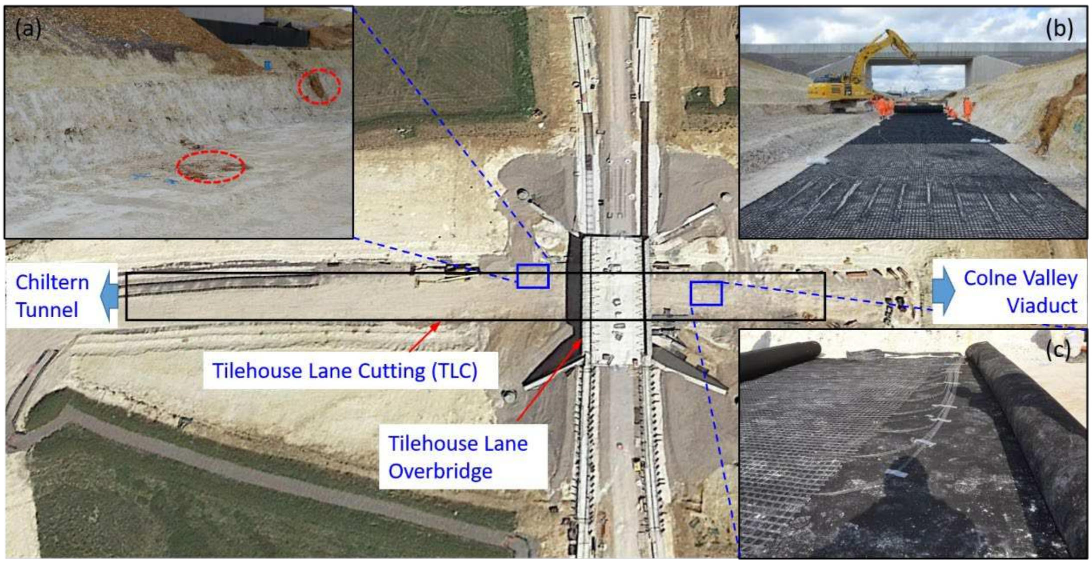


Figure 7: Large-scale monitoring of ground movement at Tilehouse Lane Cutting (TLC): (a) Solution features at TLC (as circled); (b) Field deployment of Sensorgrid; (c) Sensorgrid in-situ.

To protect against construction damage, the Sensorgrid is sandwiched between layers of Non-woven geotextile (HPS14) (Figure 7 (b) and (c)). Above this is a layer of geogrid Fortrac 600 MDT forming the base of the reinforced mattress, overlain by chalk mixed with 2% cement. Strain will be monitored continuously along the Sensorgrid for two years during the construction of HS2. This represents 10,000 monitoring points over 1000m^2. Temperature cables are also being embedded with the Sensorgrid to assess any (unexpected) temperature effect. The data acquired from the FO cables will be automatically processed and displayed in real-time on a web-based visualisation dashboard developed by Epsimon Ltd. This will enable the project engineers to detect any incipient ground movement, enabling them to take timely preventative action if necessary.

6. Conclusions

Controlled field experiments were performed to explore the performance of a newly developed DFOS instrumented geogrid (Sensorgrid) for ground movement detection. Water-filled bags were placed in the ground and deflated in a pre-determined sequences to replicate vertical ground movements which demonstrated the sensitivity and effectiveness of the Sensorgrid system as an early warning detection solution for local ground movements beneath earthworks. The Sensorgrid sensing system is sensitive to millimetre scale vertical settlement at depth. It is also sensitive to settlement at the sub-metre spatial scale. For large ground movements, the Sensorgrid is likely to experience large strains but, in the trials, these did not exceed the capacity of the system (both in terms of tensile strength and measurement range/limit).

As shown by the trial results, the current Sensorgrid configuration is highly sensitive to strain and can detect very small vertical displacement. Its low stiffness is likely to lead to good strain transfer in soils, which also makes it ideal for application where horizontal movement and axial strain occurs, such as for slope movements and embankment retaining walls. For applications in harsh construction environments, the Sensorgrid design is highly configurable and it can be integrated with more robust strain cables as required.

Developing a capability for early detection of ground movement which leads to appropriate preventative or precautionary measures could prove a valuable tool for the maintenance of infrastructure earthworks. These technologies may become more valuable in future because of the increasing frequency of extreme weather events and their potentially adverse impact on ground conditions and earthwork assets.

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References

Ast, W., Sobolewski, J. & Haberland, J. (2001). Final design of an overbridging for railways endangered by cavities at Grobers. Landmarks in Earth Reinforcement, Ochiai et al (eds).

Iten, M., Hauswirth, D. & Puzrin, A. M. (2011). Distributed fiber optic sensor development, testing, and evaluation for geotechnical monitoring applications. In Proceedings of the SPIE 7982, Smart Sensor Phenomena, Technology, Networks, and Systems 2011 (eds. Ecke, W., Peters, K. J. & Matikas, T. E.) 798207 (SPIE).

Kechavarzi, C., Soga, K., de Battista, N., Pelecanos, L.,Elshafie, M. Z. E. B. & Mair, R. J. (2016). Distributed fibre optic strain sensing for monitoring civil infrastructure: a practical guide. London, UK: ICE Publishing.

Klar, A., Dromy, I. & Linker, R. (2014). Monitoring tunneling induced ground displacements using distributed fiber-optic sensing. *Tunnelling and Underground Space Technology*. 40, 141–150. https://www.sciencedirect.com/science/article/pii/S0886779813001417

Möller, T., da Silva Burke, T. S., Xu, X., Della Ragione, G., Bilotta, E. & Abadie, C. N. (2022). Distributed fibre optic sensing for sinkhole early warning: experimental study. *Géotechnique* 72 in-print. https://www.icevirtuallibrary.com/doi/abs/10.1680/jgeot.21.00154

Network Rail (2021). A review of earthworks management. https://www.networkrail.co.uk/wp-content/uploads/2021/03/Network-Rail-Earthworks-Review-Final-Report.pdf

Winters, K. E., Quinn, M. C. & Taylor, O.-D. S. (2020). Assessing the frictional resistance between fiber-optic sensor cable and different soil types. *In Geo-Congress 2020: Modeling, Geomaterials, and Site Characterization* 164–171. https://ascelibrary.org/doi/10.1061/9780784482803.018

Xu, X., Kechavarzi, C., & Barker C. (2021). Monitoring of tunneling intercepted end-bearing piles using distributed fibre optic sensing. *Proceedings of the International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Porto, Portugal, 30 June-02 July 2021, 1503-1507.

Zhang, C. C., Zhu, H. H. & Shi, B. (2016). Role of the interface between distributed fibre optic strain sensor and soil in ground deformation measurement. *Sci. Rep*. 6, 36469.