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Application of InSAR for geotechnical asset management on England's Strategic Road Network

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Abstract

National Highways operates, maintains and improves England's Strategic Road Network (SRN), comprising England's motorway and major A roads. The organisation is responsible for the management of nearly 50,000 geotechnical assets. National Highways is increasing its use of different remote survey techniques, including earth observation, and is integrating them into the suite of available tools to manage its geotechnical assets. Interferometric Synthetic Aperture Radar (InSAR) is a radar imaging technique that uses two or more unique synthetic aperture radar (SAR) images to detect and measure centimetre- and millimetre-scale surface deformation over time. The application of InSAR is an emerging technology in geotechnical asset management. To date however the application of InSAR technology has primarily been focused on the monitoring of hard infrastructure in urban areas or single assets (e.g. bridges, buildings, mines). Few case studies and guidance exist on the application of InSAR to support the inspection and monitoring of linear geotechnical assets. Ultimately, this has potentially contributed to limited uptake of the technology within the industry. This paper reports on recent trials undertaken by National Highways across the SRN in England to understand the benefits, challenges and limitations of InSAR to support the inspection and management of its geotechnical assets. Disseminating these findings will help to build a use case and provide support and guidance for other highway and geotechnical asset managers. This knowledge will allow those responsible for the operation and maintenance of geotechnical assets to better integrate the technology into existing management practices.

Keywords: Asset Management, Remote Sensing, Highways

1. Introduction

Understanding the condition of geotechnical assets (or earthworks), which are vital for supporting linear transport networks and associated infrastructure (e.g. pavements, drainage, structures, telecommunications equipment), is imperative for ensuring the safety, continued performance and resilience of these networks (Tosti et al. 2020). Ground deformation and geotechnical defects can provide an early indication of earthwork performance issues which could lead to serviceability limit state or ultimate limit state failures. Therefore, understanding and assessing such movements is of particular importance across a network.

InSAR (Interferometric Synthetic Aperture Radar) is a radar imaging technique that uses two or more unique synthetic aperture radar (SAR) images to detect and measure centimetre- and millimetre-scale surface deformation over time (Bovenga et al. 2006). Its application for geotechnical asset management is currently emerging. The opportunity InSAR provides in having regular repeat data capture, and being able to operate in all weather, and day and night, providing national coverage will allow organisations to identify and investigate geotechnical defects before they might have been recognised using traditional approaches to physical asset inspection alone; where inspection frequency can range from 1 to 10 years depending on the risk (DMRB, 2020). The historic record of InSAR data also enables users to provide a time series analysis of ground movements that could provide insights into historical performance, validating geotechnical deterioration models.

To date the application of InSAR technology has primarily focused on the monitoring of urban areas or single assets (e.g. buildings (Mililo et al. 2018), bridges (Selvakumaran et al. 2020) and mines (Wang et al. 2020). Few case studies and guidance exist on the application of InSAR to support the inspection and monitoring of linear geotechnical (or earthworks) assets. This has potentially restricted uptake of InSAR technology within the linear infrastructure sector.

This paper reports on a series of trials undertaken by Arup AECOM on behalf of National Highways across the Strategic Road Network (SRN) in England to understand the benefits, challenges and limitations of InSAR to support the inspection and management of its geotechnical assets.

2. National Highways and the Strategic Road Network

National Highways operates, maintains and improves England's SRN. Comprising England's motorway and trunk roads that span approximately 6,900 km, the SRN carries a third of all traffic (by distance) and two-thirds of all heavy-goods traffic, while representing only 2% (by length) of all England's roads. National Highways has an aspiration to integrate remote sensing and earth observation techniques into the suite of available tools to manage its geotechnical assets (Ní Bhreasail et al. 2018).

Figure 1: (a) In February 2014, heavy rainfall led to the formation of a cavity in soluble ground, which led to the total closure of the M2 between Junctions 5 and 6; (b) Tension cracks as a result of shrink-swell of susceptible embankments on M11 between Junction 5 and 6. This resulted in closure of hard shoulder and multiple geotechnical interventions (Source: National Highways).

Comprising largely natural materials there is inherent variability in the engineering performance of geotechnical assets which can be sensitive to long-term degradation or environmental changes. Defects can arise due to the realisation of ground-related hazards, including natural hazards (e.g. sink holes, landslides); non road-related man-made hazards (e.g. mining, landfill) and; road-related man made hazards (e.g. over steep slopes on earthworks) (DMRB, 2020). National Highway's geotechnical assets have been relatively resilient, particularly during recent severe weather events and typically deteriorate slowly over their long design lives (60 years). However, deterioration is likely to increase due to climate change, increased demand and ageing of assets (Mott MacDonald, 2022; Power *et al*. 2023). Severe weather events can accelerate this deterioration and trigger a rapid decline in geotechnical asset condition, leading to defects (Vardon, 2014; Insana et al. 2021). Some geotechnical assets have been subject to reduced performance and ultimate limit state failure, which has resulted in significant impacts, in the form of delays and congestion, on the network (e.g Figure 1). Recent research by Achilles[1] has modelled the long-term response of a cutting slope on the A34 near Newbury, has suggested a potential 50% reduction in time to slope failure based on the latest climate change projections (Helm, 2022). In the UK, severe weather is likely to become more frequent and extreme in future under climate change (National Highways, 2022).

3. InSAR and Infrastructure Asset Management

SAR is a type of Earth Observation (EO) technique consisting of a satellite imaging radar system which transmits electromagnetic pulses towards the Earth's surface and records the reflected pulses via an antenna. The intensity and return time of reflected pulses are used to generate a SAR image which maps the distribution of energy reflected across pixels (with pixel size dependent on the spatial resolution of the satellite). SAR interferometry (InSAR) compares the phase of two or more complex SAR images that have been acquired from slightly different positions or at different times. Since the phase of each SAR image pixel contains range

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[1] https://www.achilles-grant.org.uk/

information that is accurate to a small fraction of the radar wavelength, it is possible to detect and measure path length differences with centimetric or even millimetric precision enabling a precise measurement of the earth's surface topography to be made (ESA, 2020). SAR data can be captured using aerial, ground or satellite-based platforms however this study focused on satellite-derived InSAR.

Several InSAR processing techniques were investigated as part of this trial study, which are used to process raw SAR data into InSAR data products. The approaches considered include:

- **Persistent Scatterer SAR Interferometry (PSInSAR)** – Uses a dominant scatterer in a resolution cell (or pixel), which are highly reflective points on the earth's surface that produce a large amount of backscatter (e.g. gantries, buildings), which over long periods of time allows for more consistent tracking of ground movement. However, movement can only be tracked at these point scatterers and the technique is reliant on a suitable number of scatterers being present across the scene (ESA, undated).

- **Advanced Pixel System using Intermittent SBAS (APSIS©-InSAR)** – the ISBAS approach combines pixels within the input radar stack which are only coherent for subsets of the total time period to be processed alongside those deemed to be coherent throughout the time period processed. This approach provides greater spatial coverage and therefore a fuller picture of ground deformation patterns (Bateson *et al.* 2015).

- **Corner Reflector SAR Interferometry (CRInSAR)** – A similar method to PSInSAR, this technique requires the installation of artificial corner radar reflectors onto the target feature. These reflectors act as effective point scatterers thereby improving measurements of the target. Although this technique has not been assessed during this task, it has supported the trial of the scoping and installation of a corner reflector at Flint Hall Farm, M25. A guidance note to support National Highways and its supply chain on the design and installation of corner reflectors has also been developed as part of this task (Arup AECOM, 2022a)

These InSAR trials used data products that were derived from raw SAR data obtained from Sentinel-1A and 1B platforms (ESA, Undated). There was intentional focus on Sentinel-1 as a source of raw SAR data as it is open-source, with associated costs related to the processing of raw SAR data into data products. As National Highways would be looking for national coverage to support the management of their geotechnical assets, the availability of open-source data potentially offers better value for money. It is important to note that Sentinel 1B recently ended its mission following a technical fault in December 2021 and will be replaced by Sentinel 1C in the 2nd quarter of 2023 (ESA, 2022). For the Sentinel Constellation, this will mean a reduced revisit time (i.e. a new data point being created) of 12 days, compared to the previous 6 days. However, the launch of Sentinel 1C in 2023 will likely see this come back to a 6 day revisit time.

For more detailed information on InSAR technologies, the reader is referred to C803 'InSAR and Earth Observation techniques for Civil Infrastructure' (CIRIA, 2022) and Arup AECOM (2022b).

4. InSAR trials on the Strategic Road Network

National Highways and Arup undertook a series of InSAR trials across the SRN. Ten proposed trial sites were selected following an initial scoping study. These sites represent varying combinations of the characteristics listed that included: locations that have in-situ ground monitoring in place: size of the defects (both in length and depth); cause of defect (e.g. geology or drainage); orientation of the road (in relation to look direction of the satellite); slope angle and asset type (e.g. embankment or cutting); density of vegetation and; access constraints (e.g. presence of dense vegetation).

Common causes of defects that are applicable to large areas of the network, such as the legacy of coal mining or the presence of high-plasticity clays that are susceptible to shrinkage and swelling, also guided the selection of potential trial sites. This was aided through spatial ground-related hazard mapping layers that are available on National Highway's Geotechnical and Drainage Management Service (GDMS).

Following the selection of the trial sites, several InSAR data providers were approached and asked to provide information on which of the trial sites would be suitable for the InSAR trials. In this paper, we do not go into detail of each trial site, and instead highlight the benefits and challenges of InSAR for understanding geotechnical asset condition by drawing on some of the findings from these individual sites. Data suppliers have also been anonymised.

4.1 Influence of InSAR data processing technique

The varied approaches to raw SAR data processing can lead to significant differences in InSAR outputs. Across the data suppliers, there was significant variation shown in the processing of InSAR data. For example, significant variation was found between PSInSAR and the ISBAS approach, where ISBAS showed complete coverage at the A56 Woodcliffe site (see Figure 2) – this aligns with previous studies showing improved coverage in rural areas using the ISBAS approach (e.g. Bateson et al. 2015). Variation was also identified across different suppliers of PSInSAR data (e.g. Figure 3).

In all cases, algorithms used to interpret raw SAR data are proprietary and further detail of the algorithms was not provided. This has meant that this study has not been able to compare the approaches beyond the InSAR data provided. The significant differences would potentially make it difficult for National Highways and its supply chain to select a single data supplier for procuring InSAR data.

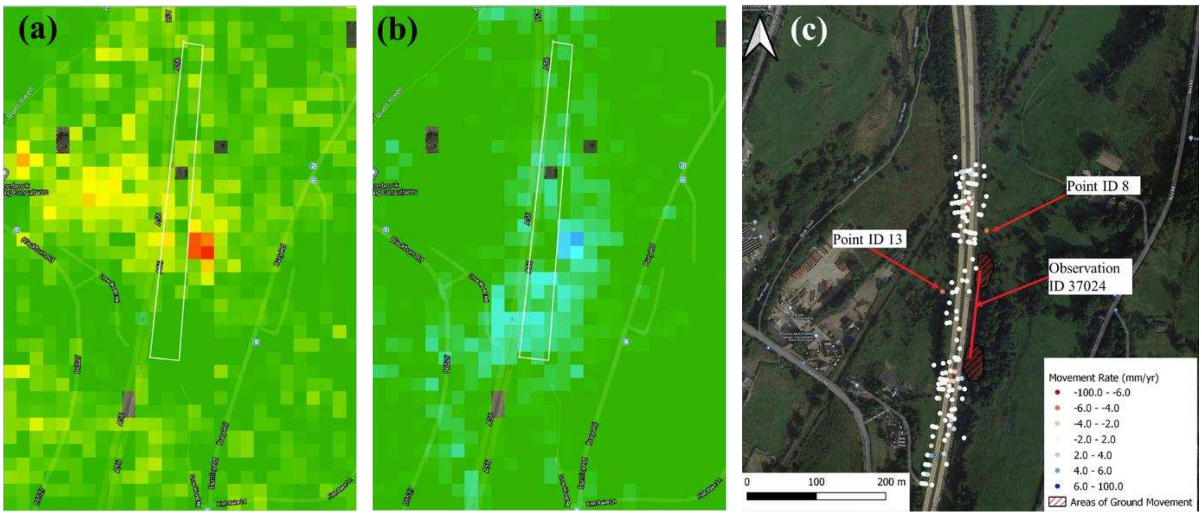

Figure 2: (a) Average ground motion rates (ISBAS approach) for 2015-2021 in the East-West direction; (b) Average ground motion rates (ISBAS approach) for 2015-2021 in up-down movements; (c) PSInSAR data points for the area of the A56 Woodcliffe cutting, with the landslip (Observation 37024) marked (InSAR Data: Terramotion (a) & (b); Satsense (c); Map imagery: Google, 2022).

PSInSAR data can be affected by the presence of vegetation. For example, one of the suppliers indicated that their data for sections of the A628 in the Peak District National Park could be associated with reduced accuracy due to the presence of moorland vegetation (see Figure 4). This was despite the SRN at this location being associated with numerous geotechnical defects. The data supplier identified that this may be a result of the rapidly growing and changing heather vegetation and the presence of water ponding in this area affecting the SAR signal. Caution is therefore required in such areas unless a supplier can prove otherwise. This is where ISBAS for example may be a more suitable technique.

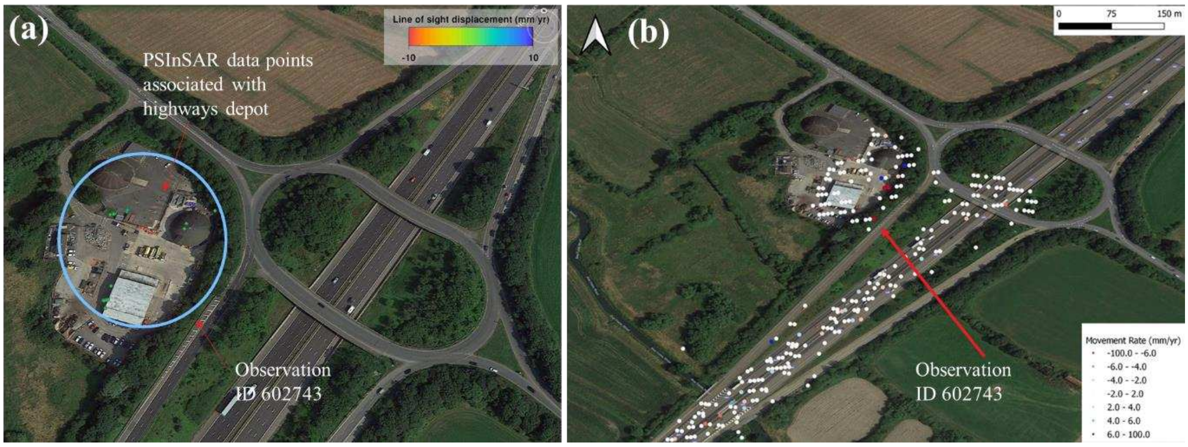

Figure 3: PSInSAR data points for the area around M5 Junction 13, showing data points from two different data suppliers (a and b) (InSAR data: Satsense (b); Map imagery: Google, 2022).

4.2 Ability to assess temporal rates of ground movement

InSAR typically has limited application if ground deformation occurs too fast, is too large or is non-linear. InSAR is typically also more appropriate for characterising relative rates of motion than measuring absolute displacement. Although this was not explicitly assessed in this project, it is known from the literature that it would be unsuitable for picking up sudden, rapid failures (e.g. rock falls, erosion, scour, rapid sinkhole collapse). This is due to the loss of image coherence. To quantify this limitation, if the ground (or structure) movement is greater than half the radar wavelength of 7.5 – 3.8 cm (depending on the sensor being used) over the revisit period (e.g. 6-7 days for Sentinel 1), then this movement could be too great to provide data that is representative of the actual movement. Therefore, InSAR is typically more effective for very slow or extremely slow movements.

InSAR based approaches (both PSInSAR and ISBAS approaches) can provide an early indication of ground movement to National Highways and its supply chain that may not be initially visible during physical Principal Inspections. For example, as shown in the time series in Figure 5 which refers to a depression that rapidly formed on an embankment on the A627(M). In early 2020 (see Figure 5 (b)) there is a rapid downward movement of approximately 30mm in the zone of the depression over 2-3 months.

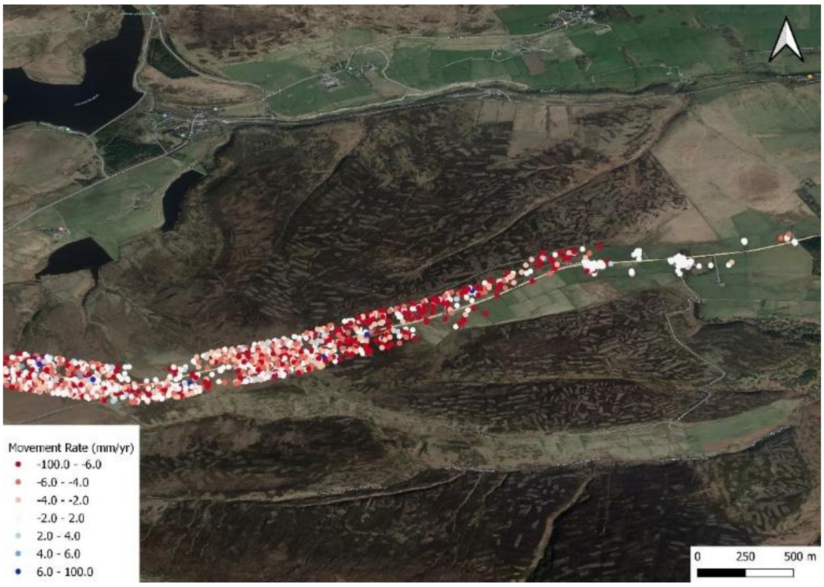

Figure 4: Example of high ground movement rates from PSInSAR data for a section of the A628 near Langsett associated with the Moorland areas visible in the image (InSAR data: SatSense; Map imagery: Google, 2022).

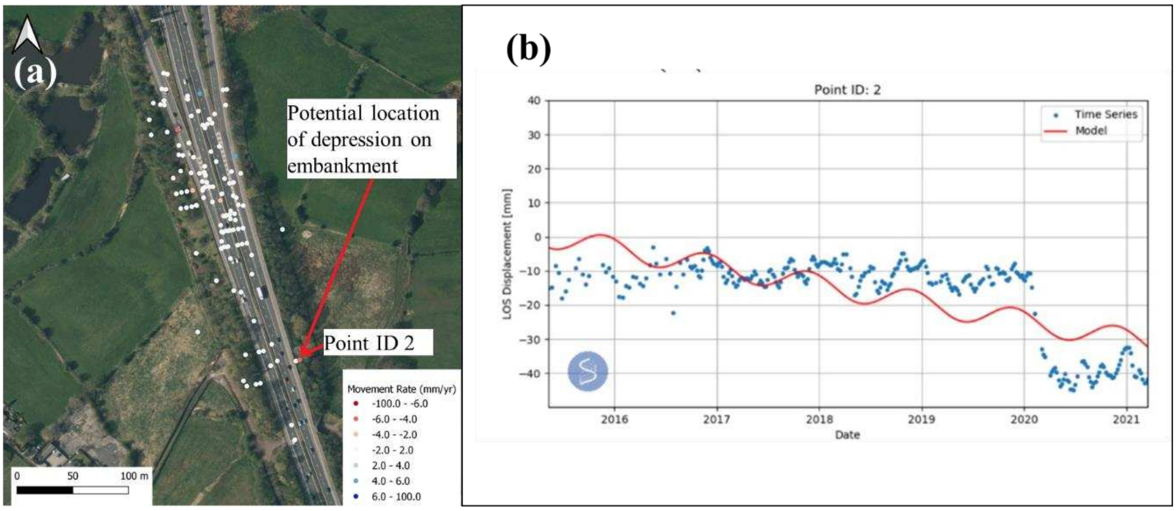

Figure 5: (a) PSInSAR data for the A627(M) near junction 1; (b) PSInSAR data time series plot for point ID 2, showing a high rate of ground movement away from the LOS in early 2020 (InSAR Data: SatSense; Mapping data: Google, 2022).

4.3 Monitoring ground movement outside National Highways boundary

Due to the national coverage of SAR data in the UK, InSAR data can provide National Highways with an opportunity to identify ground movements outside of its boundary, that may impact the operation, safety and performance of the SRN. For example, ground movement known on the A56 at Woodcliffe (see Figure 2) and the M25 example shown in Figure 6; the latter currently not associated with a reported defect and is outside of National Highways boundary. Figure 6 (b) also identifies potential cyclical shrink-swell activity in the London Clay that underlies this location.

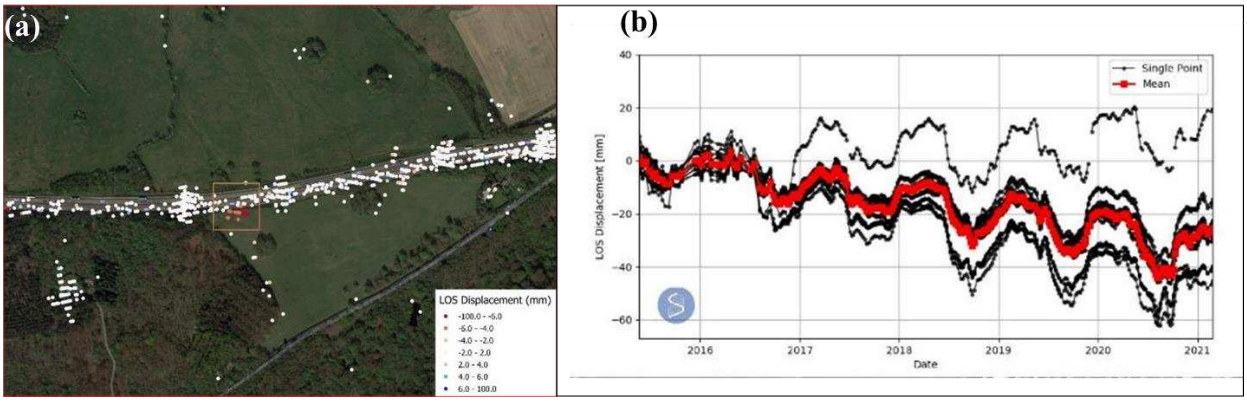

Figure 6: (a) PSInSAR data for a section of the M25 between Junction 26 and 27; (b) PSInSAR data time series of the persistent scatterer cluster shown in orange box in (a) (InSAR Data: SatSense; Map imagery: Google, 2022).

4.4 Monitoring the condition and performance of 'repaired' geotechnical assets

InSAR approaches could potentially be used to monitor the performance of 'repaired' assets. For example, a section of embankment on the M11, that had previously been repaired in June 2008 following slope instability due to desiccation of susceptible clay embankment, had shown no significant movement since being remediated (see Figure 7).

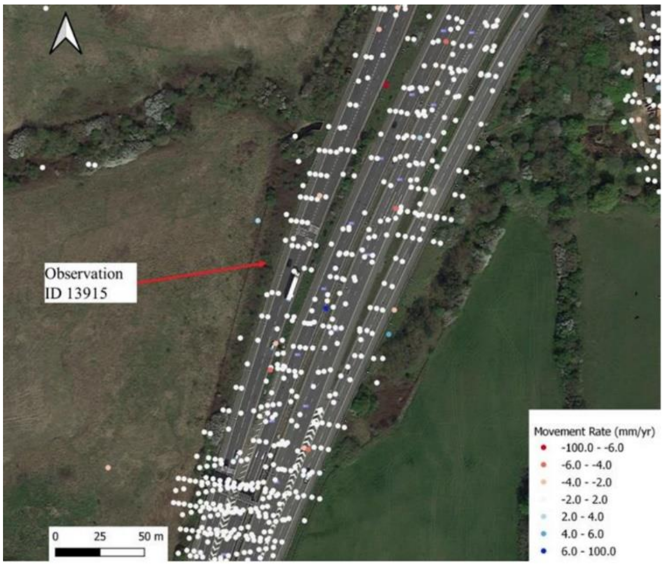

Figure 7: PSInSAR data around GDMS Observation 13915, which represents a site that was repaired in June 2008 following slope instability due to desiccation (InSAR Data: SatSense; Map data: Google,2022.

5. Radar corner reflector installation

Where there is a lack of natural reflectors, in part due to the environment conditions (e.g. densely vegetated slopes), there is an opportunity to design and install artificial corner reflectors. This trial supported the installation of a radar reflector at Flint Hall Farm on the M25 which is a site of previous known instability [ref needed]. This is to understand the potential application of reflectors across the network. Due to the regular repeat surveys, and new platforms coming online, it would be beneficial where possible to integrate the addition of reflectors into the design and construction of new assets or at locations where significant renewals are being planned. This will not only allow an assessment of the design post-construction but will also provide a long-term repository of ground movement data for a particular geotechnical asset.

An MSc project at Imperial College titled 'An Investigation Into Surface Deformation At Flint Hall Farm using InSAR and In-situ Monitoring Data' is going to explore the reflectors application going forward.

Figure 8: Installed trihedral reflector at Flint Hall Farm, M25 (Source: AECOM).

6. Conclusion

InSAR has the potential to offer geotechnical asset managers and engineers the ability to highlight previously unknown issues by providing greater spatial coverage (entirety of UK) at a higher temporal frequency compared to traditional walkover inspections. For example, some geotechnical assets deemed 'low risk' might only be inspected once in a 10-year period.

From the trials outlined in this paper, using Sentinel-1A and 1B raw SAR data, the following conclusions can be drawn:

- **InSAR can potentially support Principal Inspections and the prioritisation of inspections.** Especially where constrained access and where environmental conditions are suitable.
- However, **InSAR should be used to complement a range of other inspection and monitoring techniques** (e.g. LiDAR, aerial imagery, visual inspections). This is because small-scale features (e.g. defective drainage) that could result in asset performance issues may be missed by remote sensing alone.
- Due to the varied approaches in SAR data interpretation to derive InSAR products, National Highways and its supply chain should **engage with multiple suppliers to understand whether the approach would be suitable to derive ground movement rates** for the particular asset/route/region.
- **Where InSAR applications are limited due to the environmental conditions, radar corner reflectors may be used** to support the inspection of geotechnical assets. However, the ISBAS approach showed greater coverage in rural areas compared to PSInSAR approaches.

- **Further assessment is needed to look at the efficacy of the radar corner reflector installed at Flint Hall Farm**, as the timescales of this project have not allowed for sufficient data capture since installation. This will to a large extent be addressed in MSc and PhD research being undertaken by Imperial College London.

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