Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Practical remote survey applications for improved geotechnical asset management on England's strategic road network

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Abstract

Highways England operates, maintains and improves England's strategic road network (SRN). The SRN is supported by 50,000 geotechnical assets comprising embankments, cuttings and natural slopes. Delays and congestion on the SRN have significant economic impacts. Therefore, well maintained geotechnical assets, through proactive monitoring, are key to a safe, serviceable and smooth running network. Geotechnical asset condition, assessed through visual inspection, is costly, time consuming and can impact on safety. This paper assesses the application of remote survey techniques for monitoring geotechnical assets on the SRN using several pilot studies. Techniques investigated include LiDAR, InSAR, hyperspectral imaging and aerial photography. Combinations of techniques show promise for geotechnical asset management, with some being limited in their potential application. Conclusions presented will provide Highways England and others understanding of which remote survey techniques provide greatest practicality, benefit and cost effectiveness for day-to-day management of geotechnical assets and ultimately ensure a more resilient and safer road network.

Keywords: Sensors; Monitoring; Maintenance; Asset Management.

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1. Introduction

England’s Strategic Road Network (SRN), comprising motorways and trunk roads spanning almost 7,000 road kilometres, is operated, maintained and improved by Highways England. The availability of a safe and reliable SRN is critical for the UK economy. The SRN only represents 2% of England’s road network, but carries one-third all road and two-thirds of freight traffic (Highways England, 2015). As such, road closures and delays on the SRN result in average annual economic costs of £2 billion (DfT, 2014).

Geotechnical assets, which provide a cost-effective method of forming topographical change along highway corridors (Vardon, 2015), comprise embankments, cutting and at-grade sections (Figure 1). Approximately 50,000 geotechnical assets support the SRN. However, ageing assets, imperfect knowledge of their condition, limited resources, increasing traffic volumes and increasing environmental pressures (e.g. climate change) present constant constraints on asset owners (Glendinning et al. 2009). New innovative methods are therefore being sought to develop knowledge relating to asset condition and deterioration across their whole lifecycle to improve efficiency and ultimately increase an assets resilience to a range of external perturbations.

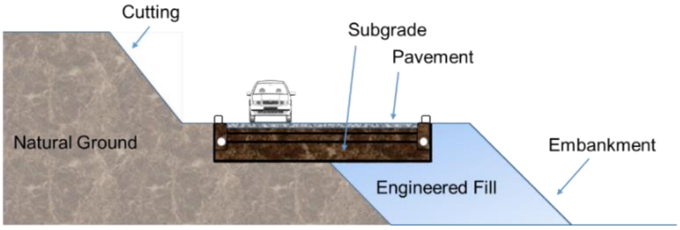


Figure 1: Definition of a geotechnical asset (Pavement and Subgrade included for context)

This paper aims to assess the practical application of remote survey (or sensing) technologies for improving Highways England’s geotechnical asset management, while also considering drainage assets, on the SRN through a series of pilot studies. Remote sensing is defined as ‘*gathering information from a distance*’ (Campbell and Wynne, 2011). Section 2 of this paper describes how Highways England understands and manages geotechnical hazards on the SRN. Section 3 provides a summary of remote sensing techniques in the context of highways asset management. Section 4 presents several pilot studies across a range of geotechnical asset types that present the potential application of remote sensing techniques on geotechnical assets. Finally, presented in Section 5 are the discussion and conclusions of the findings in terms of their practical application for improved geotechnical asset management on the SRN.

2. Understanding and managing geotechnical hazards on the SRN

Geotechnical assets typically have long design lives compared to other asset groups and can be up to 60 years. Often the design life may be extended through proactive maintenance for improved whole life costs. The SRN’s geotechnical assets are relatively young, compared to those of other similar asset owners, having been predominantly constructed since the late 1960s and are therefore designed and engineered to modern standards. This makes them generally resilient to a range of hazards and triggers (e.g. severe weather). Nonetheless, this should not lead to complacency within Highways England. A combination of ageing assets and a predicted increasing frequency of more extreme weather events, due to climate change, could prompt geotechnical assets to enter a *degenerating* phase without appropriate and timely interventions. There is growing concern regarding the longer-term sustainability of highways earthworks and potential climate change impacts (Miller et al. 2012). Thorough assessments of existing geotechnical infrastructure and changing environmental conditions are important for more efficient investment approaches (Vardon, 2015). Furthermore, Glendinning et al. (2015) state that Highways England need to understand those geotechnical assets requiring smaller interventions to improve their long-term resilience to severe weather and climate change impacts.

Ongoing research within Highways England, as part of the Geotechnical Hazard Development Programme, is working towards improving the knowledge of its asset base, to gain a better understanding of underlying ground-related hazards, known vulnerabilities and criticality of the SRN with the aim to develop a holistic cross-asset assessment process, to which geotechnical assets contribute. The SRN is subject to a number of ground-related hazards, defined as geological and environmental hazards which can lead to widespread damage and risk to human life and the built environment. These ground-related hazards can be triggered by several human and naturally induced events. However, there is current uncertainty as to the deterioration of geotechnical assets over their lifecycles, that results from the heterogeneity of ground conditions. Such hazards include:

- Natural hazards – Ground-related hazards relating to the natural environment in which the road is located (e.g. sink holes, compressible soils, or pre-existing landslides).
- Man-made hazards (non-road related) – Ground-related hazards not relating to the presence of the road network (e.g. mining, quarrying and landfill).
- Man-made hazards (road related) – Ground-related hazards relation to the presence of the road (e.g. over-steep slopes in earthworks).

Definitions, inspections and maintenance prioritisation for Highways England's geotechnical assets are currently undertaken in accordance with the standard HD41/15 '*Maintenance of highway geotechnical assets*' which forms part of the Design Manual for Roads and Bridges (Highways England, 2015). Highways England are supported in network management by twelve service providers who are responsible for the production of Geotechnical Asset Management Plans (GeoAMPs). GeoAMPs should include an assessment of hazards, geotechnical asset information, network criticality and proximity to other asset groups. Geotechnical assets are currently inspected using a risk-based approach. Typically, asset inspections are undertaken every 5 years, which is increased to annual inspections (or even more regularly) on the highest-risk assets and up to every 10 years on the lowest-risk assets.

3. Remote sensing for highways asset management

Geotechnical assets with a known history of geotechnical issues are monitored through increased physical inspections (see Section 2) and sometimes by in-situ instrumentation. Both of these methods can be costly, time consuming and will likely impact on road user safety and cause network disruption where there is a need for traffic management. In-situ monitoring isn't suitable for 'route-level' assessments of asset condition due to high labour and interpretation costs and the relatively low spatial resolution of information. Highways England therefore want to understand the potential of remote sensing applications as a more pervasive technique which can provide improved understanding of the asset base and its condition over wider spatial areas. Furthermore, the ability to be able to identify potential ground-related hazards at a stage where prioritisation of appropriate mitigation can be undertaken before asset performance is compromised is of value.

Remote sensing applications for highways asset management is not necessarily new, but many approaches remain untried for the monitoring of engineered slopes (Smethurst et al. 2017). More commonly, such approaches have been used for highway asset inventory purposes (e.g. Gong et al. 2012). Highways England have previously investigated the use of LiDAR for geotechnical assessment (e.g. Duffell et al. 2003). The United States Department of Transportation has also funded research into the use of remote sensing applications for geotechnical assessment (Wolf et al. 2015). Wolf et al. argued that remote sensing offers the potential to continuously or frequently assess the assets' performance, as required by the highways authority. For a more comprehensive review of remote sensing techniques within geotechnical asset management, the reader is directed to Ní Bhreasail et al. (submitted) and Toth and Jozkow (2016) for a more general overview.

4. Pilot studies

A number of pilot studies were undertaken across the SRN to understand the practical application of remote sensing for geotechnical asset condition and performance monitoring. Site selection and the techniques investigated were constrained by data availability, which is detailed in Section 4.1. Sites were selected to provide a full complement of different geotechnical asset types, including engineered embankments, cuttings (Figure 1) and natural slope(s). Furthermore, a trial into the use of hyperspectral data to monitor geotechnical asset and drainage condition was undertaken. Selected sites and their relative locations are presented in Figure 2.

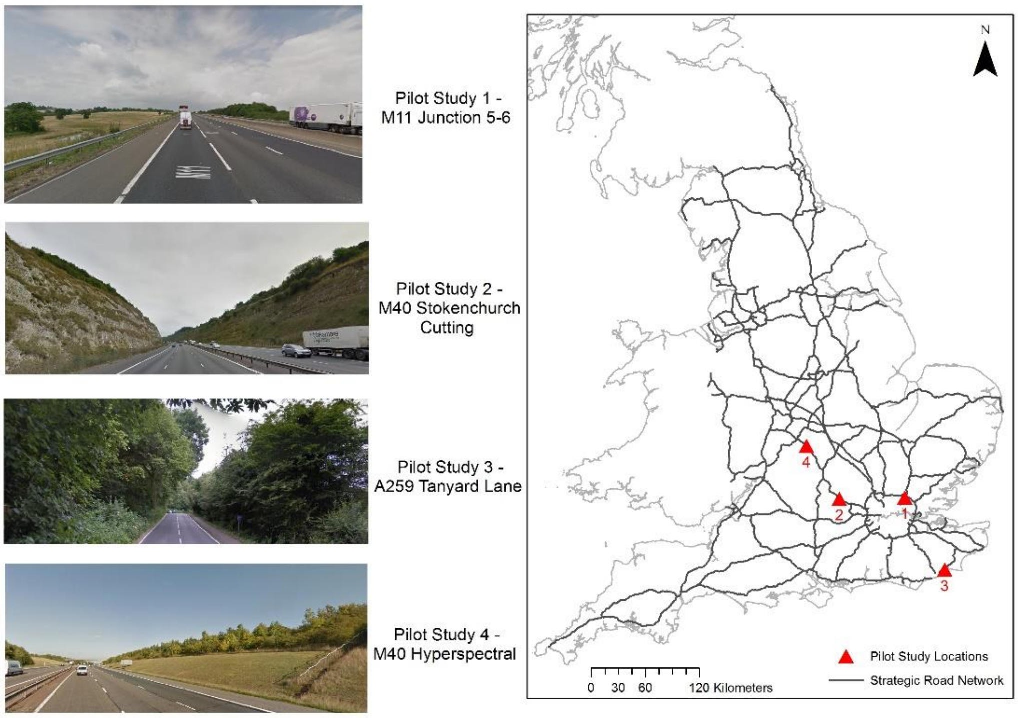


Figure 2: Pilot study locations on the Strategic Road Network (Images from Google StreetView)

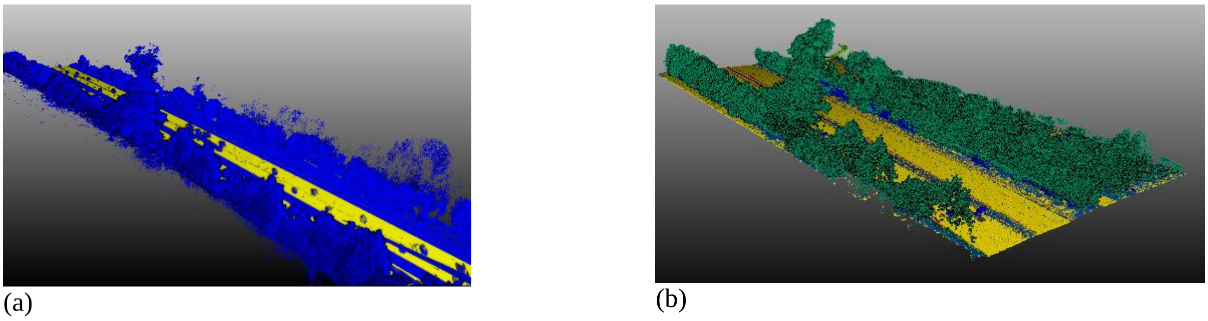
4.1 Data: summary and issues

Multiple datasets were brought together and assessed for each pilot location. This paper provides the reader with an overview of the most relevant techniques for each pilot location. A number of data issues were consistent across the pilot studies and this section provides a summary of those issues to avoid repetition throughout the paper, and are described in Table 1. It should be noted that these comments are relevant to data either owned by Highways England or made accessible at locations identified for pilot studies, and are specific to their application on the SRN.

Table 1: Remote sensing data summary and issues

Technique	**Data summary and issues**
LiDAR	LiDAR datasets were provided in raw point cloud format. Highways England have previously procured a number of LiDAR datasets, obtained using vehicle-mounted terrestrial and aerial rotary-wing mounted platforms. Point clouds were classified by the data supplier and were only assessed for their practicality in this work, and no reclassification was attempted. The classification of the vehicle-mounted LiDAR showed that principally the data had been collected for other asset groups (i.e. pavements). This was exemplified with only the carriageway being classified as ‘ground’, whereas all other features were classified as one layer, which makes extraction of ground features (i.e. geotechnical asset) difficult to differentiate from vegetation for example (e.g. Figure 3a). This makes routine geotechnical asset assessment difficult in its current classification, however this could be reclassified by the supplier. Conversely, the aerial LiDAR had an improved classification system (compared to the vehicle mounted), which allowed segregation of specific classes (e.g. carriageway, vegetation, ground, etc.) (Figure 3b). LiDAR data was viewed and manipulated using the open-source Cloud Compare software (Cloud Compare, http://www.danielgm.net/cc/). Change detection analyses presented in the pilot study examples was undertaken using the same programme.
Multispectral imagery	Multispectral data obtained from the Sentinel 2A platform (ESA, 2017) was assessed. The spectral resolution (10m) did not prove adequate for understanding the condition and performance of individual assets. This technique has not therefore been considered further. Higher resolution multispectral imagery is available. Sentinel 2 data may have applications for understanding more regional issues, such as the impact of flooding on the SRN and its geotechnical assets, which requires additional analysis.

InSAR	Interferometric synthetic aperture radar (InSAR) is an imaging technique that uses two or more SAR images to detect and measure centimetre and millimetre scale surface deformation over time (Bovenga et al. 2006). A more comprehensive overview of InSAR and its applications is provided in Ní Bhreasail et al. (Submitted). InSAR data was processed using both Persistent Scatterer (PS) and Distributed Scatterer (DS) technologies by CGG (www.cgg.com/npa). InSAR results were provided by the National Physical Laboratory as part of the PLIMM project. At a high level, the PS method provides a few number of highly reflective points at consistent locations, with low measurement uncertainty. Conversely, the DS method produced a greater number of points, but with higher average uncertainty. The application of InSAR is explored in Section 4.2.
Aerial imagery	Aerial imagery is typically collected alongside aerial LiDAR, and is an established method. Highways England have procured aerial imagery at a range of spatial resolutions ranging from 4cm to 12.5cm. This data will be explored through Sections 4.2-4.5.
Hyperspectral imagery	Hyperspectral imagery acquires data across hundreds of discrete portions of the electromagnetic spectrum, as individual narrow spectral wavebands of typically 5-10nm. It differs from multispectral imagery (Section 4.1.2) whereby only typically 10-15 discrete spectral bands are provided. Hyperspectral imagery was procured by Highways England as a trial for the entirety of the M40. The driver for procuring this dataset is based on a need to better understand the location and condition of drainage assets. Drainage plays a key role in ensuring geotechnical asset performance.


(a)

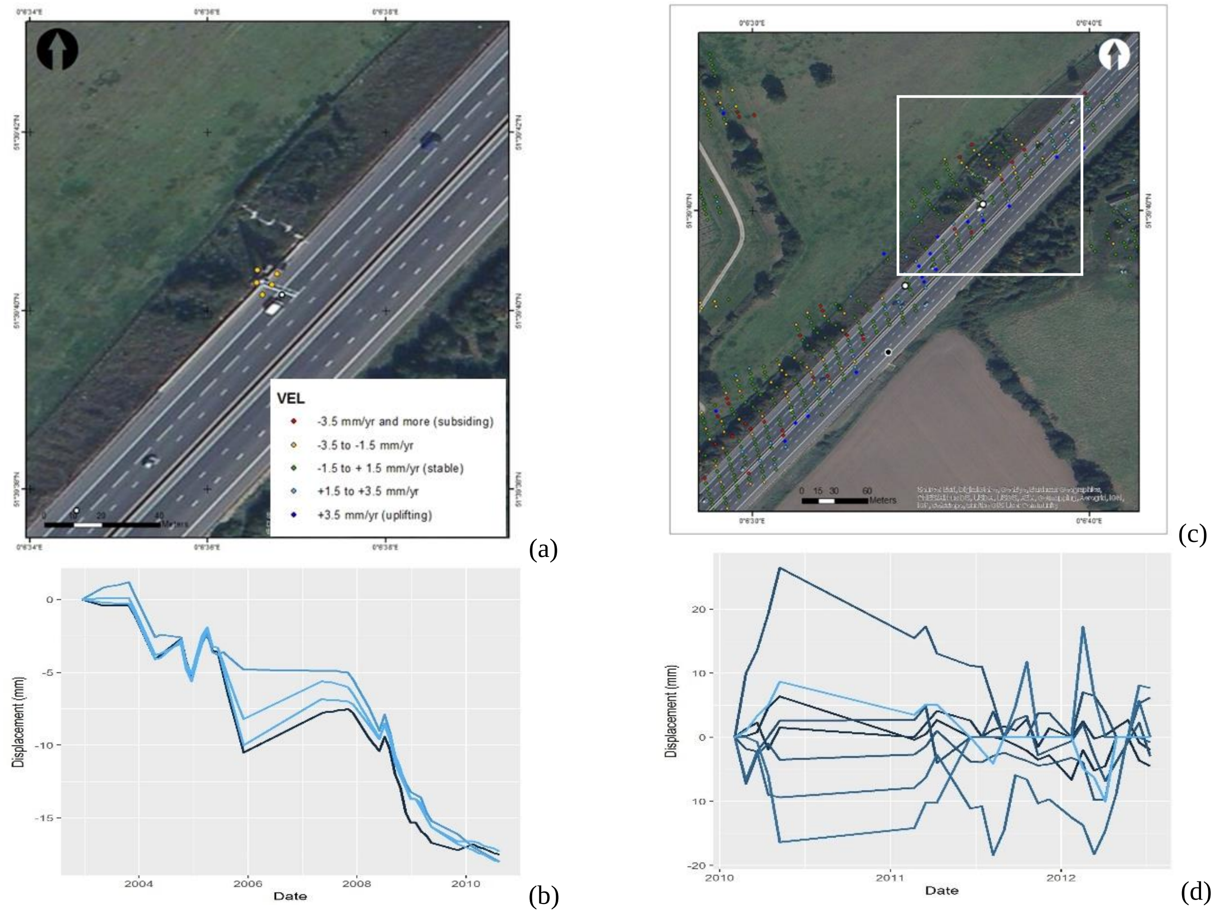
(b)

Figure 3: Example of differences in LiDAR classification for (a) vehicle-mounted and (b) aerial-mounted LiDAR retrieval (different colours represent different classifications).

4.2 Pilot study 1: M11 between Junctions 5 and 6 – Soil Embankment

A section of embankment on the M11 motorway between junctions 5 and 6 was used to assess the potential for InSAR to understand slope deformation. This section of bi-directional, three lane motorway is located on the outskirts of Greater London, connecting London with Cambridge (Figure 2). The embankment has previously witnessed a number of slope stability issues in 2003, 2010 and 2012. The embankment was remediated through the installation of sheet piles in 2014.

InSAR data was made available spanning the period 2002-2012, which allowed for analysis of embankment before and after failure. The PS InSAR data for the period 2002-2010 showed few reflective points associated on and around a sign gantry structure, which is a small scale feature, spanning an area of only 50-100m (Figure 4a). No other points were recorded on the section of the M11 studied, which identified the method as being limited in this rural location. An average ground movement of -1.5—3.5mm per year was recorded by the sensor, with approximately 6-8mm occurring between 2008 and 2010 which is contiguous with the slope stability events recorded (Figure 4b). However, a lack of ground-truthing (e.g. repetitive topographical survey or visual inspection) limits data certainty. Conversely, the DS InSAR data for the period 2010-2012 produced a greater number of points (Figure 4c), which covered the embankment slopes and carriageway. These were however limited by their relative uncertainty across points which showed significant variations in recorded movement for several areas known to be ‘stable’ (Figure 4d). The results presented here are based on historic InSAR data only and do not include new data from Sentinel missions which commenced in 2015. Sentinel-1 is now acquiring data every 6 days across the whole UK. Seasonal trends and long-term baselines can be extracted for the first time using this latest type of analysis but has not been covered in this paper.



(a) (b) (c) (d)

Figure 4: (a) PS InSAR points for section of M11, Junction 5-6; (b) time series of PS InSAR points (2002-2010); (c) DS InSAR points for M11, Junctions 5-6 with location of (a) marked by white box; (d) time series of DS InSAR points (2010-2012) (Source: NPL and CGG).

4.3 Pilot Study 2: M40 Stokenchurch Gap – Rock Cutting

Stokenchurch Gap is a steep sided chalk cutting on the M40 motorway constructed in the early 1970s. It is approximately 1,200 m long and 47m in depth at its deepest point (Figure 2). A bi-directional, three lane motorway passes through the cutting and links Birmingham and Oxford to London. Significant weathering of the chalk bedrock since asset construction has previously led to rockfalls which has led Highways England to install rockfall mitigation fencing and a catch-pit at the base of the cutting to decrease the risk of hazards to the road user. For this location, high resolution aerial imagery as well as aerial and ground-based LiDAR datasets were available. Analysis of these datasets is presented below.

High resolution (5cm) aerial imagery, obtained in 2015, provides a detailed view of the cutting (see extract in Figure 5a). A potential rockfall has been identified from the image (see Figure 5b). Three LiDAR point cloud datasets were available for the site. Two sourced from terrestrial vehicle-mounted (2014 and 2015) and one from rotary wing (2015) platforms. Due to the classification issue outlined in Section 4.1.1, it was not possible to create a true ground layer. Therefore, change detection analyses were undertaken to understand the differences between each of the LiDAR scans that included all classification types (e.g. vegetation, ground, street furniture etc.).

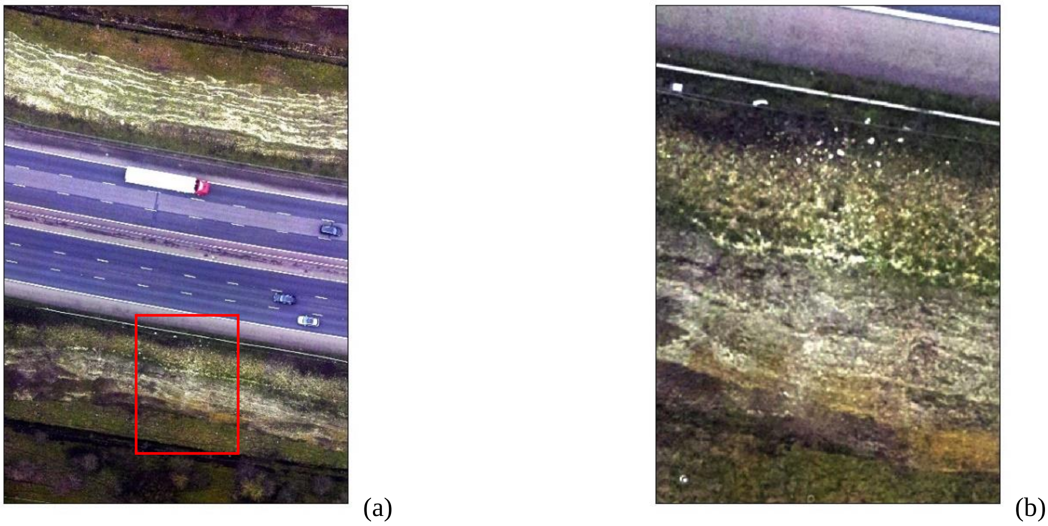


Figure 5: High Resolution (5cm) aerial imagery of the M40 Stokenchurch Gap. (a) shows a potential rockfall (location of (b) indicated by red outline) and (b) shows a zoomed in view of this area.

Comparison between the terrestrial vehicle-mounted (2014) and the rotary wing (2015) LiDAR datasets originally revealed stark temporal changes in the cutting face. However, further analysis revealed that this was a result of missing data in the rotary wing LiDAR, especially where the chalk cutting face had significant overhangs (see Figure 6a where dark patches represent no data, compared to Figure 6b). This shows that it is difficult to accurately compare aerial and terrestrial LiDAR within a rock cutting. Comparison of the two terrestrial vehicle-mounted LiDAR datasets, which were captured by the same instrument, revealed more understandable changes between the two surveys. For example, a particular change was witnessed in the growth of vegetation between these years (e.g. Figure 6). Unfortunately, these LiDAR images were not supported by aerial imagery, with only the 2015 rotary-wing LiDAR having corresponding imagery.

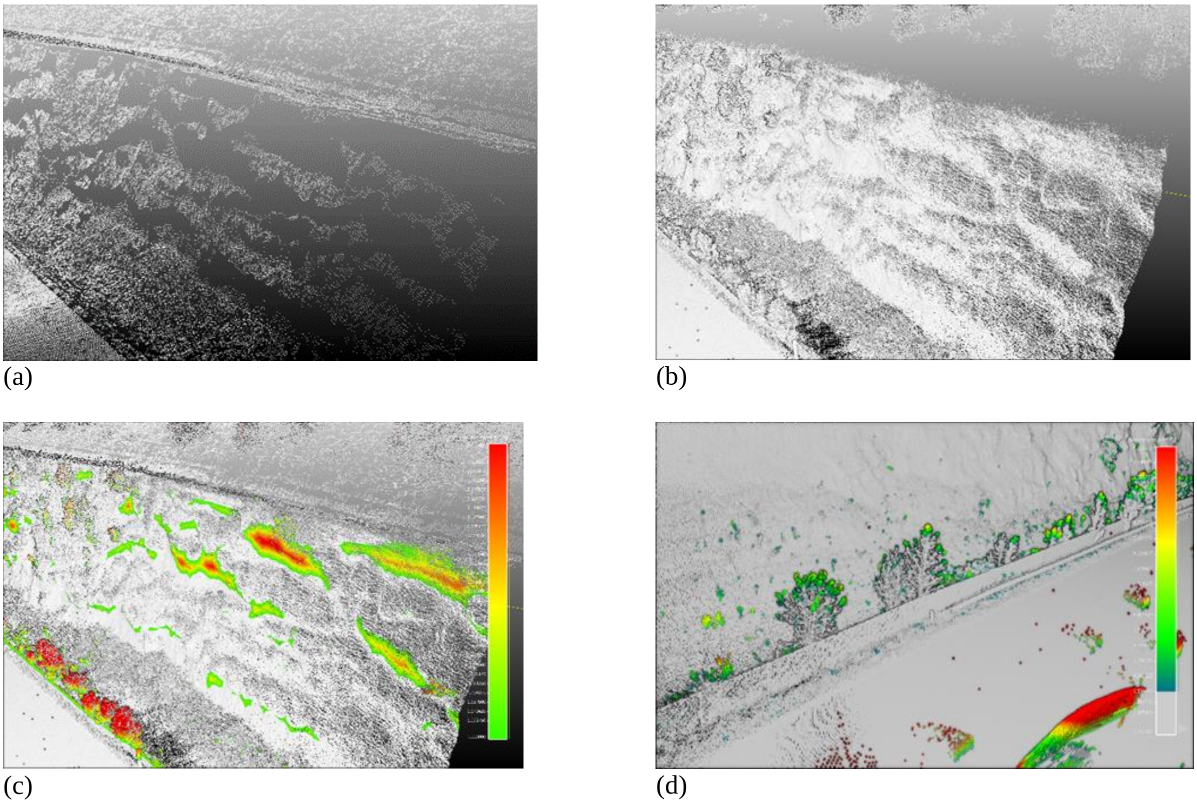


Figure 6: (a) LiDAR point cloud of 2015 aerial wing data; (b) LiDAR point cloud of 2013 vehicle-mounted data; (c) change detection between 2013 vehicle-mounted and 2015 aerial LiDAR surveys; (d) Change detection between 2013 and 2015 vehicle-mounted surveys revealing vegetation growth (red is greater change than green; a,b & c captured in same location)

Therefore, it was difficult to understand whether subtle changes in the cutting face were attributed to the detachment of chalk material. However, the method for change detection between similar LiDAR datasets revealed that this technique has promise for future asset inspection in a cutting environment.

4.4 Pilot Study 3: A259 Tanyard Lane, Kent – Natural slope (soil)

The A259 at Tanyard Lane is a single lane carriageway located near the town of Winchelsea, Kent (Figure 2). This site represents a natural slope rather than an 'engineered' asset. The area is heavily vegetated and in a rural location. During 2015, a mudslide was recorded at the location, leading to the movement of material downslope, along with the displacement of medium sized trees. The mudslide reached the side of the carriageway but fortunately did not encroach on it.

An aerial rotary wing LiDAR survey from 2016 was analysed to understand what information could be provided about the natural slope. Terrestrial vehicle-mounted LiDAR proved problematic due to the dense vegetation and inability to capture the entire natural slope and so was not considered further. LiDAR point cloud densities of the aerial data were relatively low, especially where dense vegetation was witnessed (see Figure 7a and b). However, a slope profile was obtained from the data (Figure 7d), in addition to high resolution contours (Figure 7c). This information can provide an idea of potential slope instabilities and where drainage assets are located and/or are required. Aerial imagery was also assessed and was also limited by the dense vegetation obscuring the ground and road surface.

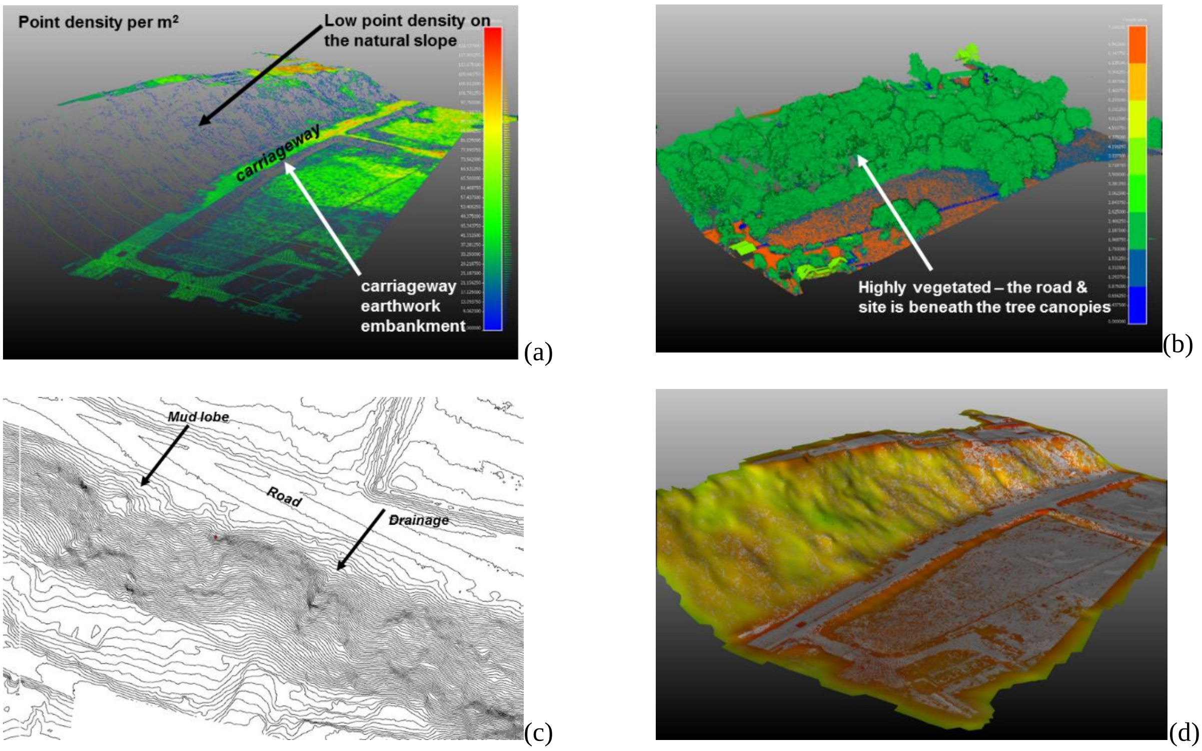
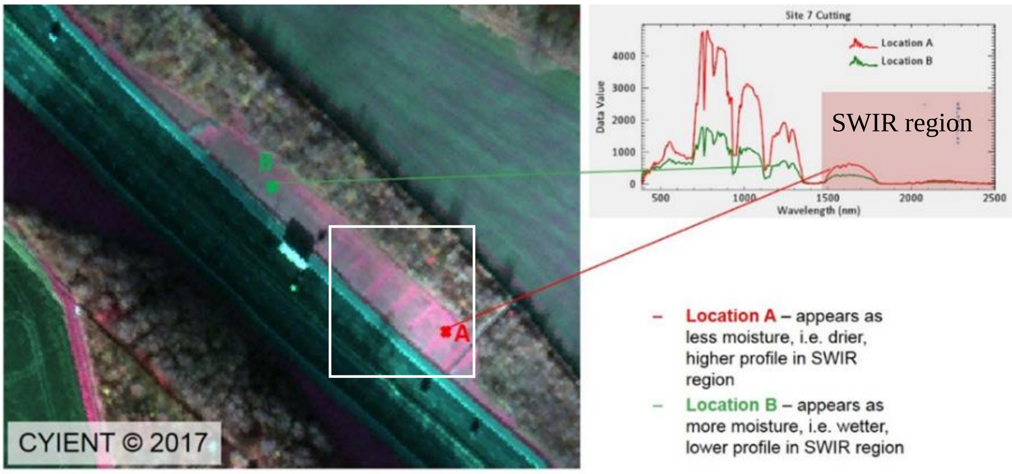


Figure 7: Results of LiDAR processing at A259 Tanyards Lane. (a) point density per m2 of 'ground' points; (b) point cloud with all classifications included; (c) 25cm contours derived from LiDAR data; (d) 3D surface interpreted from 'ground' point cloud data.

4.5 Pilot Study 4: M40 – Understanding the potential application of hyperspectral imagery

Highways England recently procured hyperspectral imagery for the M40 motorway. This is a response to the Department for Transport's requirement for Highways England to better understand the location and condition of their drainage assets (DfT, 2014). Drainage is important for the continued performance of geotechnical assets therefore, a method to improve knowledge of location and condition will benefit multiple Highways England's asset groups. Analysis showed that the survey capture date of January 2016 was not wholly suitable for many locations due to low sun angles. Hyperspectral imagers are passive sensors requiring sunlight to produce natural emissions from the earth's surface. Consequently, low sun angles resulted in extensive shadowing, especially in cuttings which made data unusable (e.g. Figure 8 where dark shadowing seen to left side of carriageway). Several locations were evaluated along the M40. Figure 8 shows the techniques potential to identify counterfort drainage (distinct purple lines running perpendicular to slope) within a remediated slope. Figure 8 shows that for Location

A, where drainage is present (distinct purple lines within white box) that there is a drier ground surface. This is indicated by dark purple colour and distinct Short Wave Infrared (SWIR) wavelength (see graph in Figure 8) above 1500 nm. In comparison, Location B which has no drainage shows up as having a wetter ground surface, which is indicated by lighter purple/green colour and distinct SWIR wavelength. These results imply that the drainage is working efficiently. However, they have not been validated by in-situ measurements.



- **Location A** – appears as less moisture, i.e. drier, higher profile in SWIR region
- **Location B** – appears as more moisture, i.e. wetter, lower profile in SWIR region

Figure 8: Hyperspectral imagery from the M40 showing colour infrared band combination revealing vertical cutting drainage present within the white box. Graph shows wavelength of Location A (red line) and B (green line) (Source: Cyient Ltd.)

5. Discussion and conclusions

This paper has assessed the potential application of several remote sensing techniques for geotechnical asset management on the SRN through a series of pilot studies. Findings were shown to be broadly in line with other studies (e.g. Wolf et al. 2015). Techniques have also been assessed against a set of key parameters that will guide their potential uptake going forward; summarised in Table 2. However, this information is applicable to data assessed, and conclusions are specific to the SRN.

Table 2: Remote sensing data summary matrix (H = High, M= Medium, L=Low)

	Data coverage	Data availability	Data quality	Ease of analysis	Frequency of survey	Cost	Geo-hazard detection /monitoring
Terrestrial vehicle-mounted LiDAR	H	H	L	L-M	H	M	L
Aerial rotary wing vertical photography (5cm)	H	H	M-H	H	M	H	H
Aerial rotary wing LiDAR	H	H	H	L - H	M	H	H
Aerial hyperspectral imaging	L	L	M	L-M	L	H	M
InSAR	L	L	L	L	H	M	L-M

Remote sensing presents infrastructure owners and operators with several tangible benefits. Improved understanding of asset condition is possible through higher temporal and spatial monitoring supplementing traditional visual inspections. This potentially provides Highways England with an ability to identify minor defects before they become significant, supporting proactive asset management approaches. More timely interventions will lead to improved efficiency and reduced whole-life asset costs. Highways England aspire to have a semi-automated approach to asset management going forward, whereby remote sensing data can be used as a predictor to potential performance failures. However, engineering knowledge would still be implicit in such processes. These combined will increase customer and personnel safety through reduced exposure to traffic management and those previously unforeseen incidents.

Highways England face a number of challenges in bringing remote sensing into day-to-day geotechnical asset management. These include the ability to manage and store large datasets, especially as network-wide surveys are procured. Once data is collected, complex analysis and interpretation is often required, which may not be available to the organisation. Furthermore, it is recognised that a combination of techniques will prove most beneficial, especially when trying to identify specific or a range of potential hazards. This study has also highlighted the issue of trying to combine and compare datasets (e.g. aerial and terrestrial LiDAR), which may be of different spatial resolutions, therefore consistent approaches to acquisition are required going forward. Additionally, this paper has investigated areas of known geotechnical issues, and so trying to anticipate areas where events have not occurred has not yet been trialled. Remote sensing data has application across multiple asset groups. Data previously procured by Highways England was not solely intended for geotechnical applications. However, asset groups have different requirements and challenges. This makes obtaining information which is applicable for understanding a range of issues problematic. Soft estates (e.g. vegetation management) for example ideally require surveys to be undertaken in summer when vegetation growth is at its maximum. Conversely, geotechnics ideally require surveys to be undertaken in the winter when vegetation cover is reduced and more of the ground can be seen by the appropriate sensor. However, acquiring hyperspectral imagery (Section 4.5) during winter months can have limited use, especially for such passive sensors.

Despite appropriate and more diverse remote sensing data sets becoming more readily available, there remains a disparity between the availability of such data and their intelligent utilisation with respect to information extraction and the delivery of practical toolsets for end users (i.e. transport asset managers) (Miller et al. 2012). Therefore, there is a need for effective knowledge transfer between remote sensing experts and transport professionals (Cigna et al. 2017). Developing toolsets which can learn from the pilot studies presented here, will be a key step in fostering the wider adoption of remote sensing techniques investigated.

Acknowledgements

The authors acknowledge considerable contributions of their combined colleagues, across a range of organisations, to the work described in this paper; Aecom for their contributions to this research task; Cyient Ltd for undertaking hyperspectral analysis on the M40; NPL and CGG for providing and processing InSAR data and Atkins for identifying the M11 location. The work described in the paper is funded through the Highways England Innovation Programme.

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