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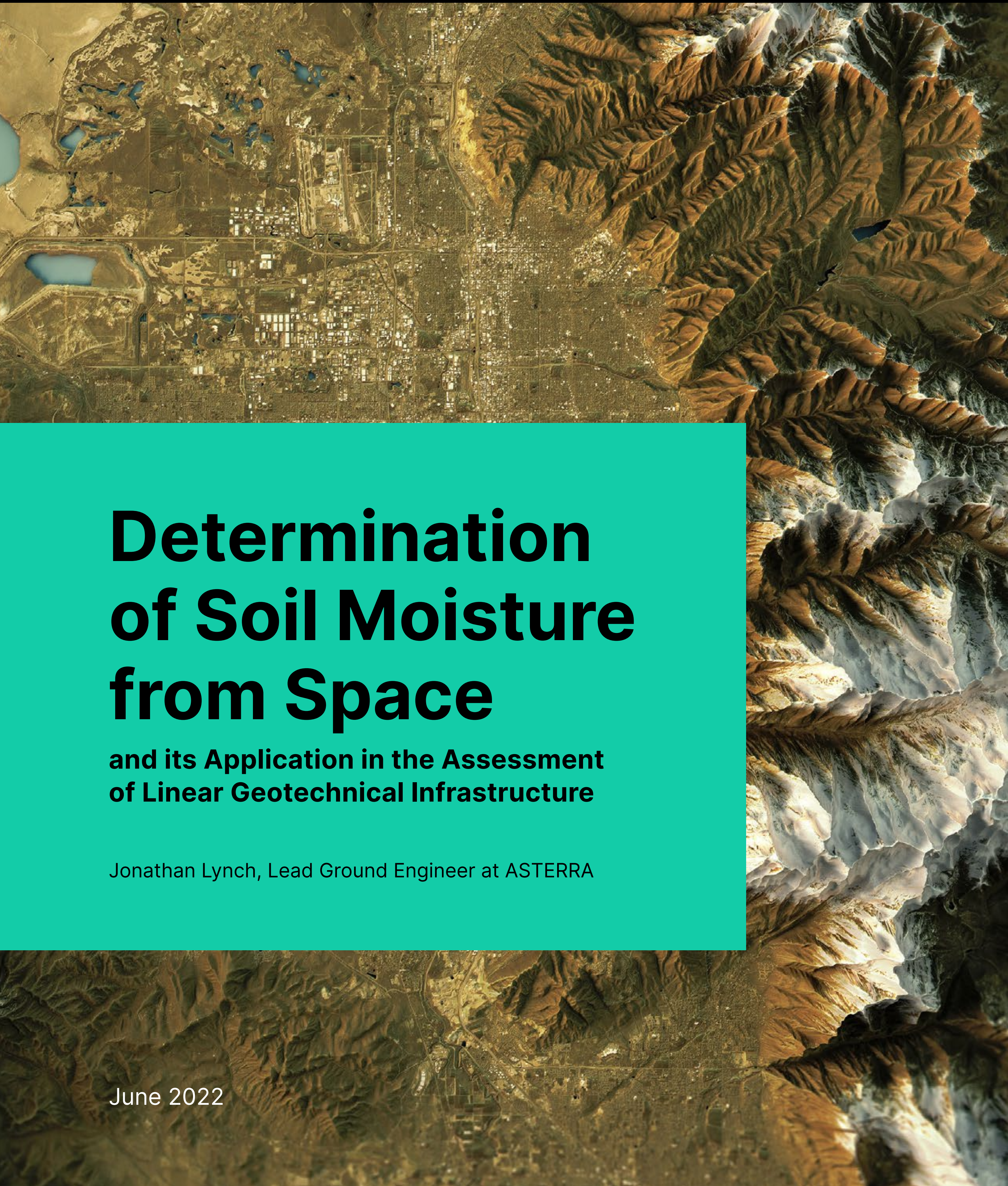

Determination of Soil Moisture from Space

and its Application in the Assessment of Linear Geotechnical Infrastructure

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Introduction

UK linear infrastructure has been severely tested by recent extreme weather events. The results of which have caused delays, significant remedial works (**Figure. 1**), and have tragically been the cause of fatalities.

Figure 1. Rail Insider Magazine, August 2020

Ongoing weather patterns such as the extreme summer and winter rainfall events and increases in rainfall annually, generally acknowledged to be caused by climate change (DfT Resilience Report, 2014), are but one of the challenges facing long linear geotechnical infrastructure going forward. Other challenges include the adaptation to Net Zero Carbon and the changes in mind set required to accommodate this, plus the threat of the unknown collapse features such as sink holes and unrecorded mine workings.

Geotechnical assets along linear infrastructure are exposed to many complex site-specific characteristics depending upon the environment in which they are sited. They can traverse several hundred kilometres through many different landscapes, changes in topography, soil and bedrock type and meteorological conditions throughout their route. If one part of the infrastructure chain is broken by any sort of failure, the consequences both upstream and downstream from that broken link can be considerable and costly.

Edinburgh-Glasgow line closed for two months after canal breaches its banks, severely damaging railway

The introduction of remote sensing techniques such as InSAR and L-Band SAR analytics have been instrumental in the development of large-scale spatial monitoring along areas of interest.

InSAR is providing benefits of being able to see incremental movements along geotechnical assets as they occur and potentially triggering alarms depending upon the monitoring set up. This deformation monitoring method is well understood for known problem areas and can assist engineers in decision making. However, with the onset of the climate change the benefits of seeing potential problematic areas along geotechnical assets before they become significant problems or indeed fail altogether is certainly of interest for any asset manager.

It is well know that the costs to repair landslips once they have occurred is significantly more than preventative maintenance. It has been estimated that emergency repairs of Network Rail lines cost 10 times more than planned works, and this in turn cost 10 times more than regular maintenance (Glendinning et al, 2009). Therefore preventative maintenance before the onset of failure is high on the priority list for asset managers, so prolonging asset lifespan and decreasing potential future costs.

Identifying those areas where potential failure may occur has not been easy. Asset managers have relied upon engineers walking along roads and railways identifying signs of potential failures. Installing monitoring equipment and capturing data over long time periods, often manually downloaded, or more recently automated where budgets are available. These installations often involve lane or track closures, working weekends and night shifts to complete the work with minimum disruption to the public users.

L-Band Synthetic Aperture Radar (SAR) can identify the specific dielectric signature of water type, mixed with soil. This specific wave length allows enables the differentiation between different types of water such as groundwater and saline water (Gadani et al, 2012). L-Band SAR is satellite based and able to see through clouds and rain, day and night, it can penetrate tree cover, dry snow and ice, and urban surfaces such as asphalt and concrete, to see into the soil layer capturing the soil moisture levels from dielectric properties which differ depending upon water type. ASTERRA EarthWorks patented algorithms allow L-Band SAR data to be converted to soil moisture content and displayed as contoured plans for engineers and asset owners to visualize potential areas of concern and verify existing problem areas.

The EarthWorks product provides a soil moisture map **(Figure 2)** for the user with specific information containing shallow soil moisture content within any area of interest specified by the user, be it linear infrastructure or large site development areas without setting foot on the ground. Contoured soil moisture heat maps are created enabling the asset owner and engineers to assess and target their inspections of known problem areas and importantly unknown problem areas for both earthwork assets and drainage. The user can either view the information within a GSI Cloud provided by EarthWorks or choose to export the data to any GIS system to perform further geospatial analysis .

In the UK, EarthWorks is currently utilised by ground engineering company Central Alliance in their GroundSat product, which takes the EarthWorks soil moisture image and analyses this spatially with slope angle, hydrogeological flow paths and other information producing slope susceptibility models. At the time of writing, GroundSat is currently being used in the assessment of some of the South Wales waste coal tips.

Existing Challenges for Geotechnical Infrastructure

The onset of climate change and its impact on the Earth's weather systems, sea levels and air temperature increases is widely publicised and recognised amongst most governments, industry and the academic communities.

Globally the effects of this are far reaching. For existing geotechnical infrastructure these effects need to be addressed and fed into existing asset management plans. For new infrastructure projects such as HS2, and Rail Baltica in northern Europe, the future proofing of geotechnical assets within these projects making them climate resilient should be readily achievable with today's engineering standards

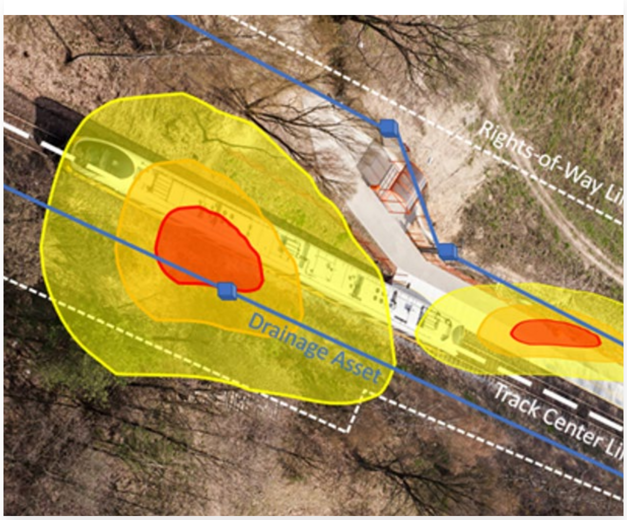

Figure 2. Example EarthWorks soil moisture map

and practice. As a good example, it has been recognised that the HS1 Channel Tunnel Rail link has withstood extreme rainfall events.

Extreme rainfall whilst the major issue in the UK is not the sole issue. Increases in sea level combined with storm events at high tide have disrupted Network Rail coastal infrastructure (St Bees in Cumbria, and Dawlish in Devon, 2014).

…the only rail line in Britain that has not suffered any material weather related disruption over the last few years, and certainly last winter, was HS1 which has been built and maintained to modern standards throughout.

(DfT Resilience Report, 2014)

The age of existing infrastructure also plays an important role. In the UK, existing infrastructure is in some cases over a hundred years old (eg. Network Rail, British Canals and sewers). Network Rail assets such as soil and rock cuttings, and embankments, are often over steep and were constructed to older standards without the present knowledge of soil and rock mechanics, and with a much lower perception of risk. These inherited assets still need to be assessed and included in asset management schemes. Any onset of failure due to asset deterioration over time has to be factored into any maintenance scheme, and therefore the prediction of a future failure timeline would be extremely useful information for operators.

Existing investigation and monitoring techniques are mostly in general focussed on localised problem areas. ASTERRA EarthWorks remote sensing techniques allow for a large spatial overview of infrastructure and crucially can include third party areas such as elevated hillsides above roads and railways, which may effect infrastructure through failure events. EarthWorks is capable of mapping soil moisture over large areas (up to 3,500 km2 per image) without even setting foot on site, significantly reducing the carbon footprint for inspection and investigation engineers, carbon saving in the process and identifying new and existing areas of concern for the asset managers. Ideally, image acquisition is performed seasonally to build up a database over a monitoring period. Soils tend not to behave in a regular fashion and changes in off site land use for example, can effect the behaviour of the soils on site. These are dynamic situations and hence regular monitoring gives the benefit of seeing changes and identifying new problems as they may arise.

The Current State of Play

Over the past 20 years geotechnical asset management tools have been available and are in use by many operators. As an example, in the UK, Highways England and Transport Scotland adhere to the guidance given in DMRB CS 641 – Managing the Maintenance of Highway Geotechnical Assets, whilst Network Rail conform with the regulator the Office of Rail and Roads and make use of data collection software for inputting individual EarthWorks data information, amongst others, into their asset management tools.

Based on previous work, Network Rail generally focus their attention on soil and rock cuttings given the greatest potential for derailments following any rapid failure (Network Rail, EarthWorks Technical Strategy, 2018). Highways England have a more general approach, although recognising that soil cuttings are more prevalent to failure events than embankments given the cuttings are exposing natural soils whereas embankments are (mostly) designed and placed in a controlled manner. For Network Rail, soil cuttings are often historical, inherited and oversteep, and with little or no records of embankment design in their inherited assets.

Figure 3 shows a deterioration curve (Glendinning et al, 2015) and indicates that EarthWork assets for Network Rail lie to the right of the deterioration model (degenerating/unreliable) expressing the general stability situation of old geotechnical assets, whilst the Highways England assets are more within the central 'reliable/degenerating' area. Newer infrastructure is still within the bedding in period, eg HS2, and HS1 (although not shown).

One of the main outputs for the users of asset management tools are the consequences and severity of failure. What would happen if there were a failure? What would be the severest outcome? What are the chances of this happening? When is this likely to occur?

Network Rail have operated a Hazard Index system for earthwork assets since 2000 (cuttings, embankments and rock slopes). It is understood this has worked well in prioritising work fronts. However, in striving for further improvements Network Rail determined, following a review in 2013, that the number of failures occurring in assets that were previously deemed to be in good condition, was unacceptable. They identified that an improvement or new approach is needed to enable prediction of earthwork failures, as far as possible, given the unpredictable nature of EarthWorks and the uncertain timing of climatic events, but also knowing with certainty that these extreme climatic events will occur, and more often. ASTERRA EarthWorks sub surface soil moisture mapping ability can highlight areas which sometimes may have never

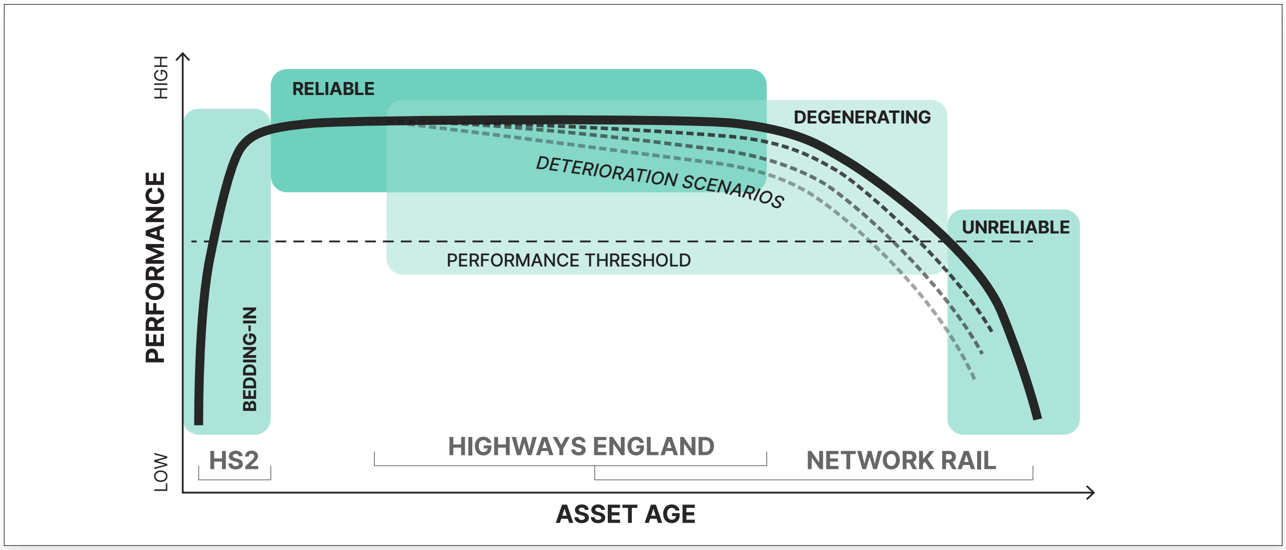

Figure 3. Deterioration curve for transport earthworks

appeared problematic based on normal inspections by engineers, but which based on knowledge of soil moisture content, slope make up and topography, could fall into the 'at risk' categories. Intervention before failure occurs has already been identified as a key element for asset management control.

What is Currently Being Done - New and Further Developments

Whilst the use of asset management tools has been common for at least 20 years, there has been continual review and development particularly recognising the onset of climate change and its effects on structural integrity, but also in the development of failure event prediction.

The Achilles Research Programme
(www.achilles-grant. org.uk) is assessing the aspects of climate change on geotechnical infrastructure, in particular EarthWorks (embankments and cuttings). This research is being conducted on the back of previous research projects such as BIONIC and iSMART and is due for completion by the end of 2022. The three main areas of focus of this program are the **deterioration process, asset performance, and forecasting and decision support.**

By means of micro (laboratory) and macro (full size) scale testing, existing knowledge is being put to the test to improve understanding of the deterioration process of existing slopes for example, approximating rough timelines for deterioration and the onset of failures. In short, the process is being proof tested against ongoing research and existing asset data.

Recent research on the impacts of the wetting and drying cycles on a clay cut slope over time (Postill et al, 2019) and numerical modelling of the same slope have compared favourably.

Further research on climatic impact using 20 years of existing meteorological data modelled against near surface pore water pressures for a soil cutting case study has been undertaken (Postill, 2019). This study has revealed that numerical modelling of pore water pressure cycles performed for that same 20 year period, compares well to the factual data. This gives confidence that by using predictive climatic change models for rainfall and temperature etc, an insight can be gained to the likely increases in near surface pore water pressures on soil cuttings. Furthermore, ongoing work has demonstrated that modelling predicts an increase in slope deterioration rates with wetter climates (Postill, 2019).

EarthWorks L-Band SAR technology can potentially identify these near surface areas of increased pore water pressure. Regular monitoring will identify these areas to users and enable preventative works to be designed crucially prior to potential failure.

Prolonging the lifespan of the asset is by far more cost effective than waiting for failure to occur and repairing it.

Ongoing Challenges

..before entering the 'Dragons Den' one must have the facts in hand...

To install preventative measures at the onset of degeneration appears seemingly the best approach. However, persuading the right people to provide the finance often requires hard evidence. Even at this stage the evidence perhaps to the financiers, remains unclear, even though it is continually being gathered and presented.

However, recent climatic events both in the UK and globally surely highlight that investment is needed. Preventative measures, rather than reactive measures, are fundamental to prolonging geotechnical assets and creating a less disruptive safer transport infrastructure able to deal with the onset of climate change.

L-Band SAR can have an important part to play in the ongoing puzzle of failure prediction and forecasting. With a greater understanding of asset behaviour using L-Band SAR, combined with the already existing investigation and monitoring techniques, asset managers will be better able to direct resources and funding to the correct areas and hopefully prevent the onset of failure exacerbated by climate change effects and prolong asset lifespan for many more decades, maintaining crucial transportation networks, keeping the economy moving and ensuring public safety.

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