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How to Safeguard Critical Infrastructure from Space

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Abstract

From collapsing dams to failing embankments, disaster can strike when engineers fail to account for the presence of water in soil. ASTERRA addresses this risk by detecting underground soil moisture as deep as 3.0 metres below ground using patented algorithms combined with AI on satellite Synthetic Aperture Radar (SAR) data. From tailings dams to waste mineral tips, road and rail infrastructure, this method can identify damage and locate potential points of failure, allowing preventative maintenance to be directed to where it is needed most, and crucially before the onset of failure can occur.

This proprietary methodology was originally used in the search for water on Mars and has since been adapted to monitor soil moisture around critical infrastructure on Earth from orbit. The process uses data from commercial satellites equipped with L-Band SAR, which can penetrate through clouds, vegetation and soil.

SAR data is processed and analysed using a patented algorithm before delivering hard intelligence to planners, engineers, and policymakers. This allows decision-makers to make data-informed choices about the repair, maintenance, and long-term planning of above and below-ground infrastructure.

ASTERRA has been transforming SAR satellite data into hard intelligence and decision-ready insights about the underground environment since 2016. This paper highlights the benefits of SAR data as a means of remotely monitoring soil moisture content and thereby safeguarding critical infrastructure.

Keywords: Moisture, Infrastructure, Satellites.

1. Introduction

Manmade earthwork assets are increasingly becoming susceptible to changes in the earth's climate and in particular to the more frequent and intensive rainfall events which creates extensive damage, or in the worse case causing ultimate failure of the assets.

Earthwork assets need to be resilient to the onset of climate change in order to sustain the environment and continue to perform for the reason which they were created. The incidences of failures or damage to transportation infrastructure, dams and mine tailings storage facilities, or breaches of flood defences are becoming more frequent, more transparent and more widely reported.

Asset managers have the responsibility of maintaining their earthwork asset networks ensuring safe and operable environments in both the private and public sectors. Significant recent events have highlighted not only the disruption and devastation caused by asset failures, but also the loss of reputation for both public and private bodies such as transportation networks or mining sectors.

Recent landslide events on the Brazilian highway BR-376 (Figure 1) causing fatalities and affecting the asset and highlight the issues associated with landslides adjacent to transportation links, whilst failures of tailings storage facilities in the South Africa mining communities of Jagersfontein and Willamstown have recently occurred in the past year.

It is well known that the costs to repair landslips once they have occurred is significantly more than preventative maintenance. It has been estimated that emergency earthwork repairs for Network Rail 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 many geotechnical asset managers.

Soil moisture data has uses across many industries, from agriculture to transportation and others. The ability to identify at high resolution, areas with high soil moisture content associated with earthworks assets is important as with the onset of climate change and extreme rainfall events the increase of more catastrophic earthwork failures is highly likely.

Figure 1: Recent landslip dated 28 November 2022 in Brazil. Image from CBMSL via MetSul.com.

Earth observation techniques and the use of synthetic aperture radar (SAR) to determine soil moisture have been studied over several decades. L-Band SAR (frequency 1-2 GHz, wavelength 15-30 cm), has the ability to penetrate dry sand up to tens of meters and moist clay up to 0.5-1.0 meter (Dall (2007), Singh et al (2018), Ulaby (2014), Zhang (2020)).

ASTERRA's use of the lower frequency L-Band SAR to determine the presence of water leaks in utility pipelines has become successfully used worldwide. The ability of this technique to pick out the location of non surfacing leaks, those which go unnoticed for months even year, has become a wide ranging technique in use by utility companies globally, with more than 57,000 leaks verified, saving millions of cubic metres of potable water since 2017.

It is also possible to use this technique within geotechnical asset management. L-Band SAR has proven capabilities of detecting sub-surface soil moisture content, more so than X and C Band SAR which have limited penetration depth and are more disrupted by the effects of vegetation. ASTERRA have developed the use of L-Band SAR for use in the geotechnical field enabling large specific areas or linear infrastructure to be analysed. This is repeatable, enabling engineers and asset managers to review the behaviour of potential problem areas over time.

2. L-Band Synthetic Aperture Radar

Satellite mounted L-Band SAR can identify the specific dielectric signature of water type mixed with soil. This specific signature allows enables the differentiation between different types of water such as groundwater and saline water (Gadani et al, 2012). L-Band SAR sensors are set at a wavelength capable of seeing 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 beneath capturing the subsurface soil moisture levels from dielectric properties which differ depending upon water type.

The use of ASTERRA's proven algorithms allow L-Band SAR data to be converted to soil moisture content which can be displayed as contoured soil moisture maps for engineers and asset owners to verify existing problem areas, and to view potentially unknown areas which could be cause for immediate or future concern.

Using L-Band SAR and dedicated algorithms it is possible to create soil moisture maps such as that highlighted in Figure 2, with specific information highlighting subsurface soil moisture content within any area of interest specified by the user, be it linear infrastructure or larger site development, dams or tailings storage facilities (TSF), without even setting foot on the ground. Contoured soil moisture heat maps enable asset owners and engineers to visualise and locate their inspections for known problem areas and more importantly target those unknown areas where the moisture has not yet manifested itself on the surface.

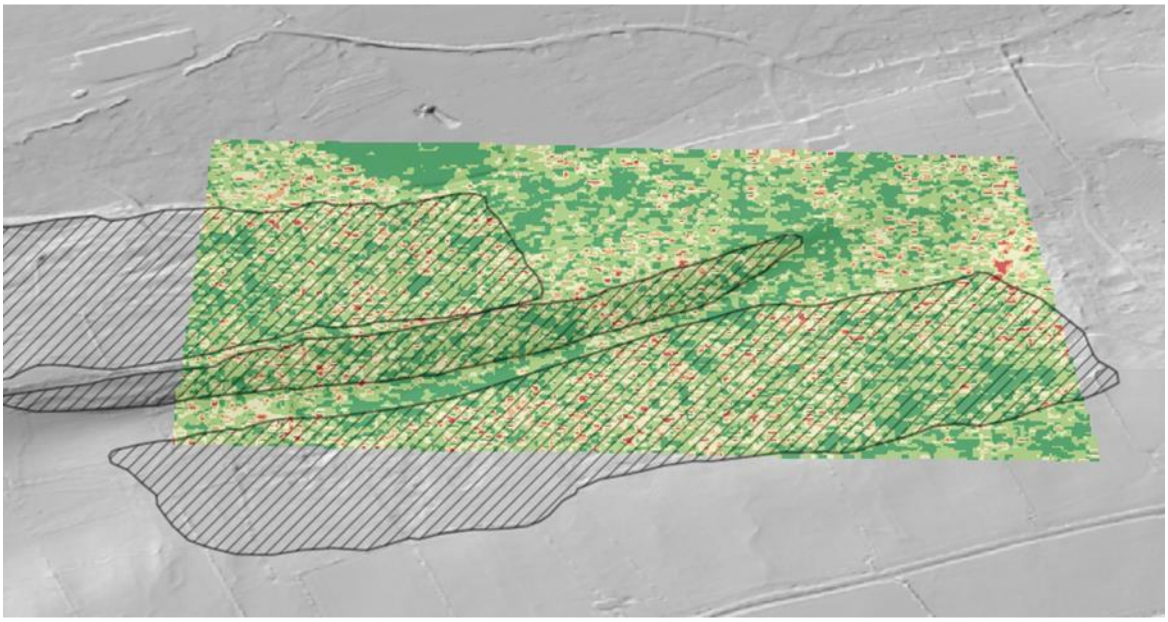

Figure 2: Example soil moisture map overlaying a Digital Elevation Model (DEM), including BGS mass movement deposits data (Contains British Geological Survey materials © UKRI [2022] and public sector information licensed under the Open Government Licence v3.0).

ASTERRA have performed ground truthing projects in the UK and elsewhere throughout the globe since 2018 in areas of differing geological settings, meteorological conditions and vegetation cover, where SAR backscatter readings have been compared to site specific soil moisture contents as summarised in Table 1. On average, linear regression values (R^2) values obtained from SAR backscatter and soil moisture tests are greater than 0.80.

Table 1: Summary of ASTERRA ground truthing projects.

Location	R^2	Soil types
UK - Crick	0.83	Clays, Loam
USA - Texas	0.85	Sand, Clay, Loam
China - Guizhou	0.83	Clays
Netherlands	0.79	Clay, Peat
Scotland	0.84	Clay, Sands, Peat

This work has provided ASTERRA with confidence that the technology works for soil moisture prediction and that future satellite acquisitions are able to proceed without the requirement of additional expensive ground truthing.

3. What is currently being done in the UK

Intervention before failure occurs is identified as a key element for earthwork asset management.

The Achilles Research Programme (www.achilles-grant.org.uk) has been 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, 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.

Research on the impacts of the wetting and drying cycles on a clay cut slope over time and numerical modelling of the same slope have compared favourably (Postill et al, 2019). 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 was also undertaken. This study 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, an insight can be gained to the likely increases in near surface pore water pressures on soil cuttings. Furthermore, ongoing work has demonstrated that this modelling predicts an increase in slope deterioration rates with wetter climates (Postill, 2020).

One of the main elements that could augment this research is soil moisture, its behaviour, its location and how this can effect pore water pressure within cuttings and embankments.

4. Current methods of Soil Moisture determination

Means of determining soil moisture content currently in use include soil moisture deficit and soil moisture index. However, both these techniques provide information at a coarse resolution (Km's to 100's metres). These methods allow asset owners to understand the nature of the soil moisture at the time of data issue on a regional basis. With regular meteorological data provision, maintenance crews may be put on standby prior to and during expected inclement weather fronts. However, the locations of potential failure areas, apart from those already suspect areas, remain unknown.

A recent report completed for Network Rail by its Weather Advisory Task Force (WATF) indicates that the use of these soil moisture indices which are products of weather prediction models, alone are not sufficient or detailed enough for representation of soil moisture in the landscape (Slingo et al, 2021).

Asterra's Earthworks L-Band SAR technology can identify elevated sub surface soil moisture concentrations and more importantly pinpoint locations at much finer resolution (metres), meaning that locations of near surface elevated soil moisture can be captured, even where there is no clear sign of this occurrence at ground level. Regular monitoring will highlight these locations for asset managers and enable inspection, investigation and monitoring, and allowing mitigating works to be designed crucially before potential failure so enabling the asset resilience needed for the future.

5. Existing Uses of L- Band soil moisture

The use of L-Band SAR is proven in the water leak detection industry, accurately locating non surfacing leaks such that utility providers can increase their leak detection and repairs. This significantly reduces losses of expensive treated water and maintains customer supply. Using this same technique for geotechnical engineering in particular for earthwork asset management, is a logical step.

Recent projects in the UK and globally have highlighted the success of using soil moisture content derived from L-Band SAR on geotechnical assets, with high correlations achieved between SAR backscatter data, laboratory and insitu soil moisture data.

Soil moisture mapping can be used for many transportation (and other) projects where soil moisture data combined with additional GIS analysis to augment existing geotechnical assessments can highlight areas susceptible to landslides (Figure 3), to confirm the highest risk areas previously identified and to identify other highly susceptibility areas that may not have yet failed. This enables asset managers to make crucial decisions to undertake mitigation measures, maintaining the operation of their assets and preventing the onset of potential slope failures which could cause significant disruption or worse, and could potentially cost up to ten times more for remediation should failure occur.

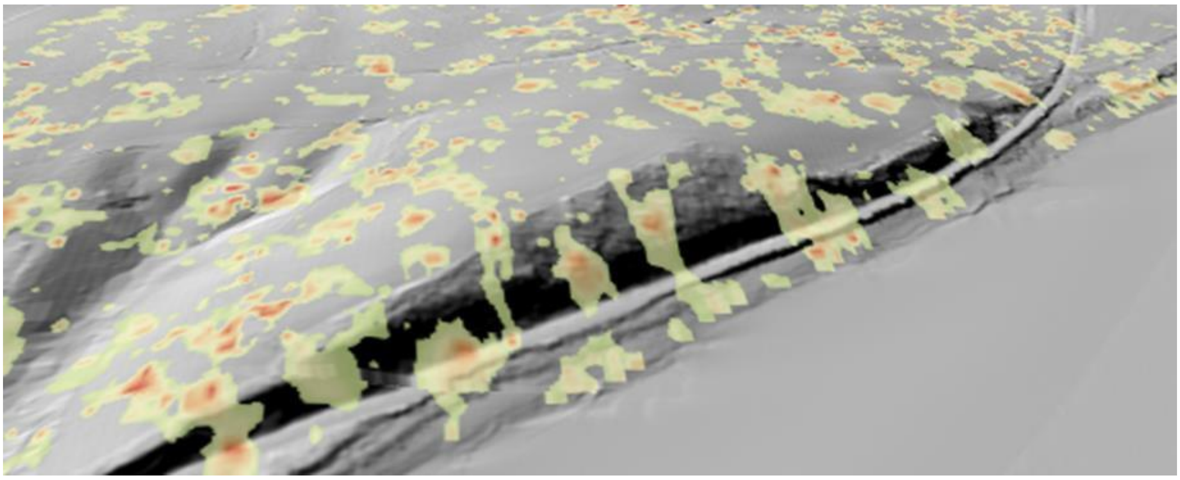

Figure 3: Example cutting with medium to high soil moisture overlaid on a LiDAR DEM (Contains public sector information licensed under the Open Government Licence v3.0).

Providing the correct tools to increase the resilience of operating transport routes and mitigating against events related to climate change events will enable earthwork asset managers to make those decisions of where to channel funding and crucially, where to undertake needed mitigation works in advance of ultimate failure.

6. Conclusion

Remotely assessing geotechnical assets over large spatial areas or linear infrastructure provides significantly more information rather than pin point data from investigations, or indexation from meteorological prediction. Thus, L-Band SAR can provide data which can assist towards decision making and furtherment of the resilience of assets to climate issues.

There is a strong need for frequent soil moisture monitoring within critical infrastructure such as transportation, dams and levees, which covers widespread areas quickly, and which can be performed remotely. Satellite based L-Band SAR soil moisture data provides a highly efficient solution due to its unique penetration capabilities and its sensitivity to the dielectric constant. Repeat images will provide the user with updated monitoring information over known target areas whilst also uncovering unknown areas, particularly those in otherwise inaccessible or remote places, which may also be prone to deterioration or failure.

Combined with existing forms of assessment the ability to see specific soil moisture conditions and locations along geotechnical assets enables asset managers to perform their duties more effectively, maintaining important assets and providing mitigation where needed to maintain their resilience.

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