Almost everything you need to know about...

Applying satellite SAR data in the construction sector

GEOFEM

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THE GREAT INFRASTRUCTURE CHALLENGE

- Legacy assets
- Increasing use
- Climate change
- Low budgets

"The nation's pipelines are ageing, as witnessed by increasing failures and leakage events, thus driving a need to employ improved inspection techniques."
ASCE Report Card 2021.

"Overall disruption to infrastructure ranges from $391 billion to $647

INTRODUCTION

The global construction industry is valued at trillions of dollars, with estimates suggesting it could reach $14 trillion by 2025. This industry plays a critical role in the economy due to its production of infrastructure, housing, and commercial buildings. However, despite the importance of geotechnical analysis in ensuring the safety and serviceability of construction projects, in many projects it is given insufficient attention. According to a study by Cornerstone Projects, 16% of all delayed construction projects in 2022 were attributed to a lack of information, including information about ground conditions.

Geotechnical analysis involves characterising the mechanical and other properties of the ground that supports and interacts with buildings and infrastructure. These properties are then applied using appropriate calculation methods to predict the response of the ground to construction activities such as new buildings, basements, earthworks, dams, and tunnels. By conducting geotechnical analysis, potential risks can be identified and managed during construction, reducing the likelihood of costly failures, and ultimately ensuring the safety and serviceability of a project. Here are some of the main issues that geotechnical analysis is concerned with:

Decarbonization

Climate change and the effects of carbon emissions on the sustainability of the environment is one of the main conversations in many sectors of the global economy. Construction is an industry under scrutiny as the operations undertaken are as damaging as they are necessary. The materials used often have high embodied carbon, leading to pressure for improved materials technology and greater efficiencies in design. Moreover, the wider issue of climate change looms large as infrastructure faces new and unpredictable challenges such as extreme weather, flooding, landslides, and coastal erosion.

billion a year in LMICs."
World Bank (2019).

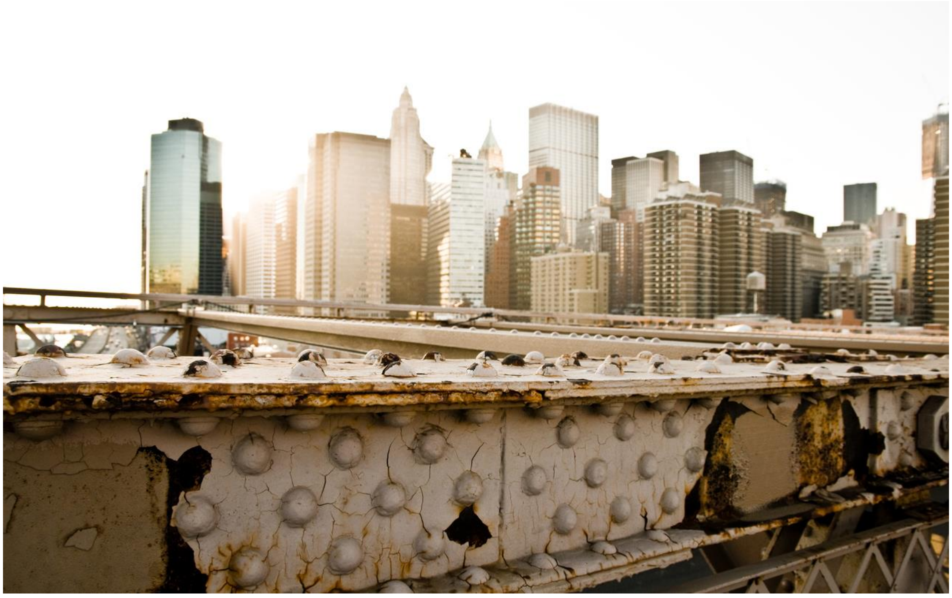


Figure 1. Ageing infrastructure

Unexpected ground conditions

A common challenge in construction that can have a significant impact on cost, schedule, and success of a project is encountering unexpected ground conditions. Weak ground, groundwater and other geohazards, such as sinkholes, expansive clays, and liquefiable soils, that were not accounted for in the original project design can drastically hinder construction output, put stress on deadlines, and lead to unplanned costs.

"A growing population and changing weather patterns are the two factors that will place the greatest pressure on our networks."
ICE State of the Nation Report 2014.

Figure 2. Increased use

Budgeting

"The climate emergency and net-zero transition present an unprecedented challenge for engineers to solve."
ICE State of the Nation Report 2020.

Budgeting is a particular challenge in construction because every project is different and is subject to the vagaries of the weather and ground conditions. A lack of insight or a narrow approach to planning and risk management can lead to costs spiralling out of control and projects being abandoned altogether in extreme cases. Unexpected ground conditions can lead to increased construction costs. Issues such as unstable soils, poor bearing capacity, or the presence of underground utilities may require additional foundation works, ground stabilization measures, or specialized equipment, all of which can substantially inflate project costs. Construction delays are a common consequence of unanticipated ground conditions. Delays in the project timeline can lead to increased labour and equipment costs, extended overhead expenses, and potential contractual penalties. Moreover, the need for on-site modifications or redesigns to address ground condition challenges can result in costly variations to the original plans. Lastly, inadequate consideration of ground conditions may compromise the long-term structural integrity and performance of the built environment, leading to potential maintenance or repair costs down the line. Proper geotechnical investigations and analysis, along with budgetary provisions for potential ground-related challenges, are essential to minimize financial risks and ensure the overall success of a construction project.

Figure 3. Hurricane Katrina recovery, New Orleans, 2005.

"Global investment in infrastructure needs to increase by 60% between now and 2030."
McKinsey and Co. (2013).

Changing Regulations

Regulations that impact construction projects are increasing all the time and vary at a regional, national, county and district level. Keeping up to date on regulations imposed in different geographical areas by different authorities responsible for aspects including health and safety, environmental protection, town planning and building control is a major challenge. New materials and technologies are constantly emerging, but regulators can take time to catch up. This leaves clients in a dilemma whether to take advantage of the benefits and increased competitiveness brought by innovation before they are formalised and regulated.

GEOTECHNIC BASICS

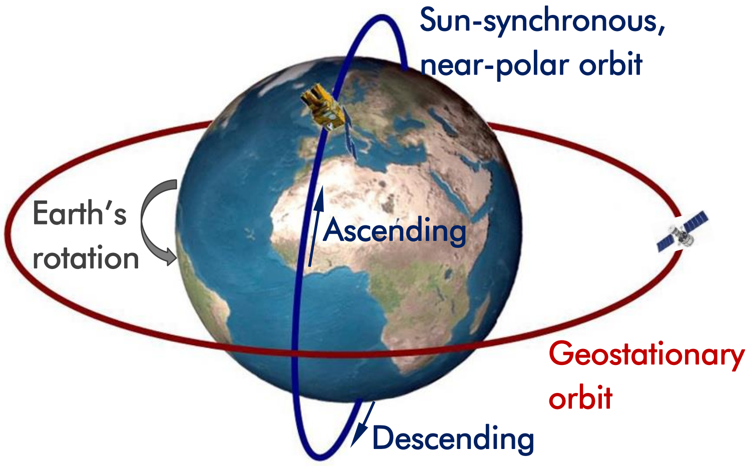


Figure 4: Satellite orbits

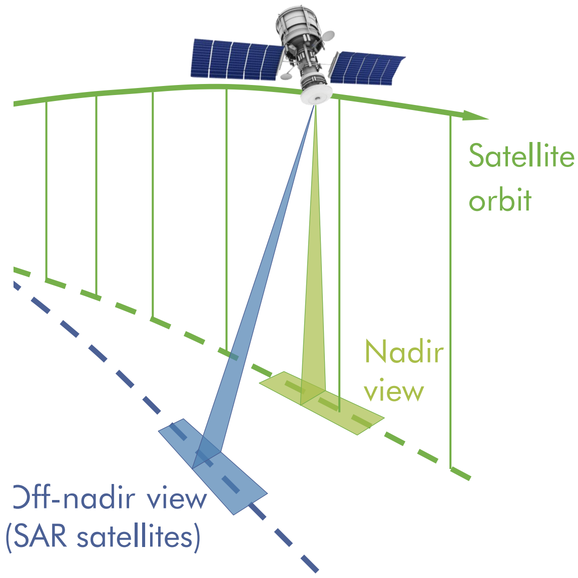


Figure 5. Satellite views

Geotechnical engineering is a fascinating field. It is distinct from other fields of engineering in that it involves the engineering of the natural materials in the ground, shaped and altered by, sometimes, millions of years of geological processes. When mastered, the unexpected becomes managed and seemingly impossible ground conditions for construction can be overcome. Geotechnical engineering can have the greatest positive impact on a construction project's success.

Between civil engineering and geology

Geotechnical engineering bridges the gap between civil engineering and geology. Experts coming from the civil engineering side are called geotechnical engineers while those coming from the geology side are called engineering geologists. The former knows more about the structures interacting with the ground, such as foundations, piles and retaining walls while the latter know more about the processes that formed the ground. Both know how to characterize the ground into its engineering properties. We will use the term geotechnical engineering throughout this guidebook but there is much overlap with engineering geology.

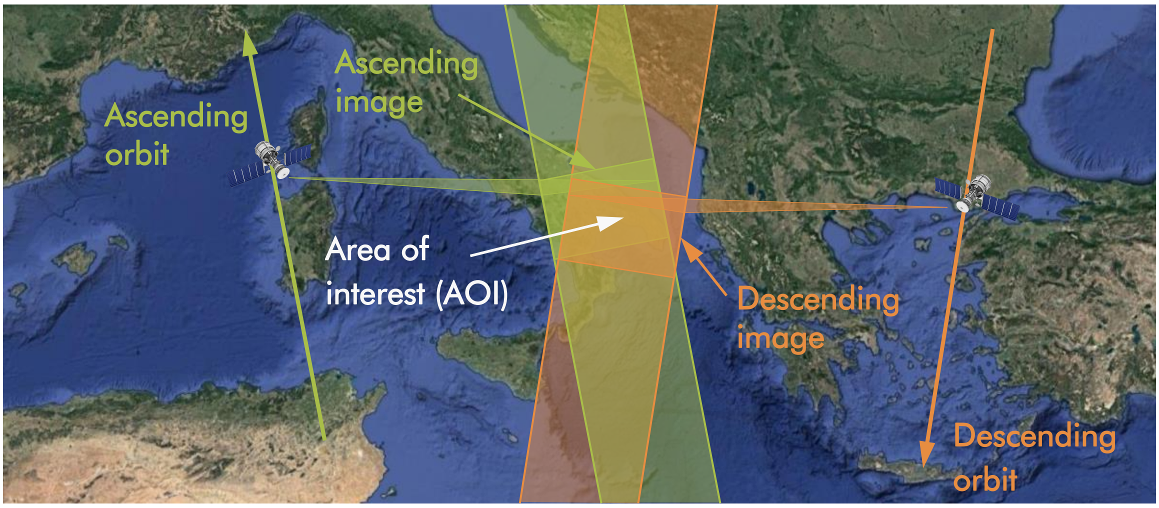


Figure 6. Acquiring ascending and descending SAR images of the same area of interest

Interpreting the ground

In contrast to other engineering disciplines, including much of civil engineering, where materials are manufactured to a specification and tested many times, geotechnical "materials" are the soil and rock already present under a site. Little is known about these materials until a site investigation involving pits, boreholes, in situ tests, sampling and laboratory tests is undertaken. A good analogy is the medical doctor trying to diagnose a patient's illness. He or she cannot see inside all the organs and relies on blood tests, ultrasound and other external examinations which he or she interprets to reach a diagnosis. Geotechnical engineers rely on the test results and observations of a site investigation from which they determine ground behaviour using their expertise and experience. Central to geotechnical engineering is this art of interpreting a finite amount of site investigation data. The ground parameters, groundwater conditions, and geological features are interpreted into a conceptual ground model that is simpler than reality so that geotechnical analysis can be undertaken efficiently but which encapsulates the important aspects of ground behaviour. Armed with this knowledge, geotechnical engineers can design suitable foundations and evaluate the feasibility of construction projects, ensuring the best possible outcomes for their clients.

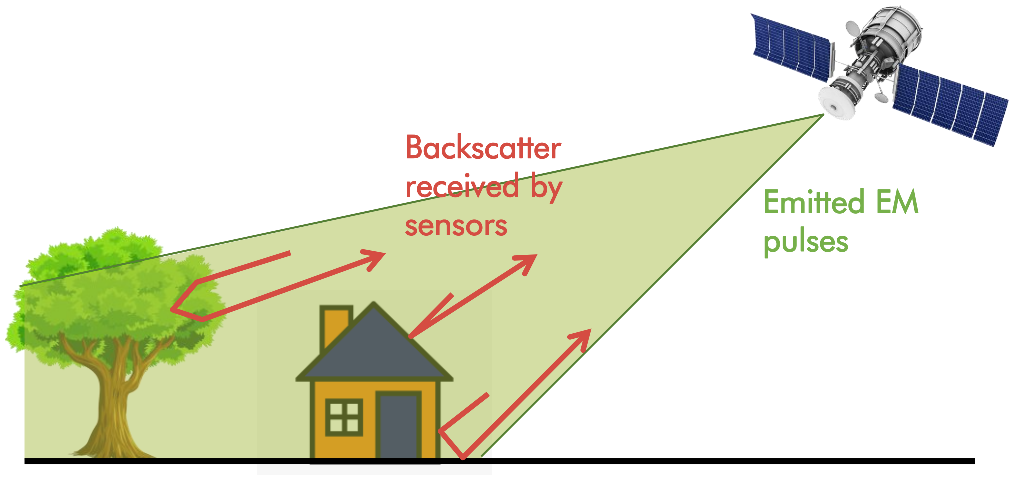


Figure 7. The all-important "radar" part of SAR

Groundwater

Soil is made up of solid particles with pore spaces between that are usually filled with water and air. The proportions of water and air in the pore spaces can have a profound effect on the engineering behaviour of the ground – hence why landslips tend to occur after heavy rainfall. Construction work in rivers and excavations below the water table require an area to be dewatered. Critical to the success of any dewatering measures is the prediction of groundwater flow rates and flow paths to ensure that the working area remains dewatered. Through the interpretation of hydrogeological data and groundwater flow analysis, geotechnical engineers can predict patterns of groundwater flow and devise robust strategies for dewatering and drainage to avoid the hazards and delays associated with excessive groundwater.

Advanced Analysis

Geotechnical analysis is the application of calculation methods to predict ground response to construction activities and numerical analysis (e.g., finite element analysis (FEA)) is the most advanced of the analysis techniques. By creating precise simulations of construction sites, geotechnical engineers can predict ground movement, ground stability and evaluate soil-structure interaction, including structural forces and spring stiffness values. With these predictions, engineers can optimize designs, ensure structural integrity, and effectively mitigate risks stemming from ground movements. This becomes particularly vital in densely populated urban areas, where construction activities can impact neighbouring properties, utility services, and transportation infrastructure assets.

Integrating Satellite Remote Sensing and GIS

The integration of satellite remote sensing and Geographic Information System (GIS) technologies further advances geotechnical analysis. By harnessing the power of satellite data, engineers can gather crucial information about the Earth's surface, such as ground surface displacement and soil moisture changes, over an extended period. This data-driven approach provides more insight on the behaviour of the ground, facilitating the identification of potential geohazards such as landslides, sinkholes, and expansive clays. The combination of geotechnical engineering expertise and satellite data analysis enables a comprehensive understanding of site characteristics and facilitates the assessment of infrastructure asset susceptibility to various geohazards.

What satellite SAR can do…

- Measure ground surface and structure displacements for a high density of points over large areas.
- Measure changes in soil moisture for a high density of locations over large areas.
- Determine historical values of displacement and soil moisture from archived satellite images going as far back as 1991.
- Do all this at reliable time intervals, no matter what the weather, day and night.
- Assess infrastructure asset condition across entire networks quickly, regularly, consistently.

What satellite SAR cannot do…

- Measure displacement and soil moisture of objects hidden from the line of sight of the satellite (e.g. deep below the ground surface or under a dense forest canopy).
- Measure displacement at specific, predetermined locations (unless corner reflectors are installed).
- Measure displacement and soil moisture accurately while surface textures are changing (e.g. during earthworks, snow cover or planting new vegetation).
- Measure displacement and soil moisture continuously (typical intervals are 1 to 6 days).

COMPARE APPROACHES

In this chapter the four main approaches to infrastructure asset condition assessment, including satellite SAR data, are summarised and compared. Each method is rarely used in isolation since their attributes complement each other. For example, satellite SAR data provides quick, broad coverage of the ground surface while sensors may be installed at specific problem areas to obtain more detailed information, including below the ground surface.

This chapter includes a brief description of each approach and a comparison is summarised in the table on the following page.

Visual inspection

This involves a physical visit to the asset for an optical inspection, examining exposed and visible areas, sometimes measuring what is accessible and evaluating and recording the condition of an asset. Quantitative measurement is limited and there is often insufficient structure and specification to the inspections to allow practical storage of information and comparison between successive visits.

It is the oldest approach but remains the most powerful method to gather qualitative information with the benefit of *in situ* human observation and understanding. Its strength lies primarily in the investigation of known problem sites but, no matter what level of competence is provided, there is a limited amount of information available to the naked eye. Assets can have hidden defects, or the early signs of a developing defect are usually too small to detect visually. Also, there are the constraints of time, access and type of data that can be gathered. The time interval between inspections (typically around two years) means defects can substantially develop unseen between inspections.

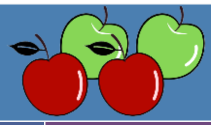
Visual inspections also come with significant financial costs, particularly for those with large networks of assets, and place personnel in potentially hazardous environments on a routine basis.

Periodic visit-based monitoring (PVM)

PVM involves visiting the asset with portable measuring equipment that is brought to and taken away from the asset on each visit. For example, bringing a probe to site to measure the vertical profile of inclinometer tubes installed in an embankment. It provides quantitative information and is often introduced after a visual inspection or satellite SAR data has identified a particular issue for further investigation. As such, it tends to be applied in a focussed way with a narrow scope and for a limited duration. The time interval between measurements is relatively long and can become erratic, depending on the resources available. As with visual inspections, this can allow defects to develop or worsen undetected until the next visit.

It has relatively low cost for short durations because the measuring equipment can be used on multiple sites or rented. It becomes expensive for long durations and more frequent visits, particularly in remote locations, due to the demand on labour.

COMPARE APPROACHES



	Visual inspection	Periodic visit-based monitoring	Continuous sensor-based monitoring	Satellite SAR
Description	Physical inspection, looking for defects and changes since previous inspection.	Monitoring of key parameters by instrumentation taken to the site on each visit.	Sensors installed at the site for continuous monitoring for a defined period.	Measurement of displacement and soil moisture across ground surface at regular intervals.
Information available	Based on what can be seen, limited quantitative.	Detailed quantitative but only at each visit.	Detailed quantitative, detect changes and trends of behaviour.	Quantitative, detect changes and trends of behaviour over longer periods.
Observation of changes	Widely spaced observations, difficult to quantify changes.	Observations only at chosen intervals, long-term trends.	High frequency observations, short and long-term trends.	Low frequency observations, long-term trends.
Data type	Visible, qualitative, condition.	Measurable, quantitative, trends.	Measurable, quantitative, trends.	Measurable, quantitative, trends.
Access	Regular site visits.	Regular site visits.	Installation and maintenance only.	No visits.
Equipment	Human eye, camera.	Portable measuring equipment.	Installed sensors.	None.
Measurement frequency	Low	Low	Continuous	Medium
Vulnerable to vandalism, theft	No	Possibly	Yes	No
Data costs	Per inspection.	Per visit.	Installation and maintenance.	Free or varies (commercial data).
Alarms	May be late due to low frequency.	Some alarm capability depending on visit frequency.	Specific trigger levels can be set for short and long-term warnings.	Long-term warnings of increased susceptibility.
Reliability	Generally good, visits may be postponed due to weather or other factors.	Generally good, visits may be postponed due to weather or other factors.	Good but sensors may malfunction, so redundancy needed.	Very good.

Continuous sensor-based monitoring (CSM)

CSM involves the installation of sensors that measure parameters at high frequency (e.g. hourly) thereby providing essentially continuous monitoring. Using the same inclinometer example from the PVM description, CSM differs in that sensors, such as a vibrating wire tilt sensors, are mounted permanently along the tube to record inclination on a continuous basis without the need for regular site visits with a portable probe. The data can be stored on a datalogger for occasional download in situ or more commonly stored on cloud-based servers for real time access. CSM has high levels of accuracy and precision that cannot be achieved with the other techniques.

Installation costs are high due to the high number of sensors that are typically required, but once installed the ongoing monitoring costs are low because no site visits except for occasional maintenance are required. As with PVM, it provides quantitative information and is often introduced after a visual inspection or satellite SAR data has identified a particular issue for further investigation, with CSM tending to be preferred for monitoring over long periods or on a semi-permanent basis. It is particularly useful for providing short-term warning of an imminent, brittle failure to trigger immediate evasive action to protect users of an infrastructure asset which cannot be provided with the other techniques.

Satellite SAR data

Satellite SAR data, which is described more fully in the next chapter, is the only technique that does not require any visit to the asset, giving it the distinct advantages of being the safest technique with the lowest carbon footprint. It provides data across large areas of all the ground surface and built environment that is visible to the satellite. Therefore, it does not provide data at locations well below the surface (e.g. tunnels) and may not provide data at locations obscured by dense vegetation.

It provides quantitative, objective data for whole networks in an instant, every few days or less, at significantly lower cost per unit area or length than the other techniques. It should be regarded as a “Stage 1” technique for rapid, whole-network assessments, based on which the other more detailed techniques can be assigned to locations identified as at risk.

CASE STUDY 1

Gauteng, South Africa

The densely populated Gauteng province includes the cities of Johannesburg and Pretoria but 25% of it sits on dolomite rock making it highly susceptible to sinkholes. While sinkholes tend to occur with little or no warning, precursors such as ground settlement that may be imperceptible to the naked eye can often provide an early warning.

InSAR displacement data showing sinkhole precursor

THE CHALLENGE

- Local changes in ground or building movement can provide early warning of sinkholes but surveying regularly the 5,000km^2 of dolomite in Gauteng would be too expensive and impractical.

THE SOLUTION

- Regular measurement of ground and building displacement by InSAR analysis of satellite images.
- In a pilot study including known historical sinkhole events in Gauteng, precursors to sinkhole development were identified.

THE BENEFITS

- A proven, cost-effective method to provide an early warning of more sinkhole events.
- Proactive maintenance reduces the danger, cost and disruption of sinkhole events.

MEET YOUR FRIEND SAR

Let's learn some more about how satellite SAR data is used in infrastructure asset management, see some common applications and address the frequently asked questions.

Displacement measurement

The movement of objects and the ground surface between successive satellite passes is measured by calculating the phase difference between successive images as illustrated in Figure 8. Rather than direct displacement, the output is fractions of the phase. If all displacements are less than half a wavelength (a few centimetres) then they are easy to determine but if they are greater than half a wavelength this leads to ambiguity. The phase difference between two SAR images is shown in an interferogram, such as the one in Figure 9 obtained from two SAR images, one taken before and one after the magnitude 6.7 earthquake in Bam, Iran. The coloured fringes indicate that ground surface displacements caused by the earthquake increased to several times the wavelength (2.8cm in this case) used to produce the images.

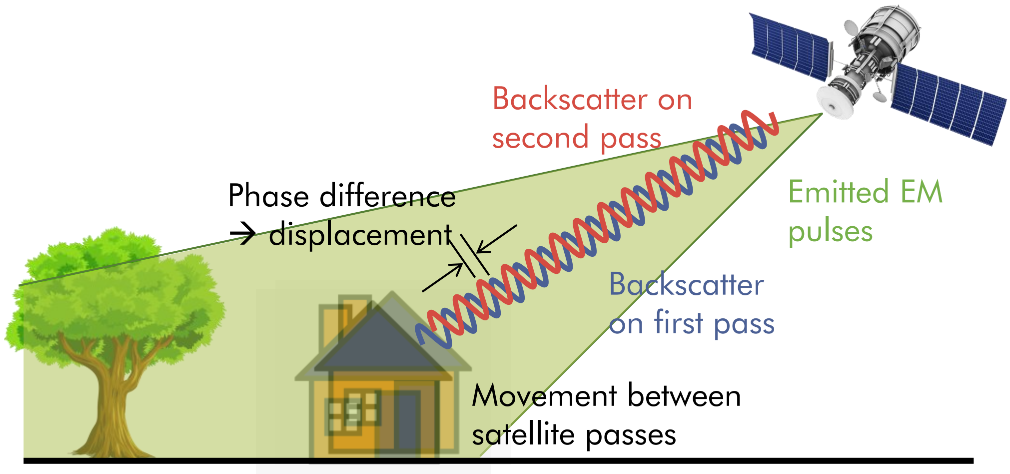


Figure 8. Displacement measurement by satellite SAR

Displacement output is obtained by correcting for topography using a digital elevation model (DEM) in a process called differential interferometric SAR (DInSAR). Further processing to remove residual topographical errors, orbital errors, atmospheric effects and data noise produces a displacement map with centimetric precision. The displacements are in the line-of-sight (LOS) direction between the object and the satellite sensor which will be at some inclination to the vertical.

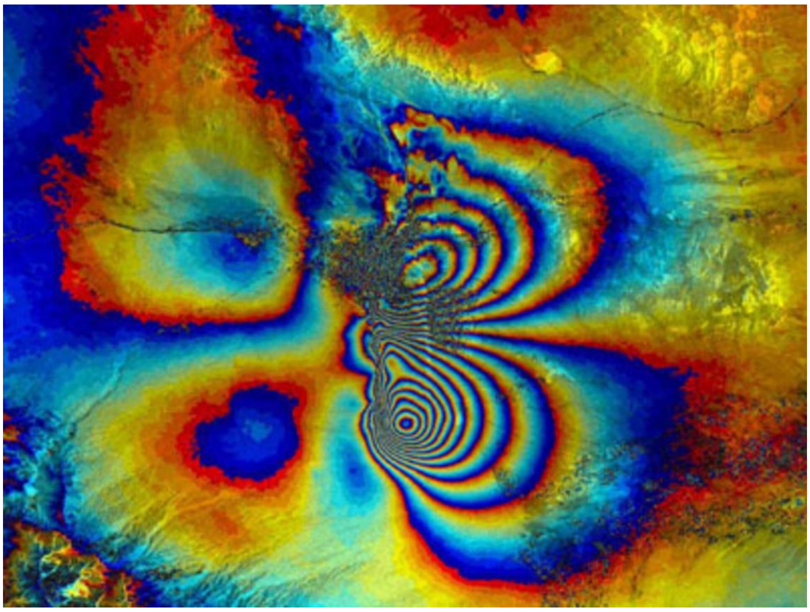


Figure 9. Interferogram of ground motion associated with the Dec 2003 earthquake at Bam, Iran ©ESA.

Displacement: getting millimetric precision

Analysing a time series stack of images – usually a minimum of 20 – enhances displacement precision by improving corrections for errors such as atmospheric effects and residual topographical errors. There are several algorithms to do this which are suited to different conditions, but they all enable the spatiotemporal analysis of the radar phase across multiple images to produce displacement data with millimetric precision and about 2-4mm accuracy depending on the frequency band.

Either average velocity or displacement over different time periods can be calculated and the data presented as coloured dots or pixels overlaid on maps or optical satellite images to indicate their location, such as that shown in Figure 10.

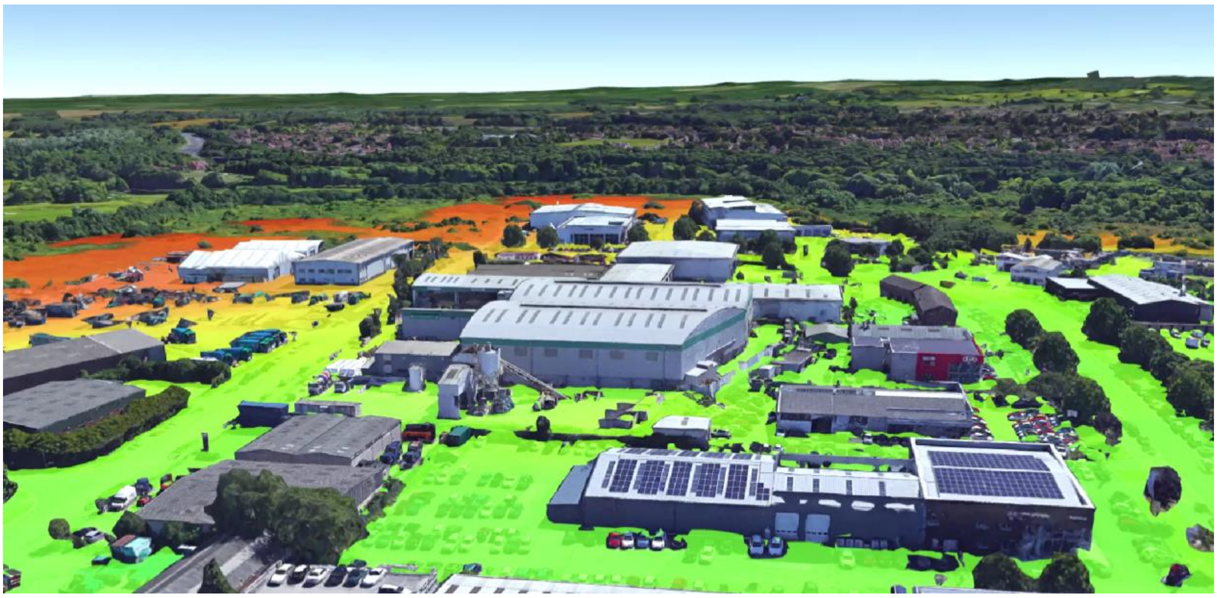


Figure 10. Ground surface vertical velocity (mm/year) presented as coloured pixels on a 3D surface model

Vertical and horizontal displacement

The displacements obtained from InSAR, whether from one pair of images or a time series, are in the line-of-sight (LOS) direction, i.e. along a straight line from the satellite antenna to the object on the Earth's surface. The ascending and descending orbits have different LOS directions on opposite sides of the vertical axis at known incidence angles as illustrated in Figure 11. Displacement data is derived independently from ascending or descending images. Positive values denote movement towards the satellite and negative values movement away from the satellite.

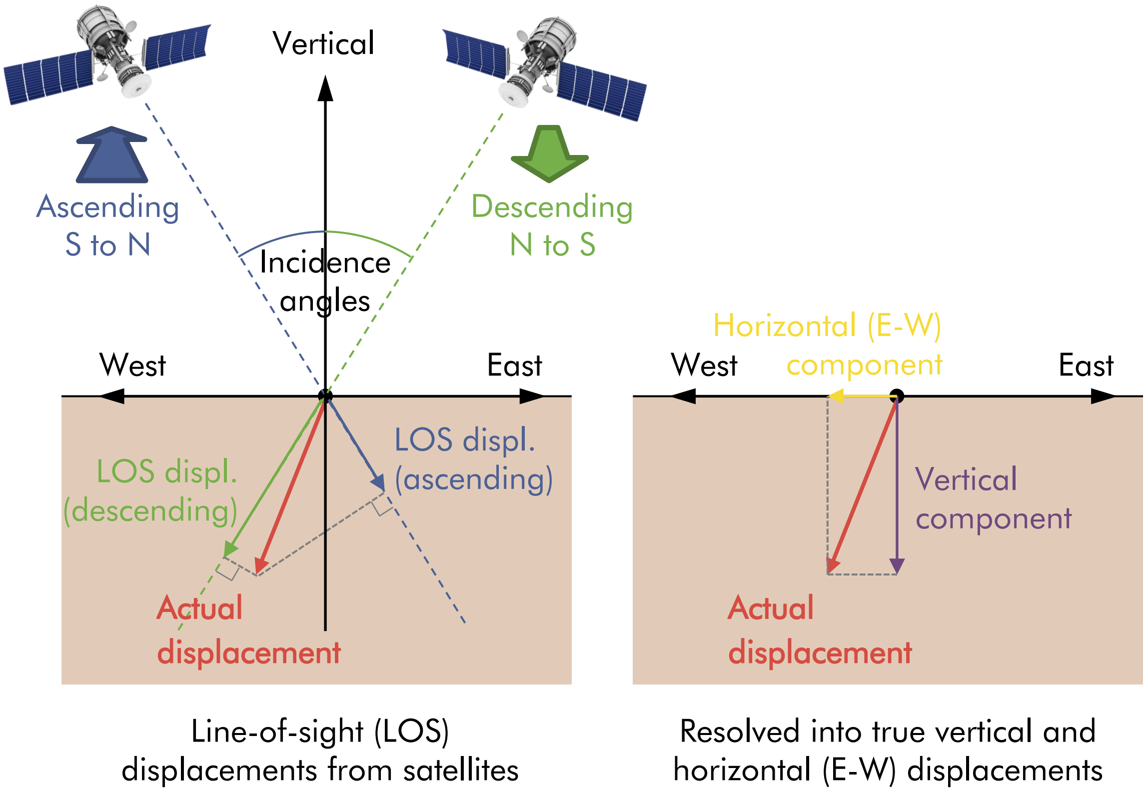


Figure 11. Converting displacement data from LOS to true vertical and horizontal (E-W)

On its own, LOS displacement data provides an indication of patterns of movement. If it is known that movements are predominately vertical (e.g. heave and subsidence of a horizontal ground surface), then vertical displacements can be deduced straightforwardly. If the prevailing direction of displacement is unknown (e.g. on sloping ground), then one set of LOS displacements may be insufficient to deduce the true pattern of movement.

When both ascending and descending orbit LOS displacement data at known incidence angles have been obtained, then displacements can be resolved into true vertical and horizontal (east-to-west) directions, or in other directions such as in the direction of east-west sloping ground. Some temporal interpolation is required because the ascending and descending images are not acquired at the same time and some spatial interpolation is required because the measurement points may be distributed differently between the ascending and descending images.

Horizontal displacements can be determined currently only in the east-west direction due to the near-polar orbit of the satellites and the east-west inclination of the satellite views. Data analysis techniques to decompose displacements into the horizontal north-south direction are under development and will be available soon. Also, new satellites with mid-inclination orbits, such as at 45° to the polar orbit, offer the possibility of detecting north-south horizontal displacements more easily in the near future.

Soil moisture

The amplitude of reflected SAR signals depends on a number of factors, in particular surface roughness, slope angle and the dielectric constant of the ground. Soil moisture influences the dielectric constant so, with all other factors constant, changes in the amplitude of received signals between successive images indicate changes in soil moisture. With some in situ measurements to determine absolute values of moisture content and to calibrate their variation with SAR amplitude, useful maps of soil moisture, such as that shown in Figure 12, can be produced. This a very useful application of SAR data in geotechnical engineering because geohazards such as landslides and swelling clays are heavily influenced by changes in soil moisture.

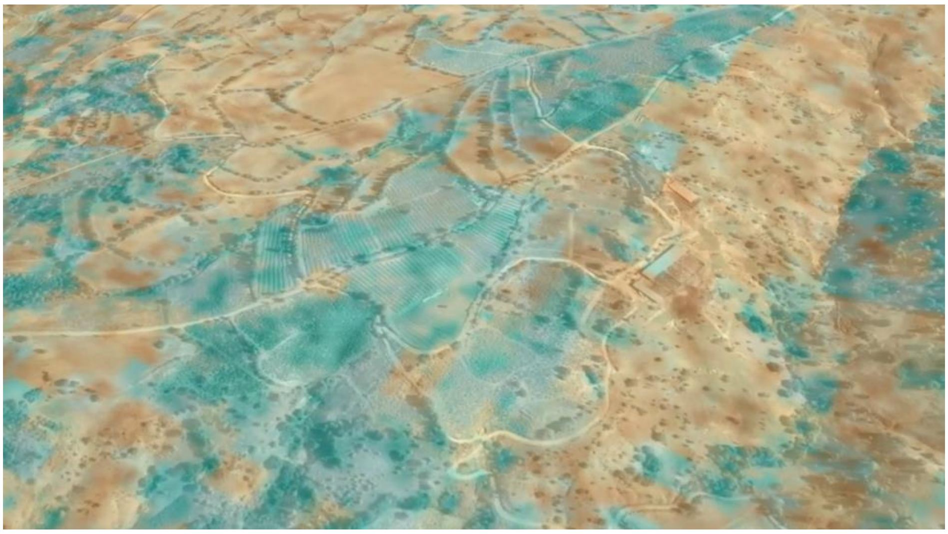


Figure 12: Calibrated satellite SAR soil moisture output

GIS

Large data files of displacement, soil moisture and other data associated with their geolocation are created. These are best uploaded to a web-based geographical information system (GIS) for viewing the data overlaid on maps, optical satellite images or 3D surface models. GIS also allows the plotting of temporal graphs and profiles, setting warning trigger levels and downloading specific data sets of interest.

FAQs

What's the spatial resolution of data?	This depends on the satellite. Freely available Sentinel-1 data has a resolution of about 5m in the range (E-W) direction and about 20m in the azimuth (N-S) direction. Some commercial satellites have much better spatial resolution and planned missions have sub-metre values.
How accurate is the displacement data?	The displacement accuracy is about 2-4mm on accumulated displacement and 1mm/year on velocities. But note that displacements may be the average of various reflecting objects within a pixel (20m x 5m in the case of Sentinel-1 images) or from one particularly strong reflecting object, so the uncertainty is greater on the spatial distribution of displacement within each pixel than the averaged displacement value itself.
How often is data recorded?	Freely available Sentinel-1 data alternates between ascending and descending image captures every 3 or 6 days for most land-based locations. Commercial data may be available more frequently and some satellites can even be tasked to capture data from a location as often as daily. Note that time-series InSAR analysis for millimetric displacement precision must be repeated each time a new image is acquired.
Have these techniques been validated?	The ESA-funded Terrafirma project in 2009 validated SAR data from rural and urban sites in The Netherlands. They found standard deviations of differences between time-series InSAR and ground truth of only 1.0 to 1.8mm/year (search "Terrafirma validation" on internet). There are also countless other examples of InSAR data complemented by and co-validated with in situ surveys.
How accurate is the location of each data point?	While displacements are measured with millimetric accuracy, the location of a data point associated with a displacement value can be up to about 10m out in the horizontal and vertical direction. Higher spatial resolution tends to mean higher geolocation accuracy, so the error may drop to about 1-3m for high resolution commercial satellites.

Do the techniques still work in vegetated areas?	While the built environment reflects SAR signals very well, the natural landscape and vegetation reflect SAR signals in a more irregular and unpredictable way. Vegetation also changes and grows with time. These all mean that fewer or no measurement points may be obtained as vegetation density increases. There are InSAR analysis techniques to help overcome this in many cases. Alternatively, using longer wavelength SAR increases the penetration through vegetation at the expense of spatial resolution.
Can you guarantee that data for a particular object will be obtained?	It is possible to estimate the density of measurement points that will be obtained and the higher the density the higher the probability of obtaining data near a particular point of interest. Note that geolocation uncertainty also means that you can never be sure that a specific point in space to, say, the nearest 50cm is being measured. The only way to do this is to install a corner reflector (see below).
How far back can historical data go?	Freely available Sentinel-1 SAR data exists for most of the Earth's land surface from 2014 onwards. Earlier SAR satellite data exists from 1991 to 2012 with less complete coverage. Other commercial satellite data is likely to exist for major cities and some other areas of interest and archives can be searched.
Do the techniques work in cloud cover?	Yes, SAR operates in microwave and radio wave parts of the electromagnetic spectrum which means they go straight through clouds and operate in any weather conditions, day and night.

CORNER REFLECTOR

Where insufficient measurement points are obtained or to guarantee displacement data at a specific location, a metallic trihedral corner reflector can be installed. It needs to be designed to be the correct size (typically about 1m across) and to point in the right direction towards the ascending or descending orbit of the chosen satellite. It will not provide historical data prior to its installation.

EXPERT OPINION

Prof. Hannes Gräbe, PhD, Pr Eng, FSAICE
Chair of Railway Engineering, University of Pretoria, South Africa

Prof. Hannes Gräbe is a researcher at the University of Pretoria, focussing on condition monitoring of railway infrastructure with a specific emphasis on digital technologies and innovations that can increase the performance and competitiveness of railways.

Professor Gräbe, what are the biggest challenges faced by infrastructure today?

Ageing infrastructure, underfunding in recent decades, increased demand (pre-covid), security issues like theft and vandalism and climate change bringing increased susceptibility of assets to geohazards such as landslides, sinkholes and swelling clays.

How do geohazards affect railways?

Geohazards have both chronic and acute effects. Swelling clays and creep landslides cause continuous degradation to track geometry which is costly to repair but never goes away unless the underlying causes are identified and mitigated. Maintenance tends to be reactive and consumes infrastructure budgets year after year. There is also the risk of sudden failure of infrastructure due to a fast-moving landslide or newly activated sinkhole. These are disruptive to the operation of infrastructure and are often repaired in a rushed and reactive fashion, possibly without removing the root cause leading to reactivation of the geohazard or its migration along the route.

"Maintenance tends to be reactive and consumes infrastructure budgets year after year"

What are the recent advances in the monitoring of infrastructure?

Sensors for in situ monitoring of known problem areas, InSAR displacement and soil moisture measurement of large areas to identify problem areas, show trends and plan maintenance more proactively.

How do you see the application of satellite SAR data to infrastructure developing in the future?

Its use will only increase as asset stakeholders experience the benefits for themselves and as satellite technology continues to develop. I see InSAR being integrated more into infrastructure asset management and early warning systems, combining the satellite data with other information such as geology, topography and track or pavement geometry to provide an overall score of susceptibility to geohazards, predict trends and plan maintenance tasks years in the future.

"I see InSAR being integrated more into infrastructure asset management and early warning systems"

Landslide damage on US infrastructure: $2-4 billion per year.

"Asset management helps prioritize limited funding, developing a clear picture of where the available funding is most needed."
ASCE Report Card 2021.

THE BUSINESS CASE

Here we look at evolving infrastructure policies and the key advantages of infrastructure asset monitoring by SAR satellite data in terms of operational efficiency that together form a compelling business case for adopting this technology.

Weight of opinion

Policy makers and infrastructure experts across the globe have long recognised the huge challenges faced by all countries to manage their vast but ageing infrastructure networks. In the first ASCE Report Card as far back as 1988, America's infrastructure was described as "barely adequate to fulfil current requirements, and insufficient to meet the demands of future economic growth and development." Subsequent Report Cards have shown infrastructure condition has not improved and use has only increased. Climate change has worsened the situation as infrastructure is exposed to more extreme weather events, requiring greater resiliency.

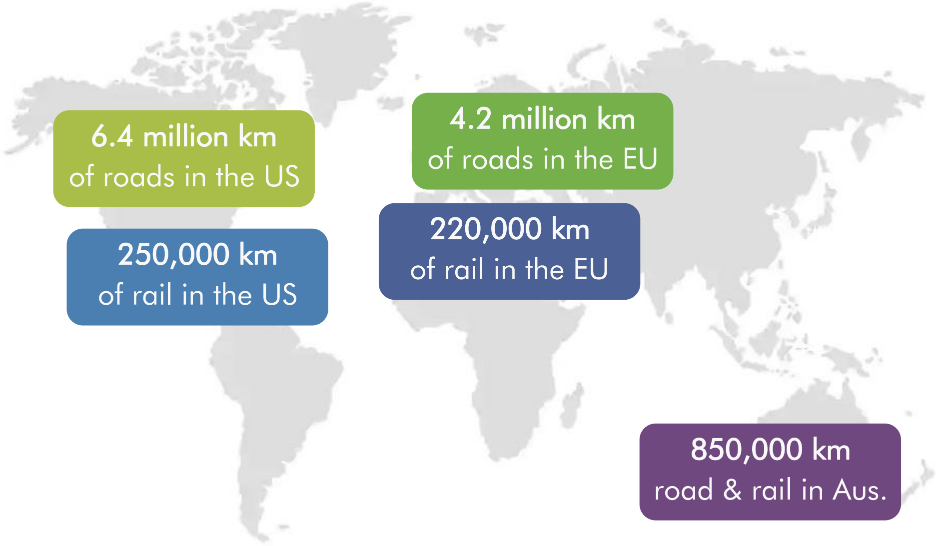


Figure 13. How will all this infrastructure's condition be assessed?

It is increasingly recognised that data and technology offer the infrastructure asset management tools that can play a large part in overcoming these challenges. Policy and opinion documents from national engineering societies have shown increased focus on the adoption of these solutions. That's not only because they are more efficient than traditional survey methods, but also because they significantly improve the management of the limited resources available to infrastructure owners. Maintenance becomes better planned because defects are known even before they become visually apparent. For example, faulty drainage may be detected by increased soil moisture content from SAR data or the first signs of displacement by InSAR analysis may pinpoint next year's landslide. So, the technology allows more proactive maintenance than ever before.

"We must focus on better using our existing assets through whole-of-life-cycle approaches and better use of data and technology."
ICE State of the Nation 2020.

Are you reactive or proactive?

When it comes to infrastructure maintenance, the benefits of a proactive approach are far reaching as illustrated in Figure 14. Satellite SAR data facilitates this approach by detecting defects quickly and before they become visually apparent.

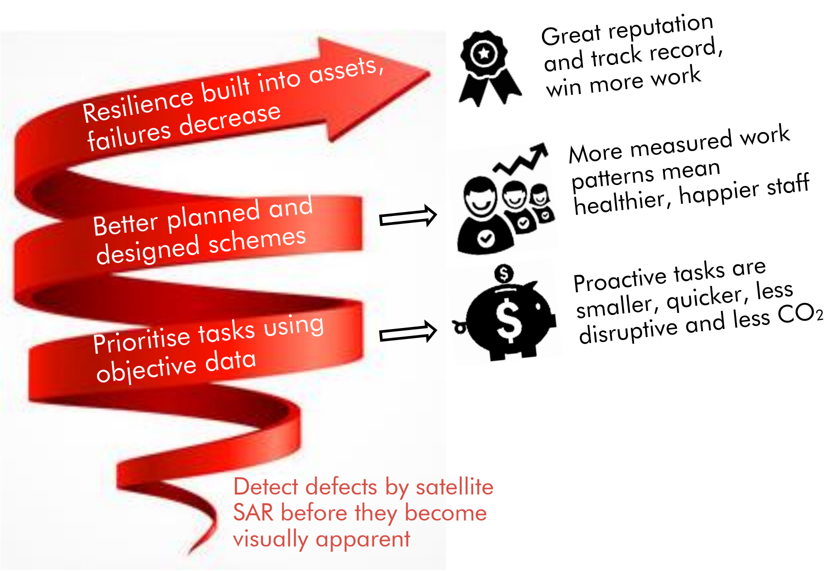


Figure 14. The cumulative benefits of proactive maintenance

"Leverage proven and emerging tech to make use of limited available resources."
ASCE Report Card 2021.

Reactive maintenance, or "firefighting" as it is often referred to on the ground, rarely builds in long-term resilience because there is never time for a properly planned and designed remediation scheme. Repair works tend to be on a larger and more disruptive scale, pressures are high, leading to an unhealthier and less safe working environment. It is very difficult to bring a permanent improvement in infrastructure performance by a reactive maintenance approach because the root cause of problems often remains.

"Data is now as much a critical component of infrastructure as steel, bricks and mortar."
National Infrastructure Commission UK 2017.

"Data is a precious thing and will last longer than the systems themselves."
Sir Tim Berners-Lee.

An early intervention in asset maintenance, as facilitated by regular, objective condition surveys, significantly extends the life of an asset as illustrated in the diagram of required versus provided asset capacity in Figure 15. Trends of decreasing capacity can be identified from the regular, objective monitoring. The trends can then be extrapolated to predict the ideal time for interventions before repairs become urgent, more costly and more disruptive. Many assets are exhibiting an increasingly rapid deterioration due to more extreme and frequent weather events as a result of climate change. If properly designed, the intervention can both raise capacity and slow deterioration of the asset, thereby significantly extending life and building in increased resilience against ongoing climate change.

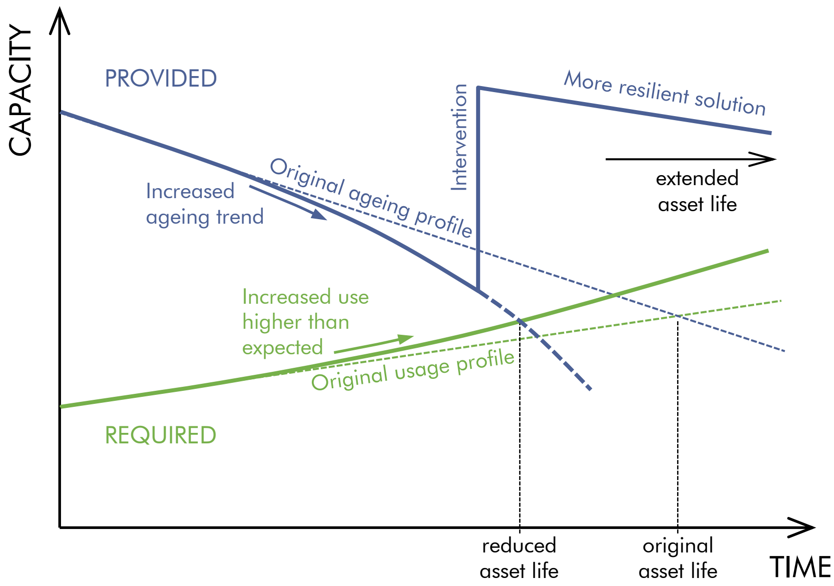


Figure 15. Improving asset resilience by early intervention

The case for satellite SAR data

The benefits of satellite SAR data sources in infrastructure asset management are many, as summarised in Figure 16. Some of the benefits are unique to this format and cannot even be obtained with other recent technological approaches.

A key benefit is the value for money offered by this technique. No other data collection method comes close in terms of the total area or linear km's and rate of measurement that can be achieved over a whole year. For example, a single, annual visual inspection at $900 per km would cost $90,000 for a 100km network. For less than half this cost, the entire 100km network could be surveyed by satellite SAR 60 times in one year!

Figure 16. The many benefits of infrastructure monitoring by satellite SAR

Saving for 60 satellite SAR surveys over 1 visual inspection

"Data-driven maintenance is needed to maximise longevity of asset life and reduce waste in the infrastructure sector."
ICE State of the Nation 2020.

Naturally, satellite SAR should not replace visual inspections but rather support them. The strength of satellite SAR data lies in its regular, whole-network coverage, avoiding the need for personnel to see the whole network so regularly. Instead, their precious time can be spent focussed on those areas pinpointed by satellite SAR data as areas of concern or those locations that are hidden from satellite lines of sight (e.g. in tunnels or through dense forests) that could be monitored by in situ methods. While satellite SAR can provide clues to the cause of a defect, such as displacement patterns or increased soil moisture, that may not be visually apparent yet, there is no substitute for investigation by the human eye.

The frequency of satellite SAR data acquisition – every 6 days or less – and the immediate, automated processing mean that defects are usually discovered earlier than on more typical inspection regimes. Furthermore, the sensitivity of displacement and soil moisture measurements means that defects may be found even before they become visually apparent and which otherwise might have been missed by visual inspection. Early detection allows early intervention which means quicker, cheaper and less disruptive remediation – reaping the benefits of proactive maintenance as highlighted in Figure 14. The longer an infrastructure asset can be kept in good health, the more its life can be extended and the greater its value to the owner.

The complete snapshot of network condition with each satellite pass is difficult to replicate with other techniques which take longer, perhaps weeks or months, to collect data from the whole network. During this time, weather conditions, the seasons and time of day could all vary. Indeed, the resilience of assets to an extreme weather event such as a flood across the whole network can be assessed in a consistent way in an instant. Furthermore, with the entire network being surveyed at the same time and processed into asset condition by the same algorithms, the bias introduced by human assessment is avoided.

Another unique feature of satellite SAR is the archive of data that already exists. On day one of implementation, at least 6 years of network condition data is available. That means asset condition trends can be identified and future trends immediately predicted. Network maintenance can then be planned years ahead in a much more informed manner.

When infrastructure asset condition trends can be predicted

Since the data is collected remotely, no site visits or equipment are needed. So, there is no disruption to the operation of infrastructure and no long journeys to site or along route networks, reducing the carbon footprint of these tasks. It also means personnel can spend more time safely in the office and only visit locations identified with potential defects or those sites hidden from satellite lines of sight.

All the data is immediately stored on a secure, web-based GIS accessible from any device with internet access. So, time is saved by avoiding record-keeping and archiving of survey data. Trigger levels can be set so that the pertinent people are informed immediately when any defect has been identified on the network.

CASE STUDY 2

Dubai-Fujairah Freeway, UAE

The Dubai-Fujairah Freeway is a 45 km highway across the UAE, including a section through the rugged Hajar Mountains with enormous volumes of cut and fill. Some sections are supported on record-breaking 70m high reinforced soil walls and on their 10th birthday Tensar wanted to check how they were performing.

THE CHALLENGE

- Performance data was needed but no monitoring equipment had been installed. This meant that no retrospective data could be obtained.
- Performing in situ surveys of such large structures was expensive and required multiple return visits to detect trends.
- Working on the open highway or the steep mountainous terrain was very hazardous.

THE SOLUTION

- InSAR analysis was performed on satellite data of the area over a four-year retrospective period
- The satellite data was combined with the in situ monitoring data collected during and after construction, demonstrating the excellent wall performance over the 10 years since construction.

THE BENEFITS

- Tensar were able to demonstrate ongoing excellent performance of one of their flagship projects.
- Performance trends were immediately obtainable without having to wait months to accumulate monitoring data.
- The data was collected in a safe and non-disruptive manner without needing to visit the site.

IMPLEMENTATION

When satellite SAR data is being considered as an infrastructure asset monitoring option, providers of these services should be approached to discuss suitable solutions. At this initial stage and through all the subsequent stages possibly all the way to purchase and application, it is good to know the right questions to ask so that the service meets everybody's expectations. The purpose of this chapter is to provide outline guidance on some of the issues that need to be raised and agreed upon when procuring satellite SAR data.

Procurement

Ideally at an early stage in the procurement process but certainly prior to signing, it is vitally important that all infrastructure asset stakeholders as well as the provider of the satellite SAR data understand the purpose of the data collection. All need to be clear on what output will be produced following processing and presentation of the data and agree that it is appropriate for the intended purpose. The output should also be obtainable accurately by a well-defined process. All these are important because satellite SAR data involves advanced and continuously developing technology that may be unfamiliar to some stakeholders. A thorough engagement process with potential providers is recommended so that the right data sources and processing techniques are proposed to meet the needs of a project and to help ensure that stakeholders fully appreciate the service being offered.

"A thorough engagement process with potential providers is recommended"

For example, it may not be possible to obtain satellite SAR data for the entire length of an infrastructure network due to some sections being hidden from the view of the satellite by dense vegetation. It is better to discuss these issues openly and alternative data collection methods arranged beforehand, such as short lengths of regular visual inspections, rather than stakeholders learning later that there are gaps in network coverage.

The starting point for internal discussions is to set the goals and objectives of the infrastructure asset monitoring and to decide what information is required. To plan the full regime of monitoring that may include other techniques as well as satellite SAR data. Which parts of the network inventory should be included? Will an initial pilot study be undertaken if the techniques are being applied for the first time? Is the desired monitoring area visible to satellites at all the locations? Note that larger areas provide a greater opportunity for comparisons between sections and to pinpoint unusual or at-risk asset performance.

The duration of the monitoring is important as is the frequency of output generation and these need to be considered within the life-cycle planning of the assets. Will the results be reported at set intervals in a formal manner, or the data uploaded to a GIS platform and stakeholders notified of an update? Is the monitoring intended to facilitate maintenance planning or to provide early warning of possible failures?

Once the goals and objectives of the monitoring have been agreed internally, detailed discussions with potential providers of satellite SAR data should be held to reach a common set of expectations for the information that can be obtained. Providers can confirm which parameters can be obtained in different parts of the network, the likelihood of obtaining sufficient measurement points, the accuracy and precision of data, spatial resolution, geolocation accuracy and frequency of measurements. They can propose strategies and options for increasing the amount and quality of information obtained.

An important consideration is for the internal resources and protocols within the relevant stakeholder organisations to be planned and ready for the arrival of the first satellite SAR data. Who will be responsible for viewing and interpreting the data, monitoring trends and acting on alarms? Will the client or data provider be responsible for interpretation and recommendations? Do either the client or provider have sufficient in-house expertise and resources to view and interpret the data? Engineers are needed for interpretation and decision making, in particular to avoid false alarms, but a different skill set to those associated with other asset monitoring methods may be needed. Specialist skills are needed for data analysis, communication and storage.

"Who will be responsible for viewing and interpreting data?"

"Engineers are needed for interpretation and decision-making"

All the new information needs to feed into forward work planning and the decision-making process on the timing and nature of maintenance interventions.

Standards

The processing of satellite SAR data into high-precision outputs of displacement and soil moisture, for example, uses relatively recent technology that continues to evolve. Consequently, there is not much formal standardisation of the techniques although the techniques are scientifically rigorous, validated and peer reviewed. The growing use of these techniques in infrastructure asset monitoring means that there is a need for a degree of standardisation and standards development is in its early stages (see *Future* chapter).

Nonetheless, there are standards in related fields that should be adopted by providers and specified by clients. These include standards for data formatting (ISO/TR 19121:2000 *Geographic information — Imagery and gridded data*) and metadata formats (ISO 19115 *Geographic information — Metadata* in three parts) to facilitate the transfer of data more easily between databases and platforms. ISO 19650-1:2018 *Organization and digitization of information about buildings and civil engineering works* defines a common data environment (CDE) where the large amount of project and asset information collected these days should reside. PAS 1192-5:2015 *Specification for security-minded building information modelling, digital built environments and smart asset management* provides principles and requirements for managing smart asset management data securely.

There are also standards covering the broader field of asset management, such as ISO 55001:2014 Asset management — Management systems — Requirements which includes general requirements on the gathering and management of data as well as the selection of appropriate monitoring techniques when problems or concerns have been identified. PAS 55-1:2008 Asset Management, Part 1: Specification for the optimized management of physical assets published by the Institute of Asset Management (IAM) provides general monitoring requirements. It defines reactive and proactive monitoring and their application to review issues already identified or to provide advance warning.

Specification

As in all procurement, specifications can range from the very detailed to the quite open. With the processing of satellite SAR data into outputs such as displacement and soil moisture being relatively new technology under continuous development by various providers, open specifications based on performance and outputs are more suitable. Independent advice on specification should be sought at an early stage from potential providers of satellite SAR data.

Satellite SAR monitoring of infrastructure networks creates very large volumes of data that need to be accessible but managed securely to protect intellectual property rights and commercial interests and to keep sensitive information from getting into the wrong hands. So, data security is an area where organisations may choose to specify work in a more detailed way. Some of the standards described in the previous section provide specifications for data security.

Data back-up is essential to protect them from corruption, hardware failure and other risks. Greater data protection is gained by using different types of secure storage in different locations, such as locally and on cloud-based servers, while still having sufficiently fast access to the data.

Data visualisation is another area where specification may need to be more detailed, particularly if data needs to be displayed on existing infrastructure asset management GIS platforms. Some of the standards described in the previous section provide standard data formats for portability that may be adopted. Overlaying the data on maps or optical satellite images helps in the visualisation of the data and should be a standard requirement. Also, dashboard tools such as the plotting of temporal graphs or isochronous horizontal profiles and the possibility to download data in a transferable format to other data analysis software, e.g. spreadsheets, should come as standard. Warnings when pre-defined trigger levels are reached can also be specified to be managed by the GIS platform. Specific requirements on the security of GIS platforms are also summarised in the box below.

Web-based GIS SaaS minimum requirements

The web-based software-as-a-service (SaaS) is accessed using any of the latest versions of a modern web browser. No installation is required on the user's PC or device.

It should follow industry standard security protocols for web apps. The web app, database and geoserver should be hosted on a cloud server with disk encryption, SSL encryption and web application firewall (WAF). Data should be replicated for backup purposes to a remote location on a cloud server and again encrypted.

A closed registration policy should be adopted, meaning that a user can only gain access by invitation from the system administrator and authentication is needed before accessing any data. A strong password policy should be employed with password expiration and two-factor authentication to increase user login security. Each user is then connected to a specific set of data with no access to other data.

Pricing

The cost of providing processed satellite SAR data for infrastructure asset monitoring depends on a multitude of factors, as summarised in Figure 17. Note that there is not necessarily a linear relationship between certain factors and price. For example, if the study area were doubled in size, the cost of providing the data would not double because some of the tasks are automated and would simply involve some slightly longer computer processing times. So, economies of scale do have a significant effect.

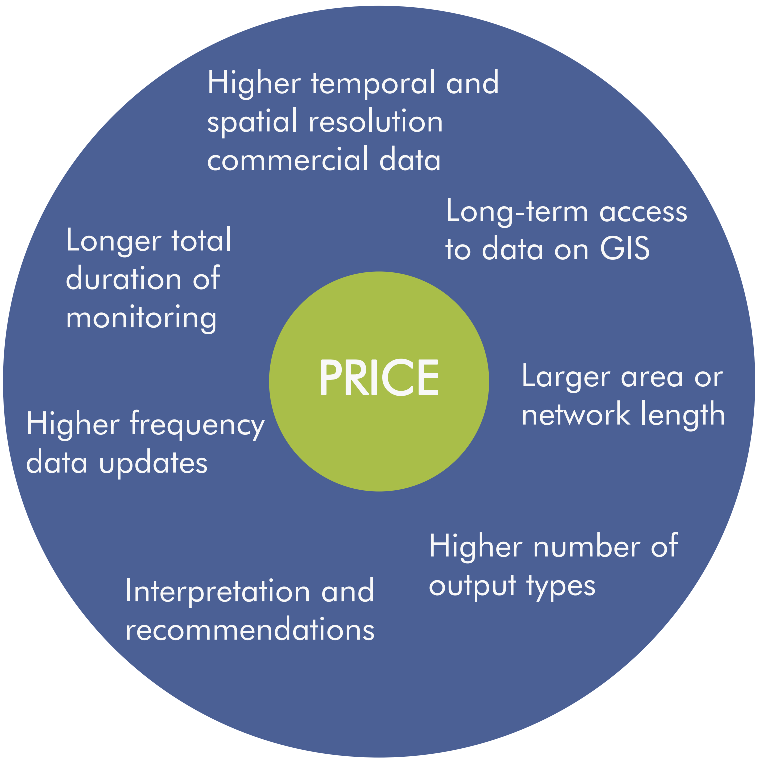


Figure 17. Factors that increase the cost of satellite SAR data

The frequency of satellite data acquisition and frequency of processing and updating output are not quite the same thing. Although data may be acquired every few days, costs can be reduced by processing data and updating output at longer intervals, say on a monthly basis, while still retaining the same temporal resolution of data. This is because time-series InSAR analysis needs to be repeated for the entire sequence each time new data is added, so the workload is much higher if the analysis is repeated every time new satellite data is acquired.

The volume of data and the length of time it needs to be accessible on a web-based GIS platform both have an impact on data storage costs on cloud-based servers.

The satellite data can make the greatest difference to the cost. It can range from cost-free to a significant proportion of project costs for commercial data with higher spatial and temporal resolution where that is required. Satellites can even be tasked to acquire data more regularly from areas of interest at even higher cost. This has a big impact on costs due to the high number of images (at least 20) usually required for analysis. Note that some analysis providers have agreements with certain commercial satellite data companies. While this may reduce the cost of acquiring the data, it means that providers can favour data from certain satellite data companies.

Satellite SAR data Procurement checklist

AGREED BY ALL STAKEHOLDERS

- ☐ Purpose of data collection
- ☐ Information needed
- ☐ Output that will be produced

TECHNICAL REQUIREMENTS

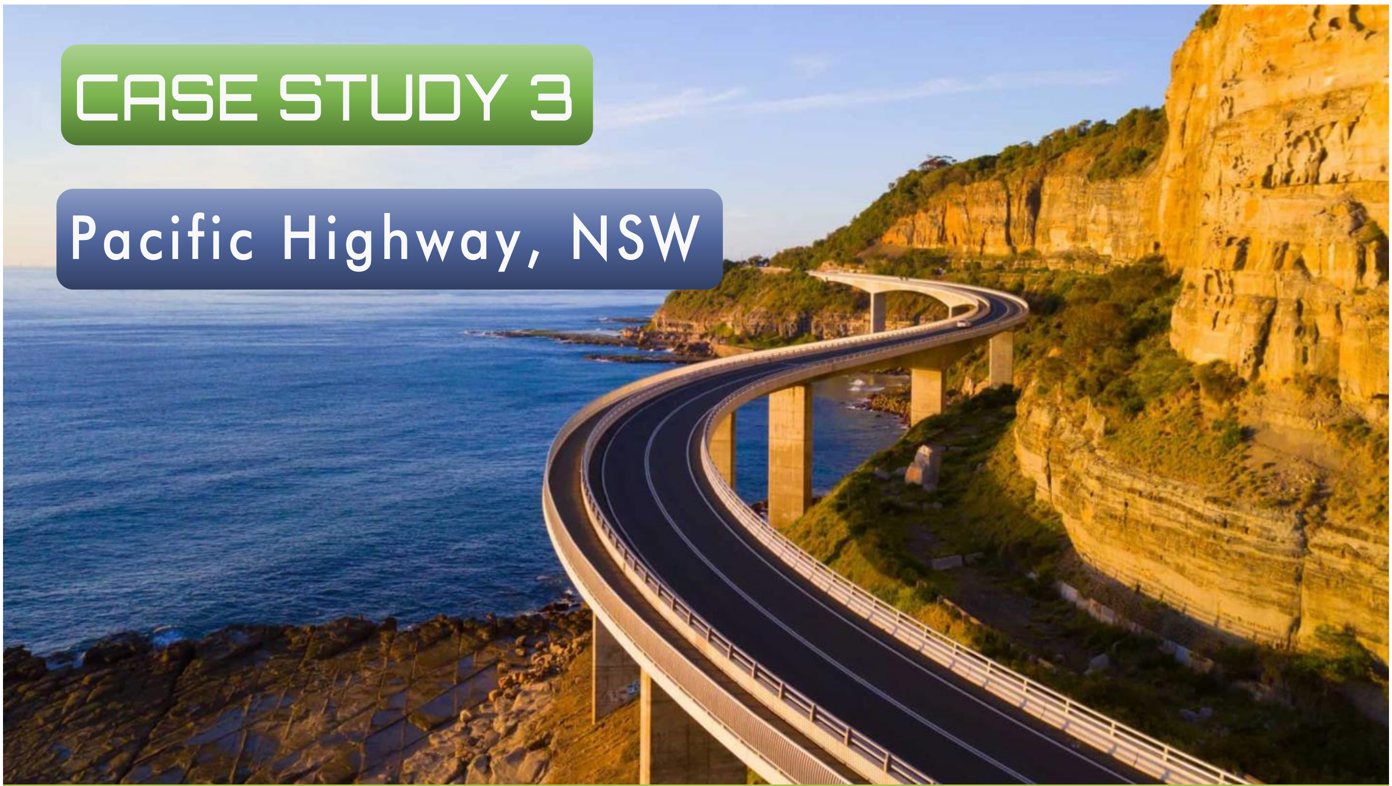
- ☐ Measurement precision & accuracy
- ☐ Network areas to be included
- ☐ Spatial resolution
- ☐ Geolocation accuracy
- ☐ Time interval between data updates
- ☐ Total duration of monitoring

PRACTICAL REQUIREMENTS

- ☐ Formal reporting
- ☐ Platform to access and view data
- ☐ Data update notifications
- ☐ Trigger levels for any warnings
- ☐ Protocols for issuing warnings
- ☐ Strategies for spatial gaps in data
- ☐ Combining other monitoring approaches
- ☐ Pilot study needed?

INTEGRATION

- ☐ Who is responsible to view the output?
- ☐ Who is responsible for interpretation?
- ☐ Who will respond to any alarms?
- ☐ Decision-making on interventions
- ☐ Who has the expertise to interpret data?
- ☐ Integration with forward work planning
- ☐ Integration with life-cycle planning



CASE STUDY 3

Pacific Highway, NSW

During construction of a new river bridge for the Pacific Highway in New South Wales, a dispute arose over displacements noticed in an existing adjacent bridge. One key advantage of satellite data is the ability to obtain information retrospectively. Combined with engineering expertise it becomes a powerful forensic tool.

InSAR bridge displacement data

THE CHALLENGE

- No displacement data for the existing bridge prior to or during construction of the new bridge was recorded, making it virtually impossible to establish the cause of the displacements.

THE SOLUTION

- InSAR displacement analysis of the existing bridge, abutments and riverbanks both during construction and for a two-year period prior to construction.
- Earthworks and other construction activities made obtaining coherent data particularly challenging, requiring a combination of analysis methods. Civil engineering expertise was needed to interpret the effect of construction activities on the displacement data and dismiss unreliable data.

THE BENEFITS

- Reliable, independently-determined displacement data – which was critical to the dispute – was available for the first time.
- A cause of the existing bridge displacements was established with a high degree of certainty.
- The dispute was settled in a more informed manner.

THE FUTURE

The increasing need to get more value from and extend the life of existing infrastructure in addition to increasing asset resilience to greater weather extremes due to climate change all point to a growth in the use and value of continuously updated asset condition data. Without large scale intervention, infrastructure failures could potentially become more frequent due to further ageing, greater use and worsening weather extremes.

The growing cost of conventional monitoring approaches, the safety-driven need to avoid site access where possible, the growing cost of site access and disruption and growing pressures for more sustainable work practices to minimise carbon footprint all mean that the adoption of remote sensing techniques of asset monitoring – satellite SAR data in particular – will continue to grow.

As more data is collected and as analysis methods are improved by utilising technologies such as artificial intelligence, predicting trends will become more accurate and it will be possible to revise the lifespans of infrastructure assets with greater confidence.

The new asset monitoring techniques will not replace the old (e.g. visual inspection) but interfacing between them needs to improve so that they are used in a balanced and effective way to maximise available resources.

The number of satellites, particularly commercial microsatellites, will continue to grow rapidly. This will bring more affordable high-resolution SAR data and higher frequency revisits. There will be greater choice of wavelengths suited to different applications and inclined orbits will permit easier horizontal north-south displacement measurement.

Increased adoption of satellite SAR data for infrastructure monitoring will bring some broad level standardisation while still allowing ample scope for further technological developments. The Geoscience and Remote Sensing Society (GRSS) of the Institute of Electrical and Electronics Engineers (IEEE) has already prepared proposals for standards development including in the field of satellite SAR data. Meanwhile, the *Monitoring in Geotechnical Engineering* working group of the ISO technical committee on Geotechnics is working on a draft document including annexes for new technologies such as satellite SAR data.

"Using AI can help extract maximum information from vast amounts of data about infrastructure assets."
National Infrastructure Commission, UK 2017.

CONCLUSION

Infrastructure owners are facing an unprecedented combination of challenges comprising ageing infrastructure, increased use, climate change and declining budgets. Assets are becoming increasingly susceptible to geohazards and, if left unchecked, failures and disruption are likely to increase in the coming years.

It has been shown that, when combined with other monitoring approaches, satellite SAR data provides a cost-effective, safe, reliable and objective means of determining the changing trends of asset susceptibility to geohazards. This allows forward planning of asset maintenance and better-timed interventions. It promotes proactive maintenance that involves smaller, quicker and less disruptive tasks than reactive maintenance. Work patterns are more structured with less pressure leading to happier, healthier staff.

As well as being corrective, maintenance interventions should build in improved resilience to the greater extremes of weather events that climate change is bringing. These can be designed in a more informed way with the trends of asset performance that can be measured today with years of historical satellite SAR data.

The continuing development of artificial intelligence technologies and launches of satellite constellations combined with the increasing need for cost-effective infrastructure asset monitoring mean that the use of satellite SAR data is likely to increase exponentially in the coming years.

Find out more about Geofem infrastructure geohazard monitoring services