Use of Orbital Synthetic Aperture Radar Data in Monitoring Geotechnical and Transportation Infrastructure Assets

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ABSTRACT

Persistent long-term monitoring of civil infrastructure such as pavements, highway embankments, and earth retaining systems is of significant interest to asset owners and stakeholders. The use of orbital synthetic aperture radar (SAR), a remote sensing technique, to assess the condition and performance of such assets has been attracting major interest from transportation agencies over the last decade. Currently, operational orbital SAR remote sensing systems have a high spatial and temporal resolution and interferometric capabilities that facilitate spatiotemporal monitoring of asset conditions along with centimeter-level deformation monitoring. This paper aims to provide a review of the use of SAR and interferometric SAR (InSAR) data in monitoring transportation/geotechnical assets. The review also sheds light on the recent explosion of the commercial SAR sector and its potential contribution to near real-time monitoring transportation assets in the near future. The basics of SAR and InSAR data and their relevance in assessing the condition of embankment slopes including a case study in Texas are presented here, along with the challenges and limitations of this technology specific to civil infrastructure. This study would benefit transportation/geotechnical academics and practitioners in understanding the advantages of using these novel remote sensing techniques as a reliable data source for asset management.

INTRODUCTION AND BACKGROUND

The 2021 National Transportation Statistics summary report states that the transportation system in the US has 4.2 million miles of highway with 3,261 billion vehicle miles traveled as of 2019 (USDOT 2021). The pavement and bridges alone in the transportation system have a replacement cost of $5 trillion (AASTHO 2020). The records for the financial year 2018 indicate that the total expenses and revenues (i.e., federal, state, and local) for highways account for up to $235 billion and $146 billion, respectively. Even with such expenses, more than 50% of interstate miles and 70% of major arterial miles have the International Roughness Index (IRI) greater than 60 (USDOT 2021). With an increase in the serviceability age of transportation infrastructures, a need for strategic planning and management to keep the functioning in an acceptable condition at a reasonable cost is of paramount importance. Transportation Asset Management (TAM) is defined as a strategic and systematic process of operating, maintaining, and improving the condition of transportation assets to a good/acceptable state at minimum cost with consideration of both engineering and economic aspects in the development of maintenance, preservation, repair, rehabilitation, and replacement actions. As per 23 CFR 515.5, "asset" refers to all the physical infrastructure components within a highway's right-of-way corridor, such as pavements, highway bridges, tunnels, signs, ancillary structures, and other physical elements necessary for the highway's operation (U.S. Government Publishing Office 2016).

Moving Ahead for Progress in the 21st Century (MAP-21) and Fixing America's Surface Transportation (FAST) Acts include provisions related to asset management and performance management for pavements and bridges where it requires state Department of Transportations (DOTs) to develop risk-based Transportation Asset Management Plans (TAMPs) for assets on the National Highway System (NHS) and prioritized state of good repair investments. Federal Highway Administration (FHWA)'s requirements specify that a TAMP should detail asset inventory, conditions, predicted future conditions, performance measures, asset management objectives, measures and targets, life-cycle planning, risk management analysis, financial plan, and investment strategies.

Pavements and bridges are the two asset categories mandated by federal regulations, but transportation agencies are encouraged to go beyond the two legacy asset categories within the Right-Of-Way (ROW). Geotechnical assets, such as retaining walls, slopes, embankments, and subgrades, within its vicinity, have a significant effect on the performance transportation system (NCHRP 2019). Assets outside NHS as well as other assets within ROW (such as slopes, embankments, retaining walls, and others) do not have any mandatory condition assessment requirement and create a gap in data. Such a gap in data limits the scope of the TAMP as these assets have significant importance in the overall functioning of a transportation system. For a DOT to start incorporating these assets, the implementation framework should at least have a lower resource (financial, technical, etc.) requirement at an initiation level (NCHRP 2019). A long-term consistent monitoring program for assets such as pavements, highway embankments, and earth retaining systems at a reasonable cost and with a quick mobilization can provide to expand the current mandated scope of the TAM. In addition, a short turnaround time in assessing the conditions of critical assets before and after extreme events in all weather will be of paramount importance to state and federal agencies like Transportation Management Center (TMC) which assists DOTs in identifying critical areas for repair and rehabilitation (Krechmer et al. 2012; USDOT 2019).

Remote sensing is a process of collecting and interpreting information about the environment from a distance typically using sensors and instruments that are located on aircraft or satellites. The process can be a useful tool for monitoring transportation and geotechnical assets network by providing valuable information about its condition and location (Jensen 2014; Stark et al. 2021). Remote sensing data can be easily integrated with other data sources, such as, weather and soil data, to create a comprehensive asset management system to track the life cycle of assets, identify potential risks, and prioritize maintenance and repair activities. Some widely used remote sensing data sources include Landsat, Sentinel-2, WorldView, GeoEye, Planet – for multispectral satellite imagery, USGS 3D elevation program, NOAA digital coast, OpenTopography, and state and local data portal – for LiDAR survey data, and Sentinel-1, TerraSAR-X, COSMO-SkyMed, ALOS-2 – for SAR data.

Synthetic Aperture Radar (SAR) is a remote sensing system capable of acquiring high-resolution, all-weather and day-night imagery of the Earth's surface. The radar transmits electromagnetic pulses that interact with the earth's surface and receives backscattered signals as amplitude and phase. The amplitude of the backscattered signal represents the strength of the radar echo received by the antenna. The amplitude is dependent on the physical properties, such as geometry and roughness, and electrical properties, such as the permittivity of the incident surface. Alternatively, the phase of the backscattered signal refers to the position of the radar wave in its oscillation cycle when it returns to the antenna. Amplitude and phase information of a SAR image can be used to generate data products such as an interferograms which can provide information on ground deformation. Generating time-series deformation from Interferometric Synthetic Aperture Radar (InSAR) is a highly effective remote sensing technique that is capable of measuring surface deformation with millimetric precision from space (Hanssen 2001; Minh et al. 2020; Stark et al. 2021).

SAR has been consistently used to monitor large spatial areas such as landslide and tailings monitoring at low cost, primarily by the geosciences/geomatics community (Carlà et al. 2019; Hanssen 2005; Hu et al. 2017; Lier 2015; Moruza 2017; Qin et al. 2020; Rosen et al. 2019). Although SAR has been widely embraced by the geosciences and geomatics communities over the past 15 years, there has been a dearth of research on its use for monitoring transportation and geotechnical assets in the US. A limited consistent long-term monitoring program, proprietary and specialized processing workflows, complicated data storage and sharing architecture, and prohibitively high cost of data acquisition and processing, are some of the reasons for SAR systems to remain within the specialized domain of radar remote sensing. However, since late 2015, European Space Agency's (ESA) Sentinel 1 program with its consistent 6-12 days revisit and open data policy has sprung interest in the civil engineering community for its use in monitoring transportation and geotechnical assets. In addition to that, the launch-ready NiSAR mission will also provide 12 days repeat cycle global coverage open data for the next decade (Rosen et al. 2019).

This paper offers an overview of the application of InSAR and SAR data in monitoring transportation infrastructures. A comprehensive highlight on the rapid growth of the commercial SAR industry and its possible impact on the management of transportation assets is provided. The significance of InSAR and SAR data in evaluating the state of assets such as pavements, bridges, and slope embankments, are discussed, featuring a case study from Texas. Furthermore, the article addresses the challenges and constraints associated with this technology, specifically in the context of geotechnical/transportation infrastructures.

GEOTECHNICAL/TRANSPORTATION INFRASTRUCTURE MONITORING

InSAR Data

One of the early reported use of SAR data for a highway transportation project in the US was by Power et al. (2006) on the FHWA's Federal Lands Highway Program (FLH) to evaluate the use of InSAR technology for monitoring slope movements affecting road networks during the late 1990s and the early 2000s. The study analyzed InSAR data from three sites with varying levels of coherence and movement characteristics to recommend an optimal condition for the use of InSAR on federal road projects. InSAR was identified as a promising tool for evaluating and monitoring the slope movement risks, either as an independent method or in conjunction with ground monitoring systems based on slope movement risk matrix. Revisits, sensor type, and provision of radar reflectors should be chosen based on coherence and slope vegetation. For instance, a low coherence slope with a high risk of slope movement is recommended to have corner reflectors (high coherence) with shorter revisits of 1 month compared to 3 months as area of low coherence produces noisy interferometric phase.

A substantial effort by the U.S. Department of Transportation (US DOT) under Cooperative Agreement RITARS-11-H-UVA and RITARS-14-H-UVA to study the implementation of InSAR monitoring techniques to allow early detection of geotechnical hazards affecting transportation system provided resulted in critical literature and training materials in the field of transportation geotechnics using the Italian X-band COSMO-SkyMed satellite's synthetic aperture radar. Bruckno et al. (2013) performed preliminary studies on the correlation of the InSAR data with sinkhole locations and rock/soil slope analysis using GIS. They also used displacement time-series to infer the condition of an infrastructure, which was validated with the field inspection. The validation of InSAR data allows for the creation of geohazard and infrastructure maps and could eventually lead to a performance-based infrastructure management system. Similarly, Hoppe et al. (2016) studied the feasibility of using these commercially available radar remote sensing technologies to monitor geotechnical assets in a transportation network. The focus was on sinkhole identification in karst terrain and rock and slope movement detection along the highway. A 40 × 40 sq.km area in Staunton, Virginia, historically prone to sinkhole development, was examined using bi-monthly satellite data for 14 months. The InSAR data was processed using the SqueeSAR™ algorithm – which involves a proprietary processing step to include permanent scatters, distributed scatters. and temporary scatters for increasing the target point density (Ferretti et al. 2011). The findings indicated that InSAR technology has promising applications in monitoring transportation infrastructure – specifically sinkhole detection and slope stability with a possibility to extend to bridges, tunnels, retaining walls, and railway lines.

A study to come up with a comprehensive and practical solution, with regard to selecting an ideal satellite configuration and effective processing workflow, for monitoring transportation-related linear geotechnical assets (slopes and retaining walls) was performed by Qin et al. (2020). The authors performed a division of the area of interest (AOI), the I-77 corridor in Virginia, into smaller sections that enabled each area to be processed separately, using individual reference points. This approach resulted in a larger decorrelation length, ensuring that the atmospheric phase screen (APS) has no impact on AOI of up to a kilometer. Furthermore, the study affirmed the need to select a stable reference point for accurate monitoring. In the case of a highway slope, the pavement or highway itself was more stable than the slope, making it an ideal reference point. The optimal configuration should minimize geometric distortion while maintaining a decent signal-to-noise ratio (SNR). The study concluded that the persistent scatterer (PS) approach on the descending X-band COSMO-SkyMed (3 m resolution) with 52.6 degrees incidence angle and 8-day revisit is the best candidate for monitoring such assets. In addition to displacement, slope failures typically cause significant alterations to surface characteristics, which in turn affect the amplitude of SAR imagery. A cumulative change detection map provides an overview of areas that have experienced notable changes in historical SAR images. By processing this cumulative change map, it is possible to identify the locations of slope failures, offering valuable insights into potential risk areas.

SAR Data

In addition to the use of displacements from a complex InSAR processing, the amplitude of high-resolution SAR data acquired at the X-band has been used to map pavement roughness. The study by Meyer et al. (2020) examined the potential use of satellite radar remote sensing data, specifically X-band high-resolution SAR data, for mapping pavement roughness across the US road network. The authors showed that the amplitude of the radar data tends to increase with deteriorating pavement conditions by comparing the amplitude from high-resolution X-band Cosmo-SkyMed images with International Roughness Index (IRI) measurements. The classification model, based on exponential model and IRI thresholding, was developed to differentiate the condition of road sections with 92.6% overall accuracy in test sites in Augusta County, VA to demonstrate the potential of SAR amplitude data for pavement condition monitoring.

Since the late 2020s', Capella Space® and ICEYE® – have established a constellation of X-band microsatellites (under 200 kg.). These SAR satellites are capable of providing very high-resolution data, i.e. spatial resolution of up to 0.25 m. and temporal resolution of up to 3 hrs (ICEYE 2023; Laurila, Pekka 2020). Such characteristics make this source of SAR data from the microsatellite platform a potential information source for sustainable geotechnical and transportation asset management as well as a source for Emergency Operation Center (EOC) and TMC before, during, and after a natural disaster on the condition of critical infrastructure.

CHALLENGES IN MONITORING GEOTECHNICAL AND TRANSPORTATION ASSETS

Bruckno et al. (2013) identified that geotechnical and transportation assets suffer from issues of coherence loss in ground motion due to the significant change in surface radar response. Despite the challenge of coherence loss in areas with the sudden ground or infrastructure motion, new methods are being developed to identify scatterers that maintain coherence within various time intervals and use them to generate time-series information.

InSAR detects ground movement in the Line of Sight (LOS) direction – the line connecting the SAR sensor and target on the ground. With radar satellites flying in sun-synchronous polar orbits approximately 10 degrees off the north-south direction, InSAR primarily captures east-west and vertical movements. As the detected movement by InSAR is projected onto LOS direction, the detection is dependent on the local incidence angle and the satellite flight direction. The satellite's position relative to the slope determines whether the unstable surface moves towards or away from the satellite. A narrow angle between the LOS and slope will result in low backscatter, i.e., low SNR, towards the satellite but will be sensitive to the slope movement. On the contrary, in cases where the LOS is orthogonal to the slope, i.e., higher SNR, but the movement to the LOS direction is close to zero, rendering the satellite unable to capture ground surface movement. A case study of such phenomenon in slope along a highway was reported in a study by Qin et al. (2020). Therefore, while selecting the type of sensor and satellite configuration for a certain asset of interest, it is essential to consider the effect of incidence angle to balance the SNR. Corner reflectors are strong, human-made scatterers that often display high SNRs on SAR images and have shown the potential to provide consistent coherence measurements. These corner reflectors are made of two or three mutually perpendicular metallic plates, that reflect signals back directly towards the SAR satellite.

High entry costs and computationally intensive data processing have been a challenge for many assets owner to adopt InSAR in monitoring assets is a primary reason for limited document application in the geotechnical and transportation sector. The monitoring cost of around $100/km^2 per year was reported by Hoppe et al. (2016) and is expected to decrease in the future.

In the late '90s and early 2000s, quarterly monitoring costs ranged from $16,000 to $48,000 (Power et al. 2006). Human intervention, such as preventive maintenance or any construction activities on any existing infrastructure, causes alteration to the surface characteristics that can affect the backscattered radar signal and influence the interpretation of SAR data. Therefore, it is also essential to account for anthropogenic factors in processing and analyzing SAR data.

Despite the challenge, SAR and its derived products remain a valuable tool for monitoring, detection, and early warning of geotechnical and transportation assets, offering effective large-scale scanning and monitoring of transportation corridors with dense infrastructure. The progress in the field can be attributed to the advancements in SAR satellite technology and the growing archive of imagery. A decade ago, with only a few SAR satellites in orbit, civil engineering projects like slope monitoring might have been limited to proof-of-concept studies – using low-resolution data (both spatial and temporal). However, the increased number of operational satellites today enables monitoring of nearly any location on the earth, offering a multitude of options for geotechnical and transportation asset management.

CASE STUDY – EMBANKMENT SLOPE FAILURE IN TEXAS

The slope section of the highway embankment is situated in Denison, Texas. The slope is adjacent to the southbound US 75 Frontage, between Randell Lake Road and State Highway 91. Initial desiccation cracks were spotted in 2014 close to the slope's base, followed by a superficial failure in December 2015 as shown in Figure 1. The slope failure expanded to the pavement in 2016, causing structural damage and leading to the road's closure by the Texas Department of Transportation (TxDOT). A December 2017 site assessment disclosed significant cracks and surface failures on a stretch of pavement measuring 18.3 m. in length and 1.8 m. in depth over the southbound lane, as depicted in Figure 2. The failure continued to develop and impacted 134.7 m. section of both pavement lanes by November 2018 as shown in Figure 3.

Figure 1. Initiation of cracking at Denison Case Study in 2014 and progress to 2016

Preliminary analysis of time-series InSAR was performed at this location to examine whether the unusual slope movement could be detected. The time-series deformation for this site was created using Sentinel-1 data downloaded from Alaska Satellite Facility (ASF) Data Portal and processed using ENVI-SARScape. The preprocessing steps typically include radiometric calibration, speckle filtering, and co-registration. The interferogram is generated between any two pairs of SAR data set forward by the user. After generating the interferograms, a time-series analysis was performed. The default settings for Sentinel 1 processing were used for the preliminary analysis. Typical processing steps for time-series InSAR is shown in Figure 4. The results of the preliminary analysis of the spatial location that did not and did experience failure are shown in Figure 5 and Figure 6 respectively.

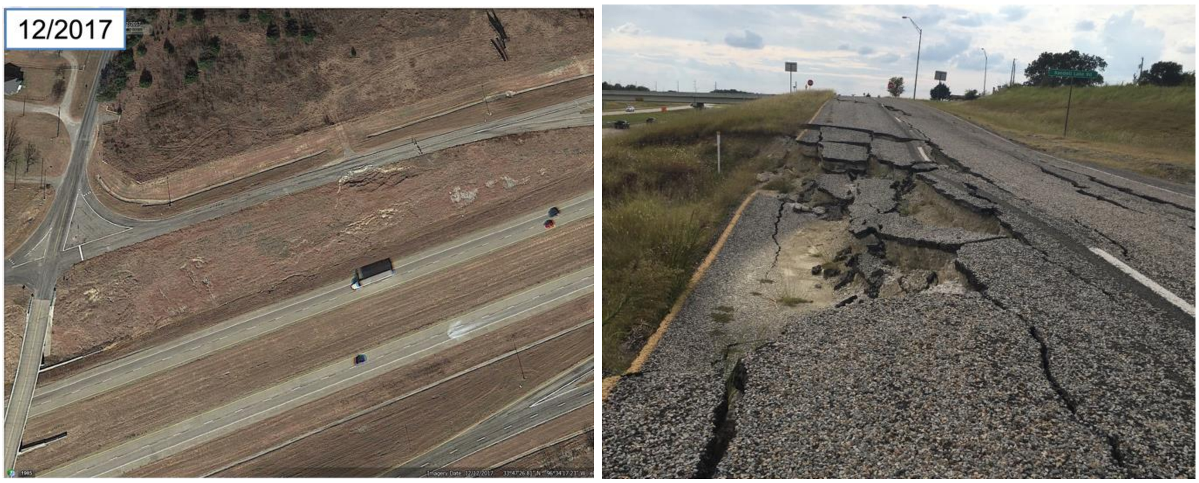

Figure 2. Severe cracks visible at Denison site during December 2017 site visit

Figure 3. Propagation of severe cracks at Denison in November 2018

Figure 5 results show that the LOS movement of the slope is small or practically non-existent. Although a small magnitude of negative movement can be till 2020 – corresponding to the timeline when the slope was rehabilitated. This suggests that even though site visit photographs and aerial imagery (Figure 2 and Figure 3) at the point of interest shown in Figure 5 do not show any visible problem, InSAR suggests that there could have been a small amount of movement which ceased after the rehabilitation work was completed in early 2020. A similar but higher magnitude trend can be seen in Figure 6 – the location of extensive failure where the time-series InSAR results show the result of LOS movement of the slope area. The higher magnitude of LOS movement in the toe of the slope until early 2020 (end of rehabilitation of slope) and then flattening, as shown in Figure 6, was captured by time-series preliminary InSAR processing. The authors believe that the ambiguity error during unwrapping is potentially present in the interferograms involving the acquisitions of early 2018 to late 2019 as the area experienced rapid slope movement. This results in lower than actual magnitude of LOS displacement seen from time-series InSAR. Medium spatial resolution and a revisit of 12 days exacerbate such potential ambiguity. The use of higher spatial resolution with short revisit would be an ideal platform for monitoring faster moving slopes.

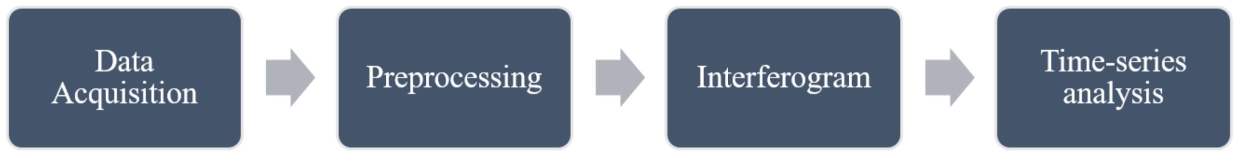

Figure 4. Typical processing steps for time-series InSAR

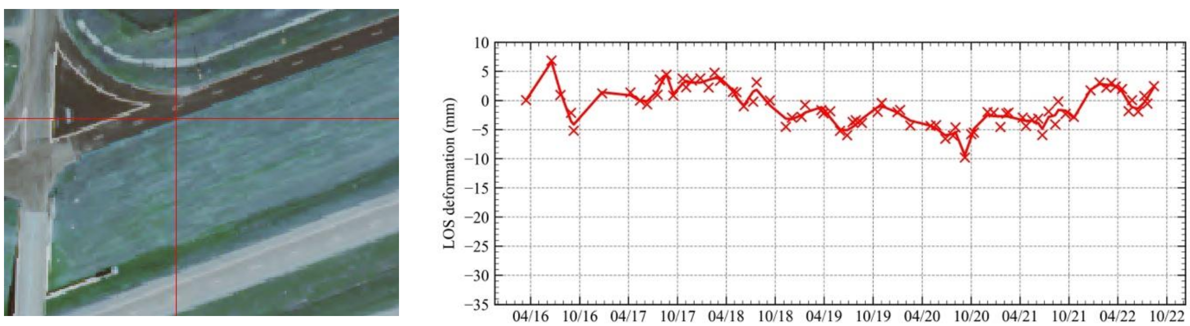

Figure 5. Time-series InSAR results of slope at the Denison location that did not show any substantial movement on site from 2016 to 2022

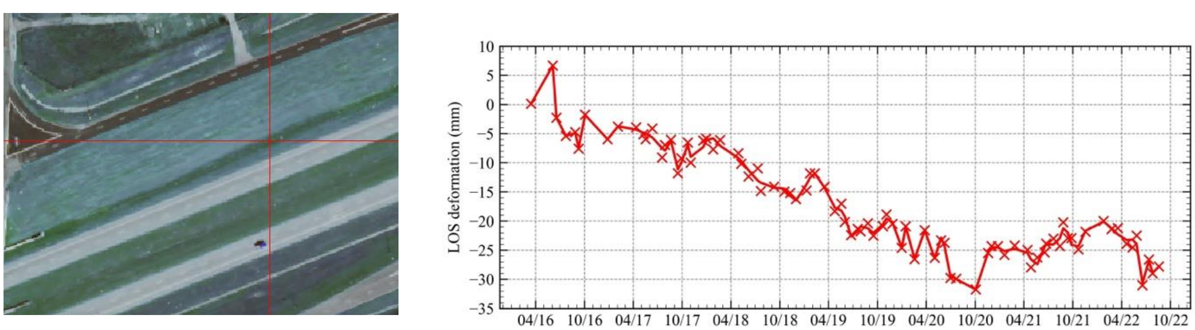

Figure 6. Time-series InSAR results of slope at the Denison location that showed extensive movement on site from 2016 to 2022

SUMMARY AND FUTURE SCOPE

This paper has provided an overview of the use of Synthetic Aperture Radar (SAR) and interferometric SAR (InSAR) data in monitoring specifically geotechnical and transportation assets. The spatial and temporal resolution offered by current operational open-data orbital SAR remote sensing systems allows for effective spatiotemporal monitoring of asset conditions. The recent expansion of the commercial SAR sector makes spatial and temporal resolution more meaningful to transportation agencies for regular and emergency monitoring of their assets. Furthermore, the challenges and limitations associated with SAR and InSAR technology for civil infrastructures are discussed. A case study of monitoring a highway embankment failure in Denison, Texas has been presented to illustrate the potential practical benefits of using these techniques. SAR and InSAR data can be reliable data sources for asset management and long-term monitoring of civil infrastructures. However, additional studies and ground-truth validations studies are necessary to understand the advantages as well as challenges and limitations in using this technology for geotechnical and transportation assets.

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REFERENCES

AASTHO. 2020. *AASHTO Transportation Asset Management Guide: A Focus on Implementation*. American Association of State Highway and Transportation Officials.

Bruckno, B., A. Vaccari, E. Hoppe, W. Niemann, and E. Campbell. 2013. *Validation of Interferometric Synthetic Aperture Radar as a Tool for Identification of Geohazards and At-Risk Transportation Infrastructure*. 402.

Carlà, T., E. Intrieri, F. Raspini, F. Bardi, P. Farina, A. Ferretti, D. Colombo, F. Novali, and N. Casagli. 2019. "Perspectives on the prediction of catastrophic slope failures from satellite InSAR." *Sci. Rep.*, 9 (1): 14137.

Ferretti, A., A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci. 2011. "A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR." *IEEE Trans. Geosci. Remote Sens.*, 49 (9): 3460–3470.

Hanssen, R. F. 2001. *Radar Interferometry: Data Interpretation and Error Analysis*.

Hanssen, R. F. 2005. "Satellite radar interferometry for deformation monitoring: a priori assessment of feasibility and accuracy." *Int. J. Appl. Earth Obs. Geoinformation*, 6 (3–4): 253–260.

Hoppe, E., B. Bruckno, E. Campbell, S. Acton, A. Vaccari, M. Stuecheli, A. Bohane, G. Falorni, and J. Morgan. 2016. "Transportation Infrastructure Monitoring Using Satellite Remote Sensing." *Mater. Infrastruct.* 1, 185–198. Wiley Blackwell.

Hu, X., Z. Lu, T. Oommen, T. Wang, and J. Kim. 2017. "Monitoring and modeling tailings impoundment settlement near Great Salt Lake (UTAH) using multi-platform time-series InSAR observations." *2017 IEEE Int. Geosci. Remote Sens. Symp. IGARSS*, 40–43. Fort Worth, TX: IEEE.

ICEYE. 2023. “Satellite Data - How to use satellite data for better decision making.” Accessed April 30, 2023. https://www.iceye.com/satellite-data.
Jensen, J. R. 2014. *Remote sensing of the environment : an earth resource perspective*. Pearson.
Krechmer, D., P. Beer, B. Boyce, A. Samano III, and N. Boyd. 2012. *Role of transportation management centers in emergency operations guidebook*. United States. Federal Highway Administration. Office of Operations.
Laurila, P. 2020. “New Benchmark in Imaging from SAR Microsatellites: ICEYE presents 25 cm Azimuth Resolution.” Accessed April 30, 2023. https://www.iceye.com/blog/new-benchmark-in-imaging-from-sar-microsatellites-iceye-presents-25-cm-azimuth-resolution.
Lier, Ø. E. 2015. *InSAR on Embankment dams Pilot on deformation measurement*.
Meyer, F. J., O. A. Ajadi, and E. J. Hoppe. 2020. “Studying the applicability of X-Band SAR data to the network-scale mapping of pavement roughness on US roads.” *Remote Sens.*, 12 (9). MDPI AG.
Minh, D. H. T., R. Hanssen, and F. Rocca. 2020. “Radar interferometry: 20 years of development in time series techniques and future perspectives.” *Remote Sens.*, 12 (9). MDPI AG.
Moruza, A. 2017. “Economic Analysis of InSAR Technology Application in Transportation.” *Transp. Res. Board 96th Annu. Meet.*
NCHRP (National Academies of Science Engineering and Medicine). 2019. *Geotechnical Asset Management for Transportation Agencies, Volume 1: Research Overview*. Washington, D.C.: National Academies of Science Engineering and Medicine.
Power, D., J. Youden, J. English, K. Russell, S. Croshaw, and R. Hanson. 2006. InSAR Applications for Highway Transportation Projects. FHWA-CFL/TD-06-002.
Qin, Y., E. Hoppe, and D. Perissin. 2020. “Slope Hazard Monitoring Using High-Resolution Satellite Remote Sensing: Lessons Learned from a Case Study.” *ISPRS Int. J. Geo-Inf.*, 9 (2): 131.
Rosen, P. A., et al. 2019. “NASA’s Next Generation Surface Deformation and Change Observing System Architecture.” *IGARSS 2019-2019 IEEE Int. Geosci. Remote Sens. Symp.*, 8378–8380. Yokohama, Japan: IEEE.
Stark, T. D., et al. 2021. *Remote Sensing for Monitoring Embankments, Dams, and Slopes. Remote Sens. Monit. Embankments Dams Slopes*. American Society of Civil Engineers.
US Government Publishing Office. 2016. “Title 23: Highways, Chapter I: Federal Highway Administration, Department of Transportation, Subchapter F: Transportation Infrastructure Management, Part 515: Asset Management Plans.” Accessed April 1, 2023. https://www.ecfr.gov/current/title-23/chapter-I/subchapter-F/part-515.
USDOT. 2019. “U.S. Department of Transportation Announces $705.7 Million in Emergency Relief for Road and Bridge Repairs.” Accessed April 3, 2023. https://www.transportation.gov/briefing-room/fhwa0119.
USDOT. 2021. *National Transportation Statistics 2021*. Washington, DC: US Department of Transportation, Bureau of Transportation Statistics.