10-16-2015

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Bruckno, Brian; Vaccari, Andrea; Hoppe, Edward; Acton, Scott; and Campbell, Elizabeth, "Integration and Delivery of Interferometric Synthetic Aperture Radar [Insar] Data Into Stormwater Planning Within Karst Terranes" (2015). *Papers in the Earth and Atmospheric Sciences*. 443.

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INTEGRATION AND DELIVERY OF INTERFEROMETRIC SYNTHETIC APERTURE RADAR [INSAR] DATA INTO STORMWATER PLANNING WITHIN KARST TERRANES

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Abstract

As part of two USDOT-funded studies focused on the development of satellite-based Interferometric Synthetic Aperture Radar (InSAR) technology, the researchers integrated InSAR-derived point cloud data into the transportation design process to optimize the location of a stormwater management system in a karst terrane. After initial validation, the InSAR data (over 1.67 million data points comprising various “scatterers”) were brought into a GIS dataframe and georeferenced to locations of known sinkholes. This dataset was then used to evaluate karst hazard within a 40x40km data frame located in the Valley and Ridge Province of Virginia. The group identified systematic kinematic differences in scatterer behavior with respect to their proximity to mapped karst geohazards, and used this method to identify unknown karst features, revealing numerous previously unidentified sinkholes. After validating the data with quantitative field correlations, the group integrated the dataset into a traditional CADD-developed design, ported into a GIS environment, and utilized the resulting integrated dataset to optimize the location of stormwater management assets within a traditionally-developed roadway project. In the process, the group developed open-source data delivery, allowing

greater flexibility, efficiency, and optimization of the infrastructure design and planning process conducted collaboratively over geospatial platforms. This data integration offers lifecycle cost benefits, improvements to the safety of the traveling public, and protection of the environment, particularly in groundwater-sensitive karst terranes. A case study of this approach is presented.

The views, opinions, findings and conclusions reflected in this presentation are the responsibility of the authors only and do not represent the official policy or position of the US Department of Transportation/Office of the Assistant Secretary for Research and Technology, or any state or other entity.

Introduction

InSAR Data and Potential Value

Synthetic Aperture Radar (SAR) is the extension of traditional radar data acquisition, in which the orbit of a satellite is used to synthetically mimic a much larger aperture (i.e., “synthetic” aperture), which allows for the delivery of images of very high resolution (Rosen et al., 2000). Each ground resolution element, or pixel, contains phase and amplitude data of the backscattered radar wave for each satellite flyover, or “acquisition”.

By applying interferometric techniques to a time series of acquired images (a “stack”), it is possible to interpret the difference in reflected radar waves in a manner that reveals changes in topography over time (Power et al., 2006). These combined images, or interferograms, are generally termed InSAR or DInSAR when applied to ground motion. Pixels that exhibit stable radar signatures over time are referred to as permanent scatterers (PS). Techniques detecting PS are known under the general term of persistent scatterer interferometry (PSI). Often sets of neighboring pixels show behavior as a group without any individual pixel providing a stable reference; in this case, these pixels are combined in a larger geographic area, and are referred to as distributed scatterers (DS). In this work, the group made use of datasets derived using two specific techniques referred to as PSInSAR (Ferretti et al., 2001) and SqueeSAR (Ferretti et al., 2011). A further refinement to these techniques provides information about scatterers that either gain or lose radar reflectivity over a temporal subset of the stack. These are referred to as temporary scatterers (TS). Under ideal conditions, InSAR data can provide millimeter-scale records of vertical change (Morgan et al., 2011). The authors use the term InSAR as a general term for all SAR applications related to topographic change and infrastructure evaluation.

While SAR data has been available since the 1950s (Sherwin et al., 1962) and airborne InSAR was first used in the early 1970s (Graham, 1974), it was not until the 1990s that InSAR was used to investigate topographic changes such as those that occur after earthquakes (Massonnet et al., 1993). Many of those applications were for large-scale, slow-moving changes, such as slowly-moving landslides (Roering et al., 2009) or changes in rock-glacier mass (Strozzi et al., 2010). Applications to smaller phenomena, such as formations of sinkholes, activity on rock slopes, or distortions to bridges or rock buttresses, have not been targets of investigation for InSAR until quite recently.

The authors validated and evaluated the use of InSAR for such smaller-scale applications by bringing the entire InSAR dataset (PS, DS, and TS) into a GIS dataframe and correlating to control data. For karst hazards, these correlative datasets included published maps of sinkhole locations and karst terranes, and records of repaired sinkholes. For infrastructure, the displacement time series of the InSAR data were used to identify potentially

compromised geotechnical assets, and the observations were quantitatively validated by field inspection (Vaccari et al., 2013).

The value of InSAR data, once validated, is evident to planners and designers. It allows generation of GIS-based geohazard, geotechnical, and surface kinematic databases. It also allows optimization of geotechnical planning in the light of a larger and more dynamic dataset than was previously available. In the Valley and Ridge Physiographic Province of Virginia, evaluating the InSAR data with regard to karst geohazard related to transportation planning and design has proven to be useful. It is worth noting that the cost of remediation, repairs, and maintenance of sinkhole occurrences alone was approximately \$1,000,000 USD during the period of Virginia fiscal years 2012 to 2014, exclusive of any cost associated with economic harm caused by transportation disruptions. A cost-benefit analysis of the wide use of InSAR data is ongoing at the Virginia Department of Transportation, but the potential for significant cost and safety benefits is clear.

Research Projects

RITA-RS-11-H-UVA and RITA-RS-14-UVA

The authors are cooperative investigators in RITA-RS-11-H-UVA (RITA11) and RITA-RS-14-UVA (RITA14), two USDOT-funded projects titled “Detection & Bridge/Landslide Monitoring for Transportation Infrastructure by Automated Analysis of Interferometric SAR Images” and “InSAR Remote Sensing for Performance Monitoring of Transportation Infrastructure at the Network Level,” respectively. The Research and Innovative Technology Administration (RITA), now supplanted by the Office of the Assistant Secretary for Research and Technology (OASRT), coordinates the US Department of Transportation’s (DOT) research programs. RITA, and subsequently OASRT, is charged with developing innovative, interdisciplinary technologies to improve the US transportation system. The initial project, RITA11, focused on evaluating whether InSAR could be successfully used to detect and quantify surface change and thereby detect incipient sinkholes. In order to make this determination, the data were first broadly validated by comparison to geotechnical assets and field conditions. Validation was performed by a team of a Virginia-licensed professional geologists and engineers. The subsequent project, RITA14, expands the analyzed areas and focuses on integrating InSAR data into the

design process, integrating planning and InSAR datasets into a GIS dataframe in order to create a decision support system which is more efficient, more cost-effective, and better protects the environment.

Selection of Area of Interest (AOI)

The authors selected a 40x40 kilometer area of interest (AOI) for InSAR data acquisition. The area, represented in Figure 1, was selected based on geological diversity and the presence of numerous geotechnical assets. This offered the potential for the formation of sinkholes and other karst features, as well as deterioration of or distortions to assets within the AOI due to karst conditions. Numerous unmapped sinkholes were detected during this stage of the investigation (Bruckno et al., 2013).

One AOI, common to both RITA11 and RITA14, is centered at -79.222°W, 38.077°N in Augusta County, Virginia. It is tectonically complex, spanning the Valley and Ridge, and Blue Ridge physiographic provinces (Dietrich 1990). Geological ages ranging from Holocene to Precambrian (Bartholomew, 1977), with frequent unconformities, are represented within the AOI. The predominant tectonic framework consists of eastward-dipping thrust faults and decollements related to repeated orogenic cycles (Rader and Wilkes, 2001). The AOI contains carbonate, non-carbonate clastic, and metamorphic terranes, resulting in both rock slope stability hazard and severe karst hazard. The karst areas range in age from Cambrian to Devonian and formed during the Taconic and Acadian Orogenies and their associated

divergent and inter-orogenic periods. Karst lithologies consist of limestone and dolostone, while non-carbonate clastic lithologies consist of interbedded shales, siltstone, conglomerates, and sandstone, and the metamorphic lithologies consist of charnockite, granulite gneiss, quartzite, greenschist, and blueschist-grade metabasalt. Figure 2 represents areas of karst geohazard within the AOI.

Several control datasets exist for sinkholes; Figure 3 is an aggregate dataset of known sinkhole locations compiled from the Soil Survey Geographic Database (SSURGO, 2015) and limited-release data from the Virginia Department of Mines, Minerals, and Energy.

Selection of Satellite and Resulting InSAR Data

COSMO-SkyMed, a constellation of four identical satellites built and operated by the Italian Space Agency, was selected for data acquisition. Each satellite is equipped with an X-band SAR operating at 9.6 GHz (Italian Space Agency, 2007). Between August 29, 2011 and June 16, 2014, 57 non-uniformly spaced SAR scenes were acquired and were processed by TRE-Canada, Inc. using the PSInSAR and SqueeSAR algorithms, which convert the data into subsidence. The resulting dataset consists of over 1.67 million PS, DS, and TS scatterers, as well as amplitude values for each 3x3 meter pixel within the entire AOI corresponding to each acquisition.

Figure 4 represents the processed InSAR scatterers, with PS, DS, and TS points all represented in blue. Heavily vegetated areas prevented backscatter from the ground

Figure 1. Overview of Area of Interest (AOI) outlined in red (ESRI ArcMap™).

Figure 2. Regions within the AOI (outlined in red) susceptible to karst geohazard (in blue; non-karst areas in grey) (ESRI ArcMap™).

Figure 3. Regions within the AOI (outlined in red) mapped as sinkholes by the VA DMME (in red), by SSURGO (in blue) and sinkholes repaired by VDOT 2000 to 2012 (in green) (ESRI ArcMap™).

and showed rapid temporal decorrelation; however, such areas tend to have limited human population and infrastructure, and are therefore of lesser value in terms of surface analysis.

Figure 5 illustrates scatterers within an area of new construction within the AOI. The scatterers represent both anthropomorphic and geomorphological features. Buffering on roads within GIS can eliminate apparent scatterers falling outside of areas of concern, and automated edge detection methods can remove scatterers coinciding with buildings from the dataset (Ferraioli, 2010).

Figure 4. Regions within the AOI (outlined in red) represented by scatterer data (represented by blue points) (ESRI ArcMap™).

Data Validation by Detection of Active Sinkholes

Because of the robust set of control data and maps of sinkhole occurrence, the research team was able to identify scatterers whose location coincided with locations of mapped sinkholes. Analyzing the time-series of those scatterers, a typical example of which is illustrated in Figure 6, allowed the research team to create simple search tools that screened for unmapped sinkholes. This was accomplished by identifying scatterers with combinations of negative displacement, velocity, and acceleration.

During the data validation period of the RITA11 research, several unmapped sinkholes were identified using these methods. Figures 7 and 8 illustrate the growth of one such sinkhole.

Case Study Integration of InSAR Data into Transportation Planning

The transportation planning process does not generally involve a sinkhole mapping program. Typically, a literature survey is conducted to evaluate karst features that may affect the project. However, the literature used for such purposes is often not current, digital versions may suffer from imperfect digitization, and the scale of such maps is often inappropriate for use in transportation planning. Integration of InSAR data into the process offers the opportunity to conduct planning and design decisions in the light of dynamic and recent data. The authors implemented this approach on a

Figure 5. Close-up of an area within the AOI represented by scatterer data (PS are represented in blue, DS in orange, and TS in green) (ESRI ArcMap™).

Figure 6. Scatterer behavior typical of emergent sinkholes.

project involving the reconstruction of an intersection and associated stormwater management features. This allowed integration of InSAR data into the transportation planning and design process.

Figure 9 represents an excerpt from the construction plans, in which a potential stormwater management basin has been sketched. Typically, drainage plans are the last element of transportation design. These locations must

Figure 7. Vesuvius Sinkhole, Spring 2012 (Hoppe 2012).

Figure 8. Vesuvius Sinkhole, Fall 2012 (Hoppe 2012).

be optimized for soil type, topography, the consideration of local landowners, and, in karst terranes, the need to avoid groundwater contamination and active karst features. The mere presence of mapped sinkholes may be of no concern if the sinkholes are not subsiding, but actively subsiding sinkholes should be avoided.

Figure 10 illustrates those PS and DS scatterers near the construction project showing only the most negative velocity, and TS scatterers showing the greatest negative displacement over the data acquisition period (90th percentile of the dataset, or PS and TS velocities greater than -6.0 mm/year and TS displacements greater than -15.0 mm during the acquisition period). Scatterers coinciding with obvious anthropomorphic features, such as buildings and transportation infrastructure, were manually removed, so that the remaining scatterers reflect geomorphological subsidence.

Underlying the scatterer dataset is the aggregate sinkhole dataset with a multi-ring buffer extending to the maximum extent of anticipated sinkhole influence. The pattern of the InSAR scatterers showing only the most negative velocity or greatest subsidence coincides with the pattern of the sinkholes. This indicates not only the presence of sinkholes, but that the sinkholes are not yet in a state of post-collapse or meta-stability (the majority of sinkholes in the Virginia Valley and Ridge are subsidence, rather than cover-collapse, sinkholes).

Because survey control was available for the project, the CADD files were portable into an ESRI ArcMap™ environment, and all of the files, along with pertinent GIS files, could be georeferenced within a common coordinate system. From there they were ported to a Google Earth Pro™ environment, where they could be quickly assessed by planners, designers, and representatives of the public in open meetings; the data could also be shared and evaluated across remote offices using ArcGIS for Organizations™. This allowed regions of greater or poorer favorability for stormwater management basins to be evaluated: Areas near actively subsiding sinkholes, and areas near production wellheads, were to be avoided.

Figure 11 illustrates the areas of mapped sinkholes with a geographic buffer zone, the PS and DS scatterers showing the most negative velocity, the TS scatterers showing the most negative displacement,

Figure 9. Excerpt from Microstation™-drafted plans.

Figure 10. Mapped sinkholes overlain by scatterers showing the most negative velocity or displacement (PS are represented in blue, DS in orange, and TS in green) (ESRI ArcMap™).

and commercial water-supply wells with a geographic buffer. The proposed construction plans from Figure 9 are georeferenced to the image.

From the image, it can be seen that the region northwest of the proposed construction shows several problematic conditions with regard to stormwater management basin locations. Not only are there historical records of sinkholes in the region, but the InSAR data shows that the area is actively subsiding.

Figure 12 illustrates the scatterer behavior for the InSAR/Sinkhole cluster northwest of the proposed intersection in Figure 11. Several of the scatterers show a net displacement approaching 15 to 25 mm during the data acquisition period, suggesting a fast rate of subsidence.

The behavior of the InSAR scatterers within the geographic buffers of the wells also varies. The scatterers within the annulus around Well Cluster 2 show an average velocity of +0.1 mm per year, while the average velocity within the annulus of Well Cluster 1 show an average velocity of -1.16 mm per year (for clarity, these scatterers are not shown in Figure 11). Both wells are terminated in water-table aquifers, suggesting that the surface depression around Well Cluster 1 may be the result of a cone of depression around an overstressed aquifer; the areas near

Well Cluster 1 are therefore less favorable for stormwater management basins than those near Well Cluster 2.

Areas where the geographic buffer for known sinkholes coincide with the selected (most negative velocity/displacement) scatterers, and overlap the geographic buffer for Well Cluster 1, are the least favorable areas for stormwater management basins and should be avoided; such an area is located northwest of the proposed intersection reconstruction. This is also an area of a topographic low (potentially the result of the area being a doline related to the sinkholes); absent other data, this area would naturally be seen as favorable for stormwater management basins. However, overtopping of a stormwater management basin in this area during weather events outside of the recurrence interval for which the basin was designed may result in the inadvertent construction of an injection well.

Areas to the northeast of the intersection are clearly better suited for stormwater management basins due to their distance away from mapped sinkholes correlated with areas shown to be subsiding according to InSAR data, mapped sinkholes, and Well Cluster 1. While stormwater management basins in this region may require more excavation in order to provide for positive drainage, a risk-reward analysis shows that avoiding potential groundwater contamination validates this decision.

Figure 11. Area of construction overlain by sinkhole and commercial wells with geographic buffer (PS are represented in blue, DS in orange, and TS in green) (Google Earth Pro™).

Figure 12. Displacement of InSAR/Sinkhole Cluster

Conclusion and Discussion

Protection of aquifers is particularly important in karst terranes, where there is often a direct hydrologic link between surface runoff and the water table via sinkholes. While records of sinkhole locations and sinkhole location maps are important tools in planning and design, the data contained in such maps are often outdated, may be found at a scale inappropriate to the planning process, and may suffer from poor digitization. Data derived from InSAR platforms, on the other hand, record a time-series of surface behavior which may be correlated with actual karst behavior. Where these data can be integrated into the design process, they offer lifecycle cost benefits, improvements to the safety of the traveling public, and protection of the environment, particularly in groundwater-sensitive karst terranes.

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