Mapping expansive soils from space

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ABSTRACT

This paper describes a new approach to detecting motion related to soil expansivity from ground motion time series data. Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique used to detect and monitor ground and surface infrastructure motion with millimetric precision using SAR satellite imagery.

A total of 74 high resolution TerraSAR-X SAR images were used to produce ground motion time series covering a large urban area (450 km^2) in Auckland NZ between August 2019 and May 2022. Sixense's Atlas InSAR processing chain produced 7.6 million ground motion time series. Data science techniques were used to locate motion related to expansive clays swelling mechanisms.

Climate data from NIWA weather stations and soil data layers from Landcare Research NZ have been included to complement the analysis. 450k building footprints from Land Information New Zealand (LINZ) have been used to map those buildings potentially affected by expansive clay seasonal movements. Finally, ground instrumentation data from the Mount Eden City Rail Link (CRL) station construction site is used to validate the observed motion precision of Sixense's Atlas InSAR.

The end goal of this study is to provide the Auckland city council cost effective added value information in the context of climate change adaptation, where erratic weather patterns pose a serious risk to building foundations.

Keywords: InSAR, expansive soils, climate change, building foundations, assets at risk, structural health monitoring

1 INTRODUCTION

With excess precipitation and soil moisture increase, expansive clays generate uplift forces (Vorwerk et al., 2015). When this phenomenon develops at foundation level, it can lead to serious building damage due to differential settlement. Swelling clays can control the behaviour of virtually any type of soil, and climate change irregularities have enforced their impact.

This paper shows how InSAR ground motion time series is used in conjunction with climate observations to provide meaningful and actionable information for the city of Auckland, New Zealand. Radar satellite interferometry is a widely used technique to monitor terrain deformation over wide areas (Bamler et al., 1998). In the third chapter, the methodology chosen to filter out the motion related to expansive soil seasonality is presented together with the input datasets used.

Finally, we demonstrate how this massive amount of geoinformation is presented to the Auckland city council via Sixense's Beyond Monitoring GIS platform.

2 INPUT DATASETS

2.1 Atlas InSAR

The Auckland Atlas InSAR high-resolution ground motion time series amounts to a total of 7.6 million measurement points with 74 dates between August 2019 and May 2022. The density of points resulted in 40,000 PS/km^2 strictly in the urban area concentrated in man-made structures like buildings known for their phase stability along the period of study (Ferretti et al., 2000). This study period enables the identification of seasonal patterns since it contains more than a full cycle (winter/summer – dry/wet season).

TerraSAR-X acquisitions in StripMap mode have a ground pixel resolution of 3x3 metres and the image footprint is approximately 50x30 kilometres on the ground. The angle of incidence (α) of the acquired images over Auckland is 33 degrees. Figure 1 summarizes the acquisition coverage and geometry of the source imagery. Given the incidence angle of 33 degrees, the potential variation of the observed displacement in Z (mm) amounts to a maximum of 16%. The difference between vertical and line of sight (LOS) has not been significant in most cases, mainly when deformation values are neglectable. However, it is recommended to take this difference into account for an accurate comparison with ground instrumentation data that measures in the orthogonal plane.

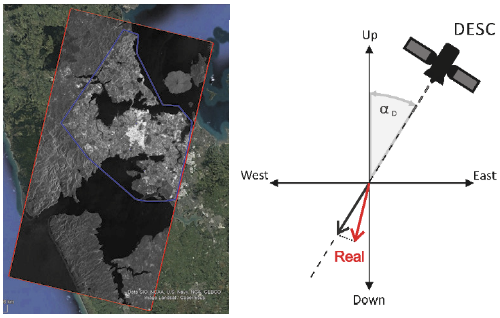


Figure 1. SAR image coverage and properties

When using high-resolution imagery with X-band, the measurement precision of movement in the Line Of Sight (LOS) is between 2 and 3 mm and the precision below 1 meter in the location.

2.2 Climate datasets

From all the available climate observations on local weather stations, soil moisture, temperature and precipitation are proposed as relevant variables influencing soil expansivity (Rogers et al., 1985). Open climate daily observations from the National Institute of Water and Atmospheric Research (NIWA) weather stations were downloaded for three climate variables (temperature, precipitation, and soil moisture). In Figure 2, data from six urban weather stations is averaged on the SAR imagery acquisition dates to understand the underlying conditions of the InSAR data processing. For precipitation, amounts are accumulated between each pair of SAR acquisitions.

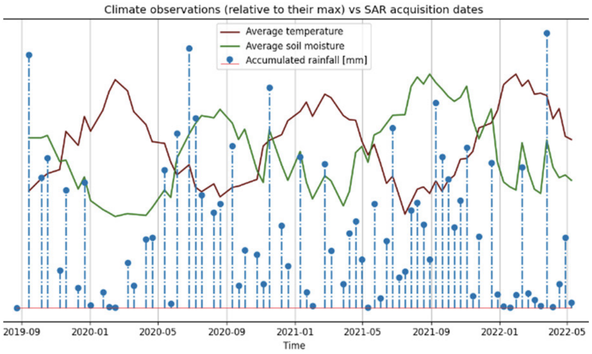


Figure 2. Climate observations vs SAR acquisitions

Soil moisture is influenced by temperature and precipitation seasonal variations. Soil moisture is at its lowest in the *dry* season, where precipitation is low, and the temperature reaches its maximum values, whereas the opposite effect can be observed in *humid* conditions.

2.3 Soil data layers

Available soil cartographies from Landcare Research NZ over the city of Auckland do not provide specific information, as they usually define the urban area as urban soil. Nevertheless, geological maps can give an approximate idea of the type of soil that can be found on the surface.

The geological map of the city of Auckland provided by Manaaki Whenua Landcare Research shows three main formations and all of which may present expansive clay minerals to a greater or lesser extent, as shown in Figure 3.

In the Auckland downtown, the Auckland Volcanic Field formation predominates, and it is characterized by Basaltic and ash deposits that, in seasonally humid climates, typically produce expansive clay minerals.

The East Coast Bays formation also occurs in the downtown and in the north and western regions of the city. This formation is characterized by turbidites that also contain expansive clay minerals.

Finally, the Puketoka formation mainly occurs in the west and south-eastern regions of the city and usually presents high variability in the sediments with occasional clays that may produce expansive patterns. Overall, the geology in Auckland shows that expansive clay minerals may be found all over the city.

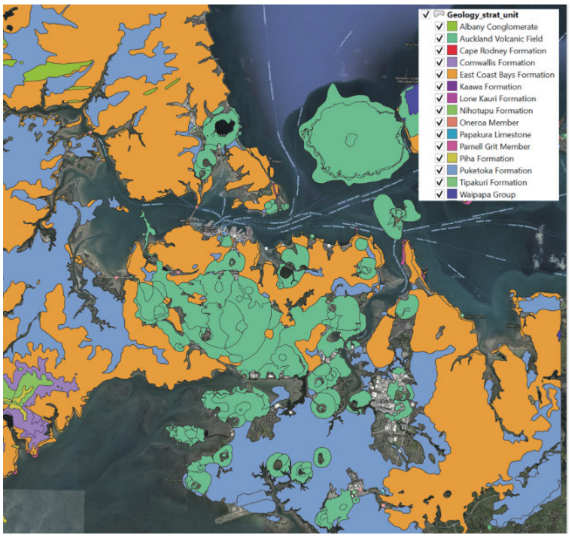


Figure 3. Formations in the Auckland Urban area

2.4 Building footprints

Over half a million building outlines have been extracted from the Land Information New Zealand (LINZ) open dataset archive. The Auckland building footprints (Figure 4) have been obtained from high resolution aerial optical imagery using the latest machine learning roof detection techniques.

The downside of this very precise and updated building footprint polygons dataset is the lack of metadata (e.g. foundation type, year of construction).

Figure 4. LINZ building footprints

2.5 In situ ground instrumentation

The City Rail Link (CRL) consists of twin 3.4 km long tunnels up to 42 metres below the city streets to create an underground rail line linking Britomart and the city centre with the existing western line near Mt Eden.

Sixense deployed and collected data from a deformation monitoring network, including Automatic Total Stations. This network has been operational since May 2020 in the area, and its mission is to provide real-time monitoring data over a valuable group of assets near the construction site. In Figure 5, ATS measurements are compared with Atlas InSAR to show the potential of using both monitoring solutions and provide cross-validation.

Figure 5. ATS versus 4 Atlas InSAR points

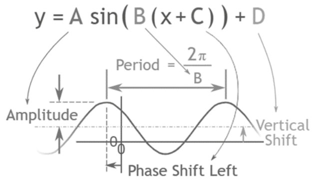
3 METHODOLOGY

The main input for the method developed to map soil expansivity is the ground motion time series obtained with Sixense's Atlas InSAR processing chain. From those, a simple data processing flow has been derived to extract those time series where the soil expansivity pattern is highlighted. This procedure consists of three steps:

First, we need to filter out those time series that do not add any value to the analysis. Noise removal has been done by means of autocorrelation and detecting sudden jumps in the time series related to phase unwrapping errors. A low amplitude filter of ±2 mm has been applied to avoid incurring issues related to the precision of InSAR measurements described in Section 2.1.

After this step, it is necessary to identify those time series with a seasonal component. This is done with sinusoidal curve fitting to the time series data and focusing on yearly periods. Thanks to this fitting, we can clearly distinguish the thermal pattern (T) from dilatation/contraction on metal materials from the seasonal pattern coming from expansive clays (E). By means of linear regression, we can remove the linear trend to focus and quantify only on the seasonal effects. This is especially useful for assessing the intensity of these deformation patterns.

In Figure 6, hotter (and dryer) months are indicated with orange vertical lines and colder (and more humid) months with dark blue:



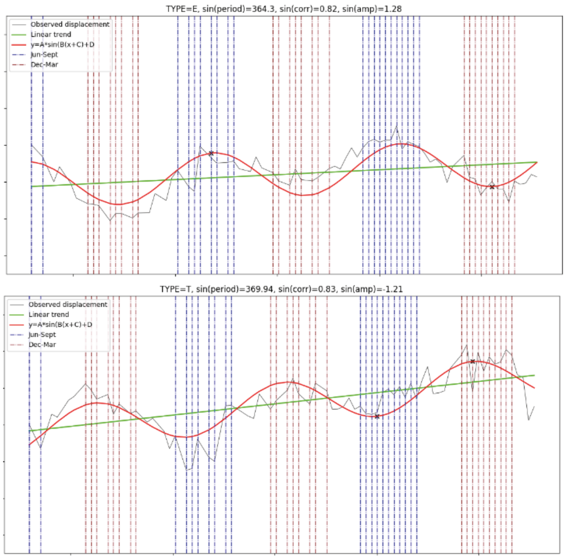


Figure 6. Sinusoidal fitting to ground motion data

Finally, aggregation of those patterns closely related in terms of correlation and distance has been performed to obtain Active Deformation Areas (ADA). This spatial aggregation technique is used to identify those ground deformation time series that represent an active deformation and meet a minimum distance requirement (spatial correlation). It is a technique used in risk assessment from InSAR datasets as described in the article (Navarro et al., 2020). Each ADA consists of a set of ground deformation time series following the same trend together with an envelope polygon identifying the area of influence.

4 OUTPUT DATASETS

After applying the seasonal filtering methods described in Section 3, 379k time series out of the 7.6M are identified as directly related to soil expansivity. From those spatially and temporally related, 61k active deformation areas are delimited. Three different GIS layers have been produced to understand the density, intensity, and possible affectations on buildings of these deformation patterns.

4.1 Density maps

Hotspot raster maps are produced with the location of the seasonal motion point coordinates related to soil expansivity. Due to the surface reflectivity properties, this map will have no data regions on vegetated and water surfaces. As stated in Section 2.3, expansive clays are present in all Auckland geological formations, and therefore patterns are spread across the city. In Figure 7, we can distinguish different concentration of expansive soil deformation patterns.

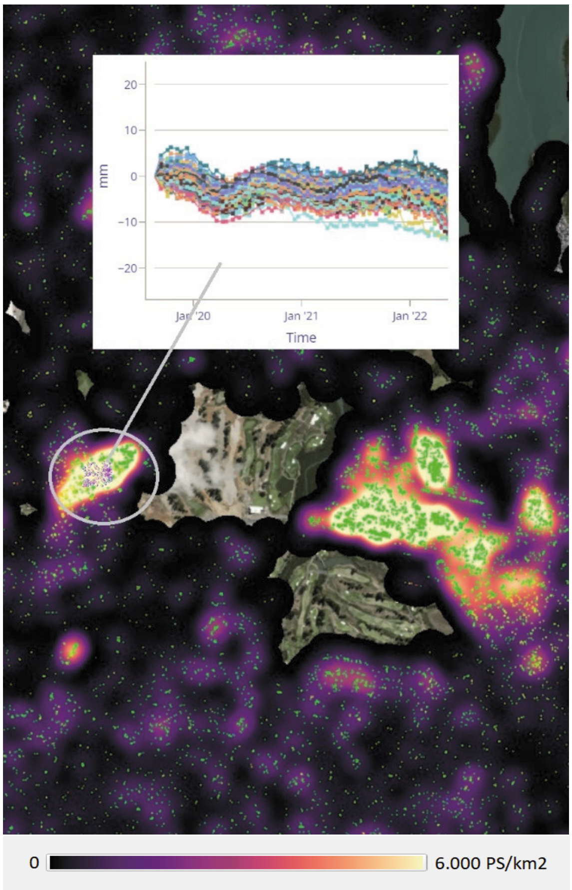


Figure 7. Expansive soil pattern density map

4.2 Intensity maps

Considering the amplitude of the sinusoidal fit without the linear trend of the time series, we can produce maps showing the variations in the intensity of these patterns. This map is useful in general/relative terms but must be considered an approximation since:

- We have considered satellite line-of-sight (LOS) ground motion observations as described in Figure 1 with the precisions described in Section 2.1.
- Amplitude of the sinusoidal fit is generally lower than the real/observed time series. The fitting acts as a smoothing function that reduces noisy values and helps in the interpretation of the results.
- In Figure 8, we can observe a histogram of the different sinusoidal amplitudes. Warmer colours are used to represent higher amplitudes.

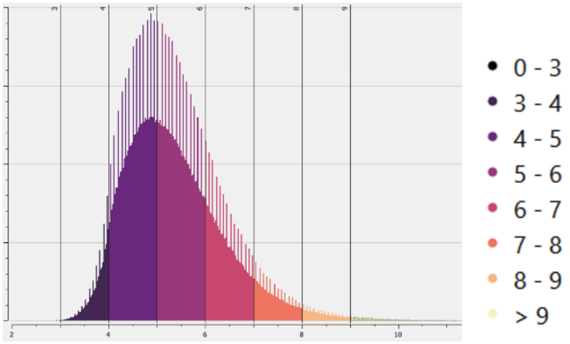


Figure 8. Histogram distribution of amp(sin(x)) approximation in mm

In the next Figure 9, we see a sample of the intensity map highlighting a set of time series exhibiting strong expansive soil deformation patterns.

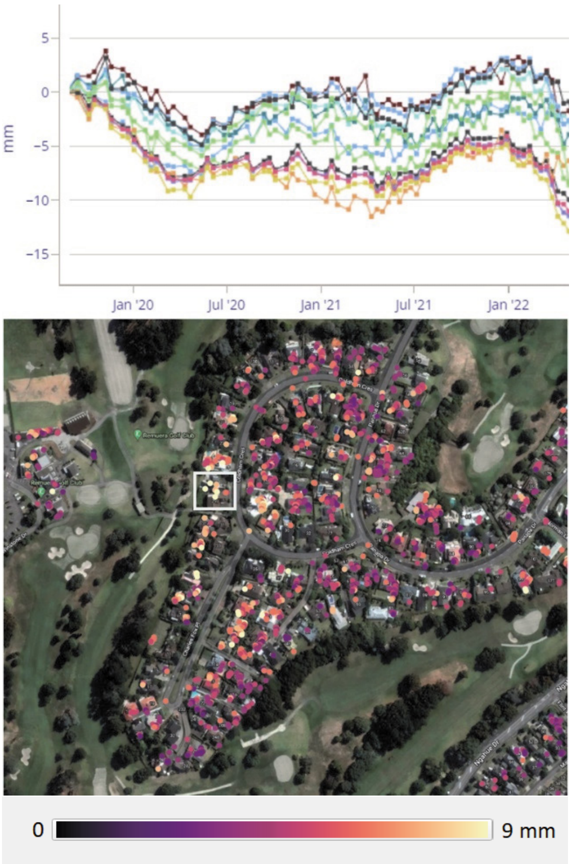


Figure 9. Expansive soil pattern intensity map

4.3 Affected buildings

To highlight those buildings potentially affected by soil expansivity, a vector layer has been produced with a subset of the half million building footprints described in Section 2.4.

Active deformation areas intersecting with the footprints and isolated points falling inside the building have been considered, leaving 133k potential buildings affected (of the total 450k buildings). From those and focusing on the mean yearly amplitude histogram, we can conclude that most of the movement amplitudes are lower than

8 mm, leaving less than 2000 buildings affected by amplitudes higher than that threshold.

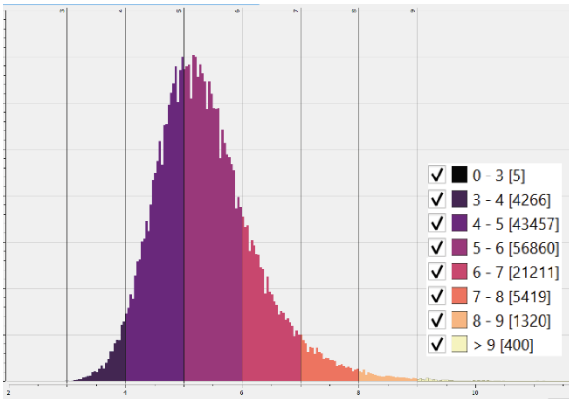


Figure 10. Histogram of amplitudes on buildings

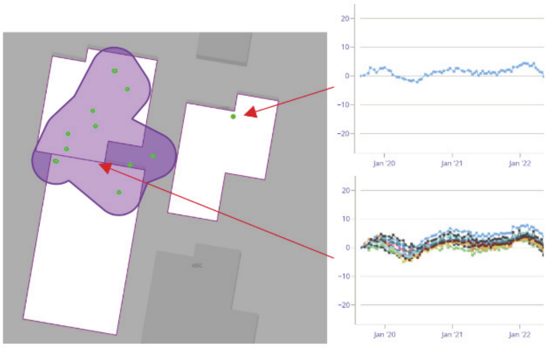


Figure 11. Buildings selection by points and ADAs

5 CONCLUSION

Expansive soil mapping on a large urban area such as the city of Auckland (450 km^2 and 450k buildings) would demand a considerable effort for in situ techniques.

This paper presents a remote sensing approach based on InSAR time series that can be used as a tool to obtain a first scan and mapping of seasonal patterns that enables control and focus on the assets potentially at risk. Due to its backscattering properties, man-made structures such as buildings typically produce high point densities, enabling this kind of analysis for intensity maps. On the other hand, vegetated areas such as parks remain unmapped due to coherence loss, and this poses a challenge in creating density maps.

A seasonal data filter has been designed and adapted to obtain those time series that show the seasonal pattern. Taking the coordinates and movement amplitude, user-friendly output map layers have been produced (density, intensity, buildings) and displayed in the Beyond Monitoring platform.

Information on urban soil is very difficult to obtain, and the presented approach will help the Auckland Council determine the intensities of expansive soil patterns across the city in preparation for the climate challenges ahead.

6 ACKNOWLEDGEMENTS

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