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11th INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

# Advanced monitoring programs from space and big data analytics for risk reduction in buildings and foundations

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**Abstract**

This paper will describe in depth the benefits brought by the combination of Atlas InSAR and high-resolution SAR imagery altogether with the latest data science techniques. The presented case study will focus in detecting urban areas affected by seasonal motion related to expansive clays across the Auckland region. The final goal is to deliver to the Auckland City Council an advanced, environmentally friendly, and cost-effective solution for risk reduction and asset management focused on buildings.

The basis for this analysis is a 7 million ground motion timeseries result obtained with Sixense Atlas processing chain over a large urban area of 450 km$^2$ in Auckland NZ. We will present a benchmark of the latest data analytics techniques with the aim of detecting those seasonal patterns that might pose a risk for building foundations. An intercomparison of three main data science techniques will be presented: Active Deformation Areas (ADA), Clustering, and Independent Component Analysis (ICA).

This paper will also demonstrate how climate and soil layers can be used to complement and support the analysis. In parallel, Sixense ground instrumentation data from the Mount Eden City Rail Link (CRL) station construction site will be used to validate observed motion precisions of Atlas InSAR.

Keywords: InSAR, Building foundations, Expansive soils, Climate Change, Risk and Assets.

## 1. Introduction

Expansive soils are those that contain minerals capable of absorbing water and are therefore affected by precipitation and temperature climate patterns. While absorbing water, they increase in volume. Swelling clays can control the behaviour of virtually any type of soil, and climate change irregularities have enforced their impact. The most obvious way in which expansive soils can damage building foundations is by terrain uplift as they swell with moisture increases [Vorwerk et al (2015)]. When this phenomenon develops below the foundation level of a construction, the loss of volume of the supporting soil generates differential settlements which can lead to notorious building damage but also of neighbouring or underground structures.

The paper will demonstrate how InSAR ground motion timeseries can be correlated with climate observations to provide meaningful and actionable information over a large urban area in Auckland, New Zealand. To do so, inputs used, selected methodology and outputs produced to answer this question are described in this paper. In the second chapter of this article the source datasets and layers are identified and described. In the third chapter, a selection of algorithms is benchmarked to identify the expansive soil ground deformation patterns from the InSAR ground motion timeseries. The fourth chapter of this article will present the different outputs produced and how they have been integrated in the Beyond Monitoring GIS platform used to deliver the results to the Auckland City Council. Finally, the original question is tackled and summarized in the conclusions section.

## 2. Available Datasets

### 2.1 Atlas InSAR

The baseline study was carried out using 48 SAR images from the TerraSAR-X satellite covering the city of Auckland (New Zealand) and its surroundings during a period of 2 years. TerraSAR-X acquisitions in StripMap mode has a ground pixel resolution of 3x3 metres, its image footprint corresponds to 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 properties of the source imagery. Given the incidence angle of 33 degrees, the potential variation of the observed displacement in Z (mm) is of maximum 16%. The difference between vertical and line of sight (LOS) will be not 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.

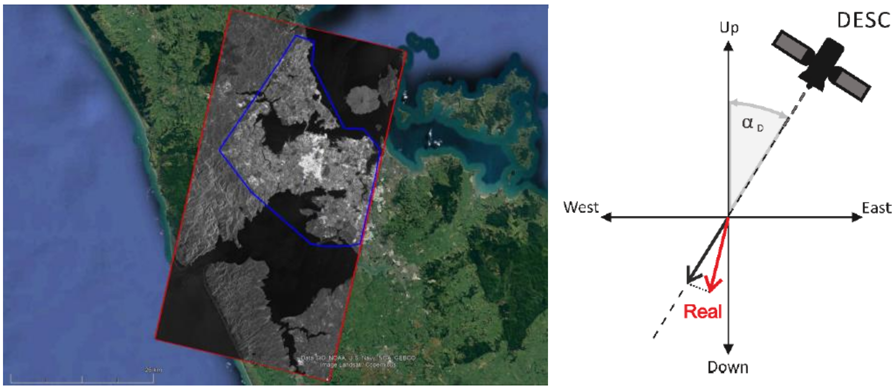


**Figure 1**: Coverage of TerraSAR-X image in Descending orbit over the Area of Interest and incidence angle.

The baseline study covers the period from August 2019 to June 2021, both included, with 2 images per month, a total of 48 images acquired in descending orbit. Following, Figure 2 is a schematic of the temporal distribution of the acquired images. This study period will enable the identification of seasonal patterns since it contains more than a cycle (winter/summer – dry/wet season).

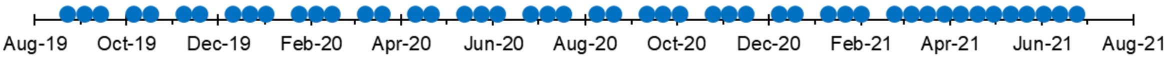


**Figure 2:** Temporal distribution of TerraSAR-X acquired images included in the baseline study.

When using high-resolution imagery with X-band, the measurement precision of movement in dZ is at least 2 mm. The precision in the location of the point in planimetry (X, Y) with TerraSAR-X is expected to be below 1 meter. The Auckland Atlas InSAR high-resolution ground motion dataset includes more than 7.6 million measurement points. The density of points is up to 40,000 PS/km$^2$ strictly in urban area.

### 2.2 Asset Layers

Over half a million building outlines have been extracted from the Land Information New Zealand (LINZ) open dataset archive. The Auckland building footprints have been obtained from high resolution aerial optical imagery. A buffer of 3 meters has been systematically applied as shown in Figure 3 to include building immediate surroundings and monitor affectation on utilities as well.

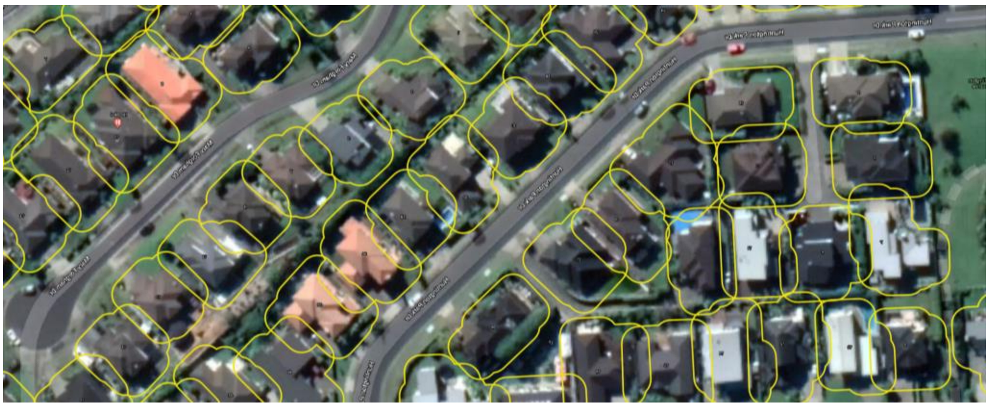

**Figure 3**: LINZ building footprints and their associated buffer distances.

**2.3 Climate Datasets**

From all the available climate data on local weather stations, soil moisture is proposed as a relevant indicator of soil expansivity [Rogers et al (1985)]. Ground deformation timeseries with high correlation with soil moisture have been identified and marked with the algorithms presented in section 3 of this article. Open-source climate daily data from the National Institute of Water and Atmospheric Research (NIWA) weather stations was downloaded for three climate variables (temperature, precipitation, and soil moisture). As seen in Figure 4, soil moisture is highly influenced by temperature and precipitation seasonal variations. Soil moisture is at its lowest in dry season where precipitation is low, and temperature reaches its maximum values whereas the opposite effect can be observed in humid conditions.

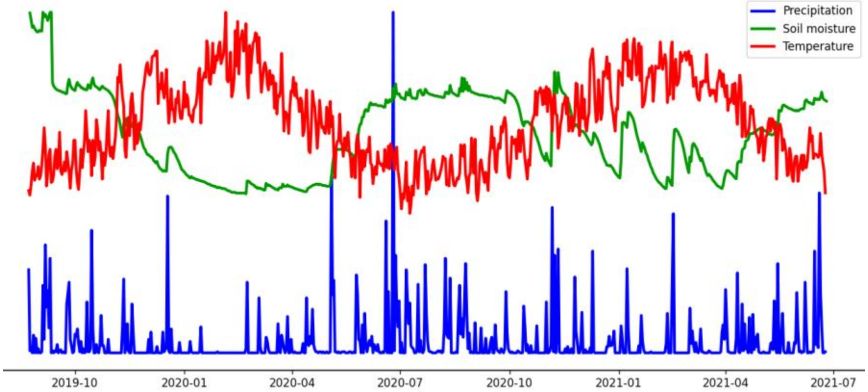


**Figure 4**: NIWA Daily data patterns/magnitudes in % for temperature, precipitation, and soil moisture - over the processed area/period.

**2.4 Soil Layers**

Available soil cartographies from Landcare Research NZ in the city of Auckland do not provide specific information over the city as they usually define the urban area as urban soil. Nevertheless, geological maps can give information on the type of soils that can be found on the surface. The geological map of the city of Auckland shows three main formations and all of them may present expansive clay minerals to a greater or lesser extent. 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 occurs also 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 occasionally clays that may produce expansive patterns. Overall, the geology in Auckland shows that expansive clay minerals may be found all over the city. In conclusion, there are no preferential zones where expansive soil patterns are expected to be found.

**2.5 In-situ Ground Instrumentation Datasets**

Sixense monitoring portfolio includes a wide variety of in-situ ground instrumentation solutions. In this section ground measurements from the City Rail Link (CRL) Mt Eden station construction site are compared with Atlas InSAR to show the potential of using both monitoring solutions and provide cross-validation.

The City Rail Link (CRL) consists of twin 3.4 km long tunnels up to 42 meters 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 has deployed a comprehensive deformation monitoring network, including many Automatic Total Stations. This network is gathering data since May 2020 in the area and its mission is to provide real time monitoring data over a valuable group of assets.

In Figure 5, a comparison between the observed displacements near the construction site is shown. The Beyond Monitoring comprehensive interface has been used to illustrate the correlation between Robotic Total Stations (RTS) and the neighbouring Atlas InSAR points. As stated in section 2.1 (Figure 1), InSAR measurements are in line of sight (LOS) which explains the neglectable differences in magnitude of observed displacements. Atlas InSAR precisions are therefore relevant to provide an expansive soils map of the city of Auckland and efficiently monitor vast amounts of urban assets.

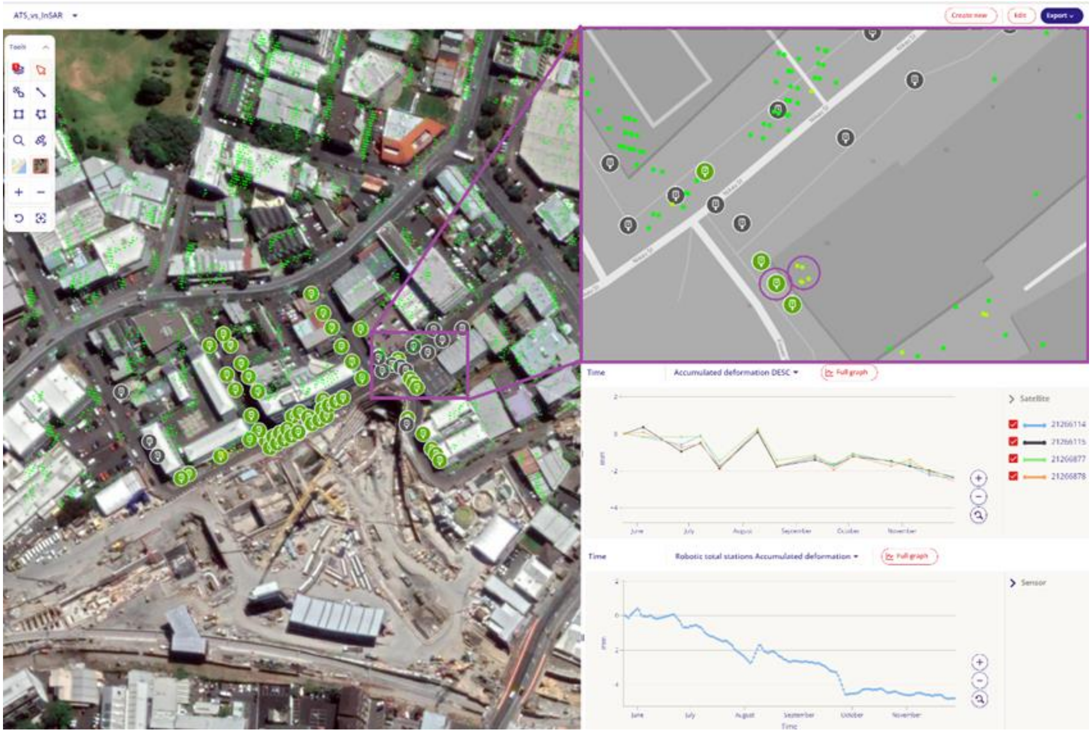

**Figure 5**: Sixense monitoring network, Robotic total station showing high correlation with InSAR measurements on the Sixense Beyond Monitoring platform.

**3. Data Analytics**

**3.1 Active Deformation Areas (ADA)**

Active Deformation Areas (ADA) is a spatial aggregation technique used to identify those ground deformation timeseries that represent an active deformation and meet a distance requirement. 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 timeseries following the same trend together with an envelope polygon identifying the area of influence.

In the presented study area, we have identified 231 Active Deformation Areas (ADA) matching the soil moisture behaviour. They were obtained by analysing their trends and correlating them with the soil moisture climate data presented in section 2. Figure 6 demonstrates an example of one of the detected seasonal areas of deformation with all the InSAR points timeseries and their associated trend.

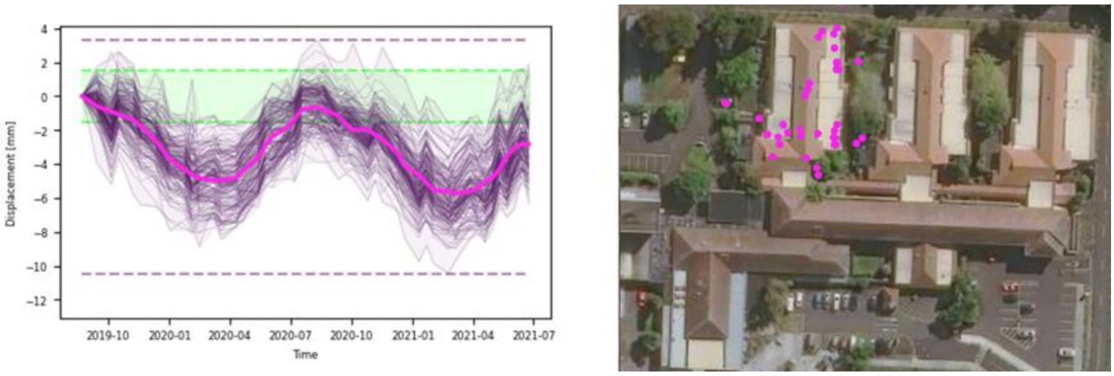


**Figure 6:** Example ADA with each of the timeseries with highlighted average/trend

### 3.2 Clustering

In general terms, cluster analysis or *clustering* consists in grouping a set of objects in such a way that objects belonging to the same group (called a cluster) are more similar (in some sense) to each other than to those in other groups (clusters). When it comes to ground motion timeseries clustering, each group is represented by its centroid. Clustering is widely used in exploratory data analysis and it is a common technique for statistical data analysis. A relevant example of timeseries data clustering is described in [Izumi et al (2021)].

In the presented study area, we have identified 8 of the 40 clusters as potential expansive soils related clusters. We have done so by analysing their centroids and correlating them with the soil moisture climate data presented in section 2. Figure 7 shows the most relevant cluster centroids.

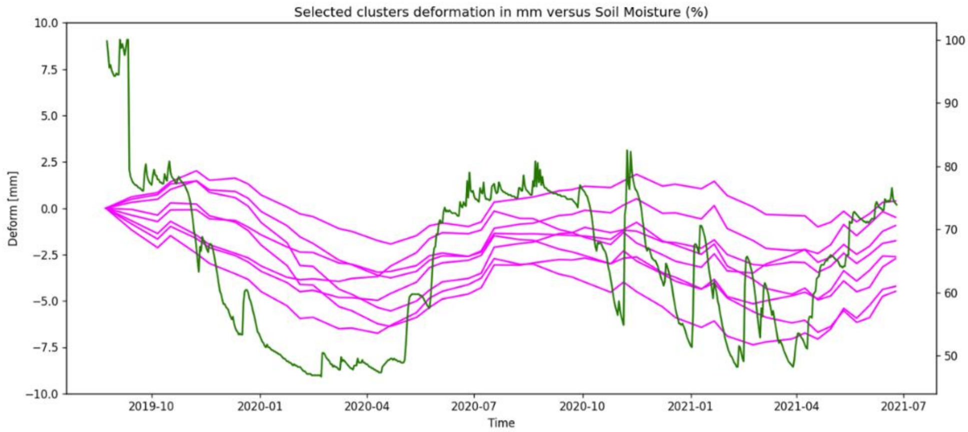


**Figure 7**: Selected clusters versus soil moisture data pattern.

### 3.3 Independent Component Analysis (ICA)

Independent Component Analysis (ICA) is the mathematical study of the components, or sources, that compose a set of observed signals. Under the assumption that each of the observed signals $(X_1, \ldots, X_n)$ is a linear combination of the independent sources $(S_1, \ldots, S_m)$: $X = AS$, independent component analysis aims at discovering the sources $S$ and the mixing matrix $A$ from analysing $X$. Analysis of InSAR data with ICA was already tested on volcanic areas with the ICASAR method [Gaddes et al 2019], which combines several ICA runs on bootstrapped samples and only keeps the sources that are consistent across runs for more robustness.

In the presented study area, each considered signal is a deformation map computed from two SAR acquisition. Each source is thus a geographic pattern, and the mixing matrix gives us indication on the strength of the source through time. This approach, complementary to looking for temporal signals, allows to continue monitoring the strength of the sources in the long run. Our implementation was used to identify 5 sources, several of which had temporal evolutions that strongly correlated to meteorological signals (e.g., soil moisture, temperature). In Figure 8 the source with strongest correlation with the soil moisture data pattern is shown.

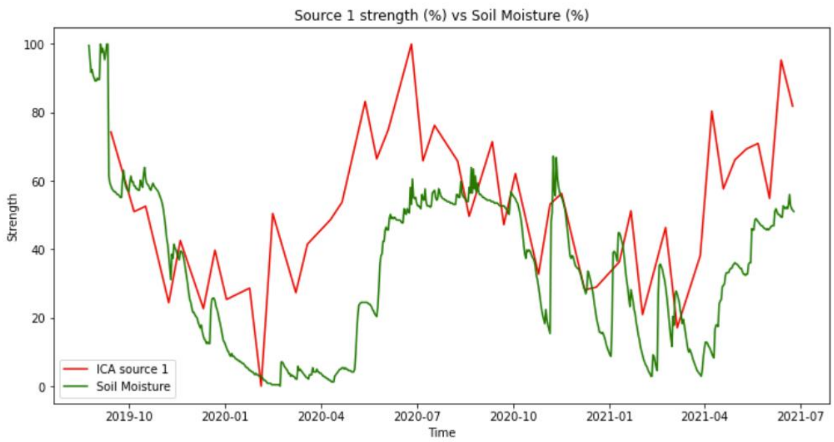


**Figure 8**: Selected ICA source strength versus soil moisture data pattern.

### 3.4 Algorithms Intercomparison

The results presented in Figure 9 show that the three methods' outputs (clusters and ADAs whose centroids correlate with soil moisture, and the second source from ICA) show very similar patterns, even though the methods treat the data in very different manners. ADAs are more selective since they include more strict distance criteria filters.


**Figure 9:** Algorithms intercomparison on the selected area of interest left to right (ADA, clustering, ICA).

### 4. Output layers

Geospatial techniques have been developed to efficiently aggregate the available 7.6 million ground deformation timeseries onto the building footprint buffers described in the section 2.2. Statistical indicators of all the timeseries within the building influence areas have been calculated for velocities and cumulative deformation. Additionally, all the measurement points with high correlation with expansive soils (~600k out of the ~7million).

These 600k points have been aggregated per building footprint adding two more indexes (presence of expansive soil patterns and their movement amplitude). Expansive soil spatial patterns can be efficiently viewed with the creation of density heatmaps. Those highlight the areas where the number of InSAR ground deformation measurements following the soil moisture trend is high. Figure 10 shows how these two layers can be browsed in the Beyond monitoring platform providing comprehensive information to Sixense's clients.

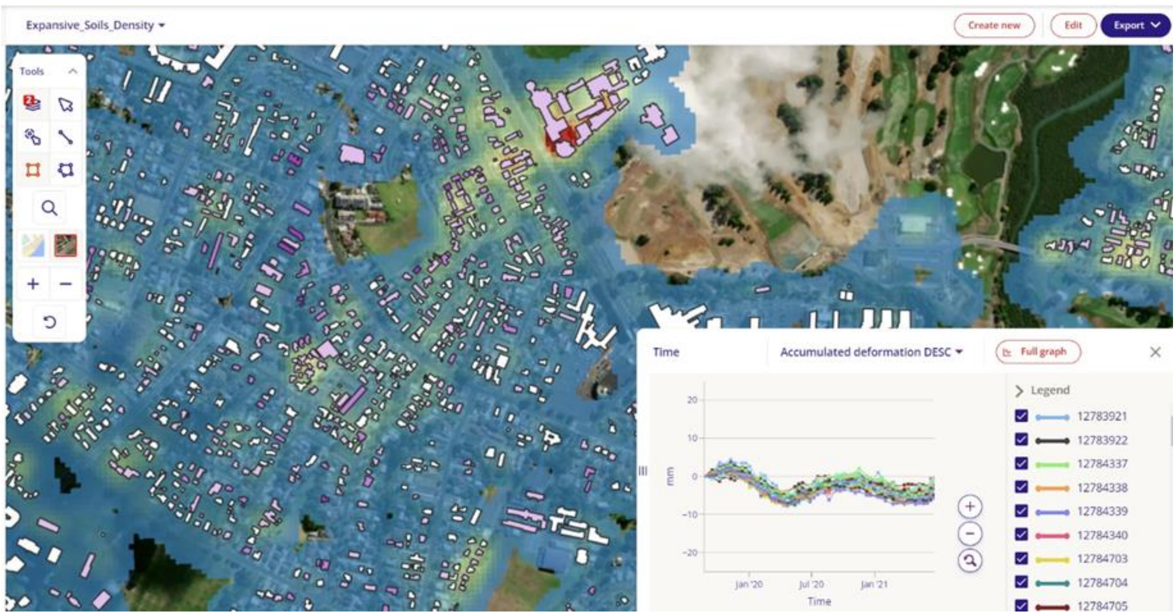


**Figure 10:** Output layers in Sixense Beyond Monitoring platform.

## 5. Conclusions

This article has presented an approach to tackle a very specific customer scientific problem: the identification of areas and assets with expansive soil behaviours over a large urban area. To do so, several datasets have been used (Atlas InSAR ground deformation timeseries, climate data, soil data, building footprints, …) together with a selection of data science techniques and algorithms (clustering, active deformation areas, independent component analysis). In parallel, we have validated the accuracy of Atlas InSAR as a ground motion measurement technique against insitu instrumentation deployed by Sixense in the Auckland City Rail Loop (CRL).

As a result of this study, over 600k measurement points following the soil moisture trend have been identified. Taking their position and movement amplitude, user-friendly output map layers have been produced and displayed in the Beyond Monitoring platform.

Urban soil is very difficult to map, and the presented layers will help the Auckland city council determine the affectation of expansive soil patterns across the city since and be ready for the climate challenges ahead.


## Acknowledgements

The presented article has been done in close collaboration with the *Auckland City Council*. Climate change adaptation is a reality, and many urban areas are facing the same issue as the one of this presented use case.

This work has been supported by the AI Program from Leonard, the innovation platform of VINCI. We would like to thank the coaches and mentors (specially Louis Dumont) for allowing us to develop, benchmark and improve our algorithms used during this case study.

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