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Mapping and monitoring urban landslides in New Zealand using Sentinel-1 InSAR data: A case study from Gisborne

Cartographie et surveillance des glissements de terrain urbains en Nouvelle-Zélande à l'aide des données Sentinel-1 InSAR: une étude de cas de Gisborne

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ABSTRACT: Landslides cause widespread economic and infrastructure damage globally each year (Froude and Petley 2018). In New Zealand, landslides frequently occur in soil and rock, triggered by high rainfall, seismic activity, land-use change and disturbance. This study focuses on Gisborne, a city where ongoing slope instability issues occurring across the steep slopes within the urban area are affecting several properties. Failure commonly occurs along reactivated slip surfaces when slow-moving retrogressive slides transition into fast-moving flows during extreme rainfall events. However, the extent and rate of slope deformation in the Gisborne area are poorly known. Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is a convenient method for measuring ground deformation, and over the past decade, SAR systems have significantly developed and provide consistent, reliable, high-resolution global data. In this study, we illustrate the potential of InSAR to detect the slow movement of urban landslides in Gisborne using Sentinel-1 data.

RÉSUMÉ : Les glissements de terrain sont des risques naturels répandus qui causent chaque année des dommages économiques et sociétaux considérables dans le monde entier. En Nouvelle-Zélande, les glissements de terrain se produisent fréquemment sur le sol et la roche, déclenchés par de fortes précipitations, l'activité sismique, les changements d'utilisation des terres et les perturbations. Cette étude se concentre sur Gisborne, une ville où les problèmes d'instabilité des pentes en cours sur les pentes raides de la zone urbaine affectent plusieurs propriétés. La rupture se produit généralement le long des surfaces de glissement réactivées lorsque des glissements rétrogrades lents se transforment en écoulements rapides lors d'événements pluvieux extrêmes. Cependant, l'étendue et le taux de déformation des pentes dans la région de Gisborne sont mal connus. Le radar interférométrique à synthèse d'ouverture (InSAR) est une méthode pratique pour mesurer la déformation du sol. Au cours de la dernière décennie, les systèmes SAR se sont considérablement développés et fournissent des données mondiales cohérentes, fiables et à haute résolution. Dans cette étude, nous illustrons le potentiel de l'InSAR pour détecter le mouvement lent des glissements de terrain urbains à Gisborne en utilisant les données Sentinel-1.

KEYWORDS: Urban landslide; InSAR; rainfall; remote sensing; New Zealand

1 INTRODUCTION

Landslides are widespread natural hazards that are responsible for substantial economic and societal damage globally each year (Kjekstad & Highland 2009). In New Zealand, landslides frequently occur in soil and rock, triggered by high rainfall, seismic activity, and land-use change and disturbance (Basher 2013; Phillips et al. 2018). Indeed, since 1843 there have been at least 600-recorded fatalities related to landslide events in New Zealand compared to 458 from earthquakes. The minimum damage costs associated with landslides are estimated between NZ $250-$300 million annually (Rosser et al. 2017). Further, with increasing urbanization, deforestation, land-use change, and climate shifts, the frequency of landslide events are expected to increase in the future (Gariano & Guzzetti 2016). As a consequence, detecting ground deformation related to landslides will remain vital for identifying and managing areas at risk to help plan for future urban developments. Landslide monitoring typically requires the continuous measurement of ground deformation, which is often done physically in the field. Although on-site visual measurements and in-situ sampling are incredibly effective, it is often in remote and dangerous places and puts people and expensive equipment at risk. However, over the past two decades, remote sensing techniques such as Light Detection and Ranging (LiDAR) (Glenn et al 2006), Unmanned Aerial Vehicle (UAV) surveys (Lucieer et al. 2014), and satellite-based Earth-observation such as optical imagery (Stumpf et al. 2017) and Interferometric Synthetic Aperture Radar (InSAR) (Bejar-Pizarro et al., 2017) have been used to map and monitor landslides to complement traditional on-site landslide observations and measurements. In particular, spaceborne SAR imaging systems provide a helpful solution to many of these problems because remote and dangerous sites can be surveyed without putting people or equipment at risk. Images can be taken in all weather conditions, allowing continuous coverage and hundreds of square kilometres can be analyzed at a relatively low cost (Ciampalini et al. 2014). The ability of InSAR to measure and monitor surface deformation related to landslide events has been well documented (Bejar-Pizarro et al. 2017; Bru et al. 2017; Ferretti et al. 2015; Hilley 2004). Today, InSAR is considered to be in the golden age of development (Moreira 2013), due to the growing availability of global SAR data. The launch of Sentinel-1A in 2014 marked a significant milestone for InSAR development, being the first civilian satellite specifically designed for InSAR analysis and producing free open access data (Ferretti 2014). Also, new and developing processing software makes the data available in easy and accessible formats. However, despite the rapid overseas take-up of this emergent spaceborne technology, the application of InSAR for geotechnical purposes in New Zealand is still in its infancy. This study focuses on applying Persistent Scatterer interferometry to map deformation related to landslides in Gisborne, an area particularly susceptible to landslide hazards because of the region's close proximity to an active plate boundary. The area encompasses steep slopes, relatively young, soft geology, deforestation, land-use change, and extreme rainfall events and extra-tropical cyclones (Franks 1988; Phillips et al. 2018). However, landslides in Gisborne have not been mapped with any precision, and the extent and ongoing deformation of landslide hazards in the urban area are poorly known.

2 InSAR FOR MONITORING LANDSLIDES

Interferometric Synthetic Aperture Radar is an active remote sensing imaging tool used to map and monitor surface deformation, with a cm to mm-scale of accuracy (Hu et al. 2014). As the name suggests, InSAR is a combination of Synthetic Aperture Radar and Interferometry. Synthetic Aperture Radar imaging systems work by transmitting an electromagnetic microwave from a sensor mounted on an aircraft or satellite to the Earth's surface, and Interferometry exploits the phase difference between two or more SAR images (Ferretti 2014). The standard InSAR technique for mapping ground movement is called differential InSAR (DInSAR), which uses the repeat pass method to compare two or more SAR images taken over the same area, but at different times (Ferretti 2014). More advanced multi-temporal InSAR (MT-InSAR) techniques such as Persistent Scatterer (PS; Ferretti 2014; Ferretti et al. 2001), Small Baseline (SB; Berardino et al. 2002) and a combination of the two (Hooper 2008), use a network of interferograms rather than just two images. This reduces the spatial, temporal, and atmospheric decorrelation, enhancing the precision of ground deformation measurements (Ferretti 2014; Hu et al. 2014). The type of method used depends on the data available, the study area and the information the user is trying to extract. The PS method uses a single SAR image, called the reference, from which all interferograms are formed and uses radar targets considered coherent over time, such as buildings for pixels (Ferretti 2014). For this reason, the PS method is better for urban environments that have more coherent targets. The SB technique works better in rural areas, as the approach uses pixels that are spatially coherent in the interferograms (Ferretti 2014). The SB method produces a network of interferograms with short temporal intervals and spatial baselines to increase interferogram correlation instead of having one master image (Hooper 2008). Deformation measurements are taken in the satellite's line of sight (LOS). The majority of SAR satellites have a near-polar orbit and a sensor with a right-looking geometry. This means the same area is imaged twice by the two different viewing geometries because the satellite moves in a descending orbit, from the North Pole to the South Pole and in an ascending orbit, from south to north (Ferretti 2014). For landslide related deformation, the movement is primarily in the direction of maximum slope, which means the optimum direction for measuring movement is parallel to the slope (Bejar-Pizarro et al. 2017). This is why east-west deformation is more readily detectable than north-south deformation, although both ascending and descending orbits can be combined to extract the vertical and horizontal component (Ferretti 2014).

2.1 *Sentinel-1*

Sentinel-1 is the most recent satellite launched by the European Space Agency as part of the Copernicus initiative. Sentinel-1A archive data is available from June 2014. In 2016 Sentinel-1B was launched and joined Sentinel-1A on the same polar orbit, reducing the satellite revisit time to 6 days in Europe and other certain areas of interest (Torres et al. 2012). For example, the revisit time for New Zealand is 12 days, and the primary imaging mode of Sentinel-1 is the Interferometric Wide (IW) swath mode, which has a swath width of 250 km, a look angle of 29-46 and a 14 m pixel resolution in the azimuth direction and 5 m in the range direction.

3 STUDY AREA

Gisborne city is located on the Raukumara Peninsula on New Zealand's North Island (Fig. 1). The city is primarily built upon the Poverty Bay Flats, a low-lying alluvial flood plain of the Waipaoa River, extending to the west of the city. Surrounding the plains are steep hills that do not exceed 800 m above sea level and display a terracette (stepped) morphology. Gisborne has one of the highest erosion rates in New Zealand, driven by steep slopes, easily erodible material, high rainfall, recent extensive deforestation and large numbers of grazing animals (Basher, 2013). The most common type of landslides in Gisborne are flows and slides in shallow soils triggered by heavy rainfall, similar to other regions across New Zealand (Phillips et al. 2018). In addition, previous records show several slope instability events occurring across the steep slopes within the urban area and along riverbanks and terraces (Fig. 1).

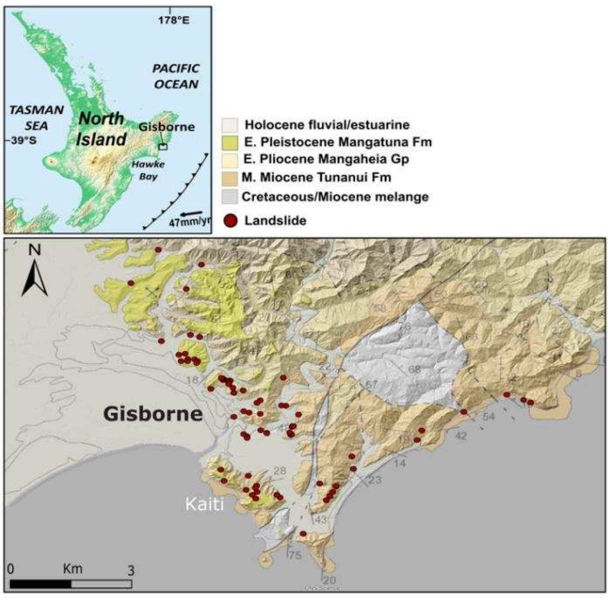

Figure 1. Study area location within regional geological setting and a geological map of Gisborne city showing the distribution of known landslide events.

4 METHODS

We applied the Persistent Scatterer interferometry technique to identify landslide-related deformation within the urban area for this study. The PS method was selected because it uses radar targets considered coherent over time, such as buildings and can provide dense pixel coverage in urbanized areas. The stack of SAR images were processed using ISCE (Rosen et al. 2012) and displacement and timeseries were obtained using StaMPS (Hooper et al. 2012). In StaMPS, the PS method uses a single SAR image, called the master, from which all interferograms are formed. Then finally, atmospheric corrections were applied using Phase based linear tropospheric corrections with TRAIN (Bekaert et al. 2015).

4.1 *Data and processing*

For this study, we used 59 descending Sentinel-1 IW swath images from October 2014 to December 2017 (Table 1) for processing.

Table 1. Details of the Sentinel-1 data used in the InSAR analysis

Orbit direction	Descending
Image dates	17/10/2014 - 24/12/2017
No. of SAR images	59
Track No.	175
Sub-swath	1
No. of Interferograms	45

The image acquired on the 6th of October 2016 was used as the master image, and 45 interferograms were processed for the PS scatter processing. The master image was selected from roughly the centre of the data set to reduce temporal decorrelation, and, at the time of acquisition, there was no precipitation to help reduce the effects of atmospheric decorrelation. All measurements were taken with respect to a stable reference point in the centre of Gisborne (Ministry of Justice building, 178.0278 -38.6687), an area assumed to be nondeforming.

5 RESULTS

The results from the PS interferometry are displayed in Figure 2. Each point represents the average velocity (mm/year) in the line of sight (LOS) direction, with positive values towards the satellite and negative moving away. The measurements indicate average ground displacements of -3 to 3 mm/year in the LOS (Fig. 2). A high density of PS pixels can be seen in the city centre, but few are observed in the less urbanized areas in the southeast and on the northern fringes of the developed areas (Fig. 2).

A site with a known landslide event has been highlighted in Figure 2 to display the PS results. The site is located near Kaiti Hill at Titirangi Drive and Wallis Road (Fig. 3), where there is a large ongoing complex landslide (Davies & Cave 2017). Retrogressive failure of the main landslide (at Wallis Road) is ongoing and has already led to the abandonment of one home, while an adjacent landslide (at Titirangi Drive) appears to be in an incipient phase of failure. The Wallis Road landslide has been particularly active from mid-2017, with slumping of the headscarp area transitioning to a constrained mudflow downslope, which then descends a cliff before terminating on the beach. In contrast, the incipient Titirangi Drive landslide at present displays much more subtle effects of deformation. This type of slope failure is typical throughout the Gisborne urban area. The location of the Wallis Road landslide and the incipient slope failure at Titirangi Drive is shown in Figure 3a. Several of the houses have PS pixels and indicate movement away from the satellite towards the coast. Figure 3b shows the time series plot that displays the relative deformation (mm) of the point highlighted in Figure 3a. The time series plot indicates the PS is moving away from the satellite, moving towards the coast between 2014 - 2017. For example in the time series plot in Figure 3b, the deformation between May and August 2017 shows movement away from the satellite downslope towards the ocean.

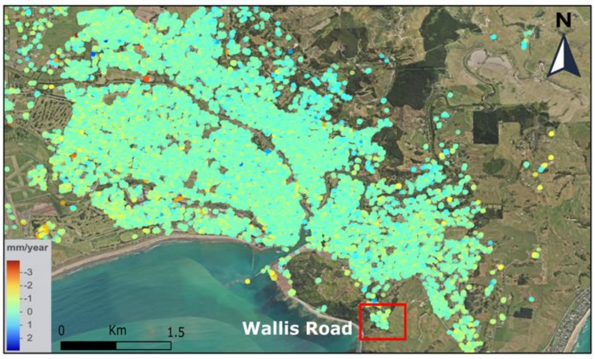

Figure 2. Distribution of the PS results in Gisborne. A high density of scatterers can be seen in the urban area. The area of interest is outlined in the red box at Titirangi Drive and Wallis Road. The results were plotted using the StaMPS-Visualizer App by Höser (2018).

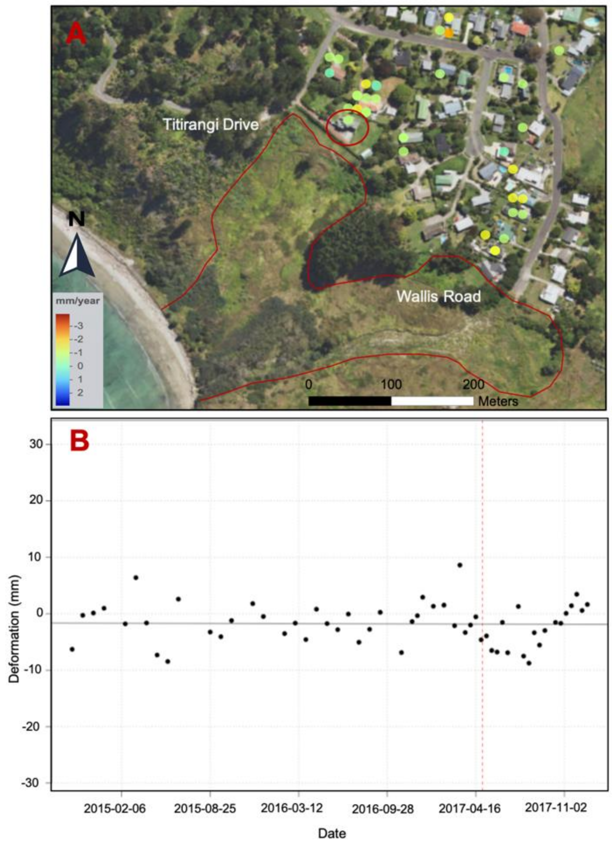

Figure 3. Map showing the PS distribution of Titirangi Drive and Wallis Road. The PS inside the red circle was used for the time series plot (a). Time series plot of the PS on Titirangi Drive, showing deformation downslope away from the satellite during the reactivation event in May-July 2017, which is represented by the dashed red line. Plotted using the StaMPS-Visualizer App by Höser (2018) (b).

6 DISCUSSION

The results from InSAR analysis at Wallis Road and Titirangi drive are consistent with the reactivation event recorded in the winter of 2017 (Davies & Cave 2017). The plot in Figure 3b also indicates that deformation began in the summer of 2017, months before the reactivation of the landslide (Fig 3b). The houses are still at risk from slope failure, and future ground movements are inevitable if the ground is not stabilised. The results show the potential of InSAR as a reconnaissance tool for detecting ground deformation related to landslide events. However, the PS technique did not detect phase-coherent pixels in non-urbanised and highly vegetated areas, and the deformation in this analysis is only measured in the direction of LOS, making it challenging to detect north-south movement. To overcome these challenges, further analysis of the study will be made using the Small Baseline technique to try and detect scatterers in rural areas and use data from descending and ascending orbits to extract vertical deformation. The vertical deformation is required to reliably extract seasonal deformation related to the clays' shrink-swell movement and infer building deformation.

7 CONCLUSIONS

Our study highlights the potential of using free open access Sentinel-1 data as a reconnaissance tool to detect ground deformation related to landslides. This study in Gisborne demonstrates how the PS technique can monitor ongoing slope movement in urban environments and examine how deformation has changed over time. The technique can assist conventional ground measurement methods in long term monitoring projects for detecting ground deformation. Although the site and slope conditions must be considered when undertaking InSAR analysis because it is less reliable in highly vegetated areas, and deformation is less sensitive on N-S facing slopes as movement is perpendicular to the LOS. However, our results are the first undertaken in Gisborne and produced using free and open access data and software. Further analysis will be undertaken to improve the results by using the Small Baseline technique and combining ascending and descending data sets to extract the vertical and horizontal deformation. Indeed, higher resolution SAR data can be used to try and increase the number of scatterers but at a higher cost. Over the past decade, SAR systems have significantly developed and can provide consistent, reliable, high-resolution global data. The development of InSAR is encouraging. In 2022 the first SAR satellite with dual-frequency radar, with both L-band and S-band systems available, called NISAR, will launch (Chapman et al. 2019). The mission is a collaboration between NASA and ISRO, and the data will be free and open. The continued technological advancement of SAR systems means a continuous and reliable global monitoring system, with high resolution, wide swath images can be achieved in the future for real-time hazard assessments, disaster management and geotechnical monitoring.

8 ACKNOWLEDGEMENTS

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