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The worsening impacts of land reclamation assessed with Sentinel-1: The Rize (Turkey) test case

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ABSTRACT

Massive amounts of land are being reclaimed to build airports, new cities, ports, and highways. Hundreds of kilometers are added each year, as coastlines are extended further out to the sea. In this paper, this urbanization approach is monitored by Persistent Scatterer Interferometry (PSI) technique with Sentinel-1 SAR data. The study aims to explore this technology in order to support local authorities to detect and evaluate subtle terrain displacements. For this purpose, a large 3-years Sentinel-1 stack composed by 92 images acquired between 07/01/2015 to 27/01/2018 is employed and stacking techniques are chosen to assess ground motion. The test site of this study, Rize, Turkey, has been declared at high risk of collapse and radical solutions such as the relocation of the entire city in another area are been taken into consideration. A media fact-checking approach, i.e. evaluating national and international press releases on the test site, is considered for the paper and this work presents many findings in different areas of the city. For instance, alerts are confirmed by inspecting several buildings reported by the press. Critical infrastructures are monitored as well. Portions of the harbor show high displacement rates, up to 1 cm/year, proving reported warnings. Rural villages belonging to the same municipality are also investigated and a mountainous village affected by landslide is considered in the study. Sentinel-1 is demonstrated to be a suitable system to detect and monitor small changes or buildings and infrastructures for these scenarios. These changes may be highly indicative of imminent damage which can lead to the loss of the structural integrity and subsequent failure of the structure in the long-term. In Rize, only a few known motion-critical structures are monitored daily with in-situ technologies. SAR interferometry can assist to save expensive inspection and monitoring services, especially in highly critical cases such as the one studied in this paper.

1. Introduction

The world's largest construction projects, ranging from highways, airports, subways and dams are recently carried out in Turkey (Srivastava and Full, 2016). Although they contribute to the country's economic growth and the demographic transition, the sustainability in cities is facing important challenges due to the lack of land for urban growth. In this context, shorelines are used for residential expansion through land reclamation and they are often exploited for expanding and developing the cities with low cost solutions. Land reclamation is a large business today, and the Ordu-Giresun and Rize-Artvinin airport projects in the Black sea region are conducted by reclamation. The small-town province of Rize, Turkey, has added 350.000 km^2 onto its size over years by reclamation process (Özhaseki, 2018). Rize hosts about a hundred thousand inhabitants and it is located on the Black Sea coast in the north-east of Turkey. This city was reported on February 21, 2018, as: "*Center of Turkey's Black Sea town Rize to be demolished, relocated aimed fears of collapse*" (Özhaseki, 2018). Indeed, the local municipality and the government are planning radical solutions such as the relocation of the entire town center in another place. The collapse risk is due to terrain subsidence. Here, the main subsidence source is the construction of buildings on artificial ground reclaimed to the sea. Since the 60 s, many multi-floors buildings have been erected despite the original planning that was forecasting a maximum of three floors per building. Moreover, new reclamation projects such as the airport construction and the marine urban sprawl zoning plan are encouraged by the authorities. However, it is crucial to monitor reclamation areas to properly plan future construction projects in an efficient way in terms of long term cost and environment.

In this context, structural health measurements can be performed,

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but they require proper demand from the building owners. In Turkey, city municipalities like Rize provide structural health information but only in response to extreme events such as heavy rainfalls, superloads and evident cracks. These in-situ measurements are very reliable but most of the time it is too late to repair the damage. Therefore, efficient monitoring systems – specifically over reclamation lands – that enable the estimation of structural health are necessary. The availability of geodetic measurements (GPS or leveling) could be very important in this context to perform local scale monitoring. Nevertheless, these standard methods are known to be time consuming, laborious and expensive as they involve intensive field sampling and require the use of special measuring instruments (Halicioglu et al., 2012).

As opposed to these traditional techniques, remote sensing methods using satellite technologies are known to be cost effective and have the advantage of obtaining large-scale information with frequent updates. Synthetic Aperture Radar (SAR) is a mature radar technology and several sensors at different bandwidths are operational and can provide data on a daily base (Moreira et al., 2013). The differential interferometric SAR (dInSAR) technique, which is based on two SAR images, has been intensively used for the monitoring of disasters created by volcanoes (Dirscherl and Rossi, 2018), glaciers (Eriksen et al., 2017; Erten, 2013), landslides (Thomas et al., 2014) and earthquakes (Erten et al., 2010). Thanks to its capability to detect deformations in the order of a fraction of the radar wavelength, dInSAR provides a unique possibility for characterizing deformation over large areas, and is therefore fundamental source of information for damage assessment (Osmanoglu et al., 2016; Aslan et al., 2018; Crosetto et al., 2011; Calo et al., 2015). Nevertheless, dInSAR cannot generally detect movements on the building level and it can be affected by large artefacts due to temporal changes at all levels (e.g. atmosphere, terrain).

Persistent Scatterer Interferometry (PSI) is an interferometric method for deriving two dimensional deformation, i.e. E-W and vertical dimensions when combining ascending and descending geometries, which makes use of the reliability of coherent targets (PSs) in time to tackle dInSAR limitations (Crosetto et al., 2016; Cao et al., 2016; Narayan et al., 2018). The deformation measurement takes place on the PS location. The importance of PSI has been highlighted intensively in city monitoring, which normally includes many coherent scatterers. Among the numerous examples, Cigna et al. (2014) highlights the condition and structural health of the historic centre of Rome, Italy, while Yang et al. (2016), Schunert and Soergel, (2016) show how PSI can be used for monitoring single building deformation. Milillo et al. (2018) shows the tunnel-induced subsidence in London, and Yang et al. (2018); Kim et al., 2005 underline the impacts of reclamation on subsidence in China. All the previous examples have employed high-resolution commercial X-band sensors, namely TerraSAR-X and Cosmo SkyMed, which have been widely used to monitor deformation phenomena induced by human activities in urbanized area (Costantini et al., 2017). A few studies have used coarse-resolution dataset along with PSI processing for city monitoring (Solari et al., 2016). Alternatively, Sentinel-1 C-band data supplies free accessible interferometric dataset with approximately weekly temporal resolution since 2016 in Europe and other selected areas, with huge amount of data available for regular monitoring (Iftikhar et al., 2018; Lasko et al., 2018; Raspini et al., 2018;Iftikhar et al., 2018; Lasko et al., 2018; Raspini et al., 2018 Raspini et al., 2018). On the building level, three measurement scenarios are possible:

1. Multiple measurements on a single building. In this case, the differential settlement can be evaluated and related to critical measures for the building structural health (Nicodemo et al., 2017). Indeed, differential settlement, i.e. variations in the vertical displacement for a structure, is the first cause of building damage and potential collapse (Wroth and Burland, 1974; Boscardin and Cording, 1989). High-resolution sensors can usually provide with many measurements per building, typically at the facade, and can be considered in this case.
2. Single measurement on a building. While a single measure is not sufficient to derive differential settlement, it can still be useful to assess if movements are higher than predictions and provide with indication for further inspections. For instance, the maximum allowable settlement is a well-known problem (Skempton and McDonald, 1956). This number is usually estimated before starting a construction project and strongly depends on the soil type and characteristics and on the building design.
3. No measurement on a building. While this case is clearly not providing any indications, estimates on surrounding buildings can still provide with relevant information on subsidence issues at a larger scale.

A relevant advantage of SAR technology is the provision of all weather data, an important factor for cities in a wet climate. Moreover, the ensured data continuity for the next 25–30 years makes the Sentinel-1 mission an invaluable opportunity for small municipalities and governmental organizations (Plank, 2014). Within this context, the goal of this article is to study Sentinel-1 PS time series across Rize to quantify the subsidence phenomena due to the reclamation and discuss how the Sentinel-1 mission provides an affordable solution for small municipalities to derive useful information. A fact check approach is considered in the study, with several news from the test area taken from local, national and international media.

The paper is organised as follows. Section 2 describes the test site, available SAR data and gives an overview of the PSI processing. Section 3 presents the processing results with four test cases covering different scenarios and Section 4 discusses and summarises the major findings of the study.

2. Description of the test site, available data and processing

The test site, Rize, is located along a bay on the Black Sea in the north-eastern part of Turkey at geographical coordinates (N 41°01′29″ and E 40°31′20″). Its exceptional location between sea and mountains makes Rize a difficult place for industrial development and urban sprawl (see Fig. 1). In this context, being cheap and easy to implement, reclamation process has become an attractive procedure. Indeed, since the 60 s, more than 404,685 m^2 of land (about one-third of Rize's city center) have been reclaimed in Rize by infilling the sea (Özhaseki, 2018).

Rize is nowadays the biggest tea-producing city in Turkey – the fifth biggest tea producer country – with its humid subtropical climate. Beyond the city center, the tea growing lands, which were covered by forests, can be easily seen in Fig. 1. In the last two decades heavy rainfall coupled with deforestation due to agricultural tea land expansion in this mountainous land has causes lots of landslides (Althuwaynee et al., 2018). The Kirechane village, marked in Fig. 1, has been heavily affected by landslides and it is taken as example in the following section.

The Sentinel-1 sensor is regularly acquiring data over Turkey at temporal resolution depending on the area, with minimum orbit repeat cycle of 6 days since 2016. Specifically, all the available data from January 2015 to February 2018 at relative orbit 145 have been considered for this study. A total of 92 acquisitions, taken every 12 days, have been considered. These Single Look Complex (SLC) data, freely available through the Copernicus Open Access Hub (Copernicus, 2018) and acquired in the Interferometric Wide (IW) swath mode, have pixel spacing of about 20m by 5 m (azimuth and range components, respectively). The center scene incidence angle is about 34deg and the acquisitions are taken in ascending geometry.

The data processing needs initial large disk space resources (about 1.5TB). Not all the data is anyhow required (the original swath size is about 250 km). The processing is performed over a selected portion of the data stack centered in Rize, spanning about 30 km along the coast