Int J Appl Earth Obs Geoinformation 74 (2019) 27–36

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Integrating geotechnical and SAR data for the monitoring of underground works in the Madrid urban area: Application of the Persistent Scatterer Interferometry technique

Adrián Jesús García[a,*], Miguel Marchamalo[a], Rubén Martínez[a], Beatriz González-Rodrigo[b], Carmen González[c]

[a] Topography and Geomatics Lab. ETSI Caminos, Canales y Puertos, Universidad Politécnica de Madrid, Madrid, Spain
[b] ETS de Ingeniería Civil, Universidad Politécnica de Madrid, Madrid, Spain
[c] Geocisa, Madrid, Spain

ARTICLE INFO

Keywords:
PSI
SAR
PSI validation
Deformation monitoring
DInSAR
Sensor fusion

ABSTRACT

The Differential Interferometric Synthetic Aperture Radar (DInSAR) is a powerful deformation control technique for civil engineering applications. However, the performance definition and limitations of the technique in tunneling works are far from being standardized. This work presents a thorough validation effort of the applicability of the Persistent Scatterer Interferometry (PSI) technique to the Madrid's M-30 tunneling works. A set of 26 Envisat images, covering from August 2003 to April 2008, were processed with two PSI techniques and the results were validated with on-ground measurements from leveling benchmarks and strips. The comparison of the deformations of more than 1500 control points has led to a global deformation difference of 2.6 mm RMS and 3.5 mm RMS with a coverage of the area of interest with persistent scatterers of 65% and 34% for the two PSI algorithms used. The limitations of the PSI technique when using SAR missions with low revisit time were shown. PSI has proven the potential to complement on ground monitoring techniques in tunneling works as soon as the limitations are overcome.

1. Introduction

The Persistent Scatterer Interferometry (PSI), the most developed differential Interferometric Synthetic Aperture Radar (DInSAR) technique, is a powerful remote sensing technique that allows the estimation of Earth surface's deformation with an accuracy of up to 1 mm/yr in optimal conditions (Armas et al., 2017; Wang et al., 2018; Castellazzi et al., 2017; Cigna and Sowter, 2017; Maghsoudi et al., 2018; Yang et al., 2018). From the initial approach of Ferretti et al. (2001), different algorithms have been proposed that exploit the phase information contained on a set of radar images taken over the same area and with the same sensor (Costantini et al., 2008; Duro et al., 2005; Perissin and Wang, 2012). Concise reviews of all the currently available techniques were carried out by Osmanoglu et al. (2016) and Crosetto et al. (2016) using as inputs the different works that have been conducted in the line of the PSI exploitation.

Although the potential and capabilities of the PSI technique have been shown in numerous applications in the last decade (Crosetto et al., 2010), the actual limits of the technique are far from being standardized. Uncertainties such as the deformation rates that can be observed, the geocoding error, the assumption of a linear deformation and the sensitivity to phase noise have limited the application of the SAR-based monitoring techniques to operational subsidence control systems. In order to put the PSI techniques at the level of the geodetic and geotechnical deformation measurement techniques, a concise and deep validation effort for each specific application has to be conducted. The outcome of this validation process should be a clear definition of the scenario and specific conditions under which PSI can be used as a reliable deformation control technique in tunneling works.

Different validation efforts have been carried out in the recent years aiming at validating the applicability of the PSI techniques to specific applications. Two main important validation works were carried out in the frame of the Terrafirma and the Persistent Scatterer Interferometry Codes Cross-Comparison And Certification (PSIC4) projects. The Terrafirma project, funded by ESA, aims at creating a European ground hazard information service. The validation activities carried out within the project were divided into two main parts: the process validation (Adam et al., 2009), and the product validation (Hanssen et al., 2008).

* Corresponding author at: ETSI Caminos, Canales y Puertos, Universidad Politécnica de Madrid, 28040, Madrid, Spain.
E-mail address: adrian.garcia.sanchez@alumnos.upm.es (A.J. García).

https://doi.org/10.1016/j.jag.2018.08.025
Received 14 May 2018; Received in revised form 25 August 2018; Accepted 31 August 2018
0303-2434/

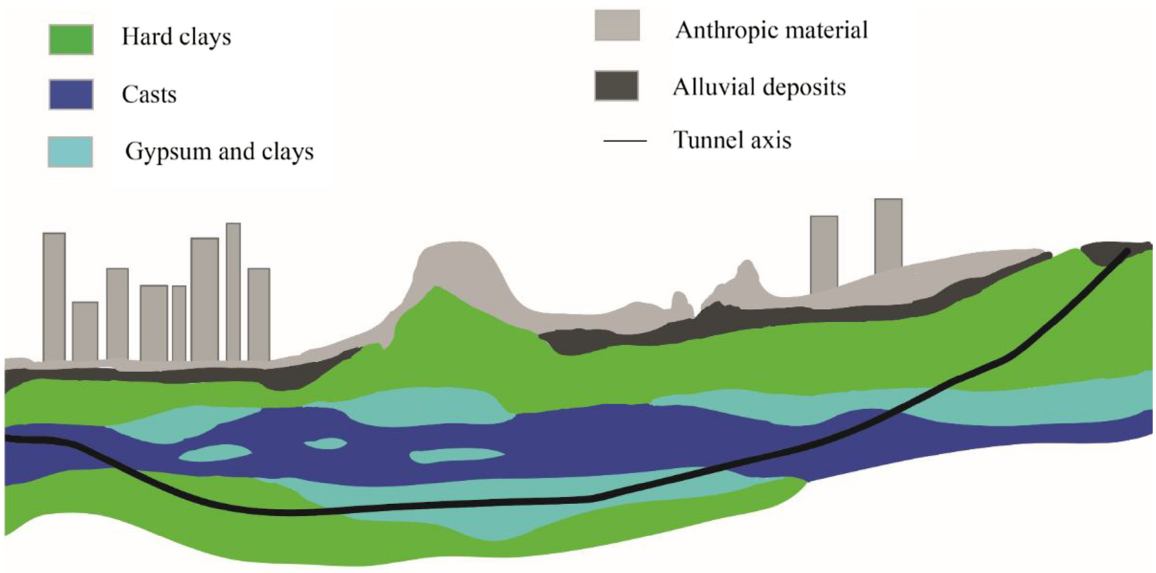

Fig. 1. Sketch of the geological profile of the area of interest.

The first one implied the assessment of the intermediate products, removing the impact of the geocoding error and allowing the assessment of errors comparing different processing chains. The product validation implied the comparison of the geocoded PSI products of 5 teams from business and academic groups against leveling measurements. Two areas were studied, Amsterdam, an urban area, and Alkmaar, an area characterized by gas exploitation. The assessment of the urban area was limited by the fact that no important construction works took place in the studied period of time and, therefore, the results can only be extrapolated to test areas with a zero or moderate deformation rates (Crosetto et al., 2010). The PSIC4 project implied the inter-comparison of the PSI results of 8 different teams without a priori knowledge of the testing environment: a mining area (Raucoules et al., 2009). The fact that no a priori information of the area was used was of great interest for the comparison of the different techniques and approaches followed by different teams. However, it does not represent the common scenario for an end-user for commercial purposes, who usually has available the historical deformation trends of the area of interest.

Other recent validation works include the work of Armaş et al. (2016) who carried out a validation activity in Bucharest using GNSS measurements, although no specific construction work was used as validation scenario. In the same line, Herrera et al., (2009) conducted a validation work of the PSI technique in the area of Murcia, which is affected by a slow subsidence, comparing the results against a limited number of extensometers. Moreover, Ferretti et al. (2007) and Quin and Loreaux (2013) conducted an experimental validation with a controlled movement of corner reflectors establishing the theoretical sub-millimeter accuracy that can be achieved under optimal conditions. Finally, Perissin (2008) conducted a validation work of the Digital Elevation Models (DEM) that can be derived from the outputs of a PSI processing.

Therefore, it can be inferred that the applicability of PSI processing, especially when applied to the monitoring of construction works, is far from being validated and the limitations standardized. In this work, a validation of the PSI technique, from the point of view of an end-user, is carried out using as the testing environment the urban area of Madrid during the construction works of the M-30 tunnel, which were conducted from November 2005 to October 2006. The outputs of a PSI processing are compared against the on-ground geotechnical techniques used during the construction work. Moreover, it will be assessed if the geotechnical measurements could have been combined with the outputs of the PSI process. Note that, in this work, it is assumed that geotechnical data refers to the on-ground measurements taken in a local reference system, such as the benchmark leveling and strip measurements used in this study. In this line, the aim of this work is the combination of these geotechnical measurements, referred to local reference systems, with the SAR data, which has a global reference system.

Two commonly available techniques, Stable Point Network (SPN) (Duro et al., 2010) and the Persistent Scatterer Pairs (PSP) (Costantini et al., 2008), are used here since they are representative techniques that are available to a general end-user. A formal comparison of all the available PSI techniques is left out of the scope of this work.

1.1. Validation scenario

The continuously growing urban area of Madrid over the last two decades led to traffic and mobility problems which had the maximum indicator in the M-30 beltway which, at the beginning of 2003, was on the brink of collapsing due to the heavy traffic. In order to ease this problem, the Madrid Council projected the remodeling plan of the M-30 implying the underground of up to 50 km of roads. One of the most important and challenging works of the framework was the southern By-Pass tunnel. This is the test site used in this work as the validation scenario. The By-Pass, located under the Enrique Tierno Galvan Park, consisted of the excavation of two twin tunnels by two Tunnel Boring Machines (TBMs). These TBMs, which are included within the biggest and most powerful ones at the time with a diameter of 15.2 m, excavated 4280 m for the southern tunnel and 3650 m for the northern tunnel. The excavation of the northern tunnel covered from November 2005 to July 2006 and from February 2006 to October 2006 for the southern tunnel.

Geologically, the tunnels are located in the Tertiary Madrid Basin and four different stratigraphic units can be observed, three with Tertiary materials (hard clays, casts, and gypsum) and the other one with Quaternary materials (alluvial deposits). On top of them, anthropic materials can be found. A schematic profile of the M-30 tunnel works can be found in Fig. 1.

The area of study comprises the twin tunnels and the surrounding area where the effects of the construction works can be of interest, Fig. 2. It has been divided into 12 different sectors, as it can be seen in Fig. 2, following the same approach of previous studies focused on the same area (Sillerico et al., 2015). Two sections of the M-30 works are of special interest for this work since they contain the higher density of