



Displacement Measurement Using SAR Interferometry – An Application to the Lisbon Regional Outer Circular and Its Neighbourhood

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Abstract: Ground displacements are a key factor to assess the safety and serviceability of any structure. A cost-effective technology for regional displacement monitoring, considering both the structure and its neighbourhood, would enable anomaly identification at an early stage and prevention actions. The objective of this work is to evaluate the stability of a segment of the Lisbon regional outer circular (*circular regional exterior de Lisboa* - CREL) through displacement measurements on the road and its surroundings using persistent scatterers interferometry (PSI).

Synthetic aperture radar interferometry is a technology that uses satellite images acquired in the microwave band of the electromagnetic spectrum. PSI is one of the most used techniques, which allows measuring displacements at the Earth surface with millimetre accuracy. Man-made structures usually have stable reflective properties to microwaves, which turn them into good targets for displacement measurement through this technique. Therefore, it is possible to obtain a high density of measurements in urban areas.

CREL is one of the most used roads to access Lisbon. The road has a length of 35 km and is fully operational since 1995. A displacement analysis using PSI was performed over an area of 50 km², centred at Caneças (Odivelas municipality), which contains 8 km of CREL. Displacement measurements were computed for 1340 points/km², every 11 days, between December 2011 and July 2013.

Two areas close to CREL were identified presenting subsidence, with approximate areas of 0.6 km² and 0.2 km². Superimposed on this trend, an oscillatory behaviour was also detected.

In conclusion, PSI is a useful technique to monitor displacements in urban areas and allowed the identification of possible unstable regions close to CREL, which may cause settlements at the road and damages at buildings nearby.

Keywords: Ground displacements; SAR interferometry; Lisbon regional outer circular.

1. Introduction

Structural health monitoring is an important task to ensure urban safety, whether it concerns buildings or communication ways. Besides, the stability of their surroundings is equally important, as the structures are affected by ground movements. Displacement measurements are important information for monitoring actions. Some usual methods for displacement observation are embedded equipment and geodetic techniques, such as levelling, tacheometry or global navigation satellite systems (GNSS). Despite providing accurate measurements, these techniques only enable displacement observation for a small number of points. These points are often located only at the structure, while usually there is not any information concerning its surroundings.

Interferometric synthetic aperture radar (InSAR) is a technology based on satellite images acquired at the microwave band of the electromagnetic spectrum. The sensor on board of the satellite emits a

beam of radiation towards the Earth surface that is then reflected and returns to the satellite, where the amplitude and the phase of the radiation are registered. From several passes of the satellite at the same location, it is possible to observe phase differences, which depend on several parameters, namely displacement at the Earth surface, topography, differences at atmosphere and at target scattering properties (Ferretti *et al.*, 2001). Multitemporal InSAR (MTI) techniques rely on datasets of images in order to separate the contributions of phase difference. Persistent Scatterer Interferometry (PSI) is one of those techniques and considers points at the Earth surface that keep their reflective properties stable at all the images – the persistent scatterers (PS). As the PS are often located at man-made structures, urban regions are prone to have a large number of these features. At least 15 images are required to estimate and remove the atmospheric effect (atmospheric phase screen – APS), which enables the estimation of altitudes with the precision of a few metres and displacements at millimetre-level. The usage of satellite images for displacement measurement enables the simultaneous observation of a wide area that depending on the image properties may span from a few tens to a few hundreds of kilometres. Therefore, InSAR is a cost-effective tool for displacement measurement that enables the monitoring of not only the structures but also their surroundings, providing useful information for safety and serviceability assessment.

In this study, an application of PSI is performed for a stretch of 8 km of the Lisbon regional outer circular (*circular regional exterior de Lisboa – CREL*), centred at Caneças, Odivelas municipality. A dataset of 35 images acquired between December 2011 and July 2013 is used. An area of 50 km² is analysed, where two regions close to CREL are identified to present possible signs of movement. Linear and oscillatory displacement trends are considered in the study.

This paper is organized as follows. Section 2 presents the study area and the dataset. Section 3 describes the method used for the processing. Section 4 contains an analysis of the results together with their discussion and section 5 shows the conclusions.

2. Study area and dataset

The study is performed over an area of 50 km² (Figure 1), spanning three municipalities (Sintra, Odivelas and Loures) and centred at Caneças (Odivelas). It contains a stretch of 8 km of CREL, which is one of the most used roads to access Lisbon. CREL was finished in 1995 and has a total length of 35 km. The stretch considered in this study contains a bridge and a tunnel.

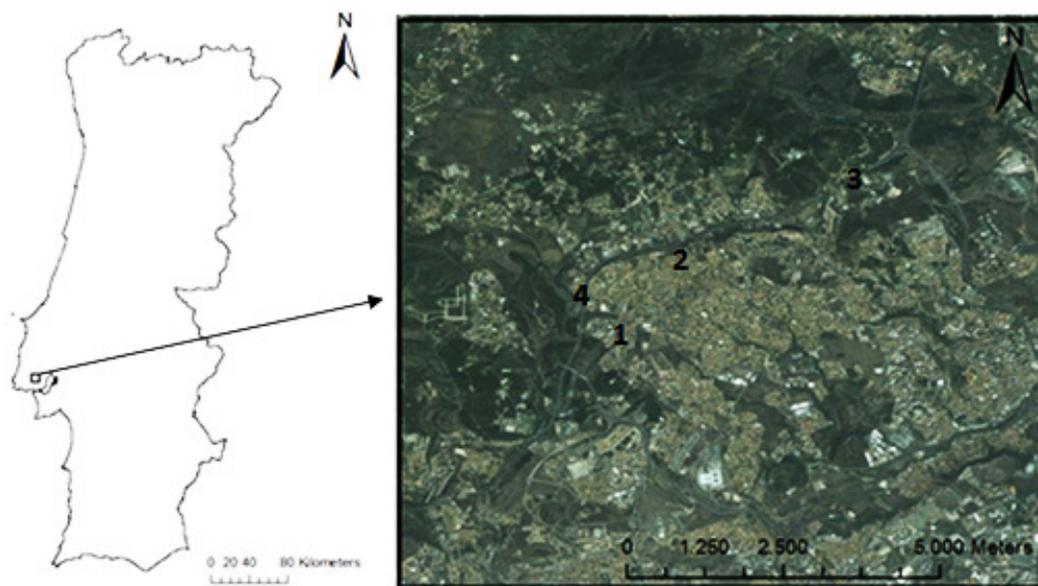


Figure 1 – Location of the study area (© Esri)

Figure 1 shows the selected study area, where the numbers represent regions of interest. Numbers 1 and 2 are urban areas close to CREL, number 3 is a tunnel and number 4 is a bridge. The geology of the study area is composed by limestone, sandstone, marls and basalt.

For the displacement analysis presented in this paper, a dataset of 35 images acquired between December 2011 and July 2013 by the sensor on board of satellite TerraSAR-X was used. These images were acquired on stripmap mode and have 3 m of spatial resolution. The revisit time of the satellite is 11 days, however there are some gaps in the time series due to needs concerning maintenance and other scheduled works. The images are from an ascending pass of the satellite and have HH polarization (both emitted and received radiation have horizontal polarization). For altimetric information, the EU-DEM digital surface model (DSM) was used with 30 m of spatial resolution.

The SARPROZ[®] software was used to do the processing (Perissin, 2016).

3. Method

The PSI technique implemented at SARPROZ[®] software was applied on the mentioned dataset. The SAR images were coregistered and then geocoded through the manual selection of a ground control point. The DSM was converted into the SAR geometry, which has two dimensions: azimuth and slant-range. Azimuth corresponds to the direction of the satellite trajectory (approximately north-south) and slant-range is orthogonal to azimuth direction and has an angle of 41.7° with the vertical. APS was estimated for a set of PS candidates. Points with stable amplitude were selected as candidates and phase models for corrections to the DSM and non-linear displacements were attributed to them. From the residuals of the comparison between the observed and the modelled phase, APS values for each image date were computed for the candidates to PS and then interpolated for all the pixels in the image. For the PSI calculation, a larger set of points was selected. For each point, previously computed APS was removed and a value for DSM correction (residual height) was achieved. Non-linear displacements were considered and a value for cumulative displacement was obtained for each PS. Temporal coherence is a measure of the fit between modelled and observed phase which varies between 0 and 1 and only scatterers with values greater than 0.9 were considered as PS.

In order to analyse the presence of seasonal behaviours at the study area that could be masking signs of possible instability, a set of around 200 PS whose displacement time series presented an oscillatory behaviour were chosen and their average displacement was computed in order to obtain a trend common to all the points (Figure 2). Linear velocity and correlation to this oscillation were calculated for each PS and analysed separately (see section 4).

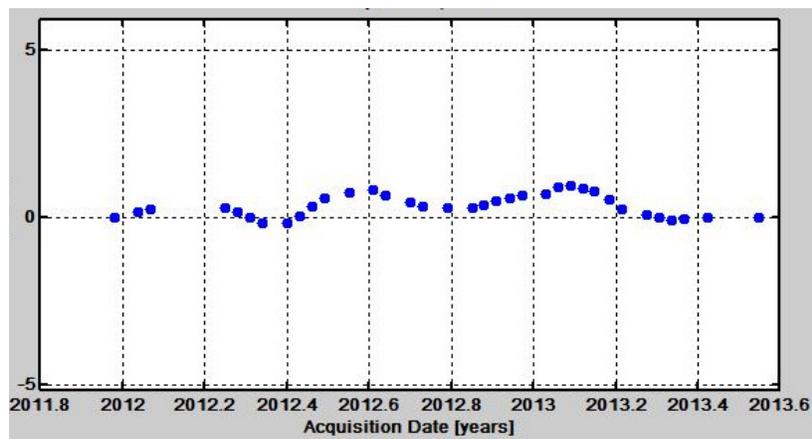


Figure 2 – Average oscillatory behaviour; units of vertical axis are millimetres

Four smaller regions were selected for more detailed processing: two urban areas close to CREL which presented signs of subsidence (regions 1 and 2), the tunnel (region 3) and the bridge (region 4). The urban areas were processed considering the oscillation from Figure 2, the bridge analysis used temperature values as a seasonal trend and the tunnel was processed using non-linear displacements.

4. Results and discussion

4.1 Non-linear approach

From the processing performed with PSI considering non-linear displacements for the whole study area, a large number of PS was obtained for the urban zones, reaching a density of 1340 PS/km². However, at vegetated areas the number of PS is low as there are not many targets keeping stable reflective properties at those regions. A map with cumulative displacement for each PS was obtained (Figure 3).

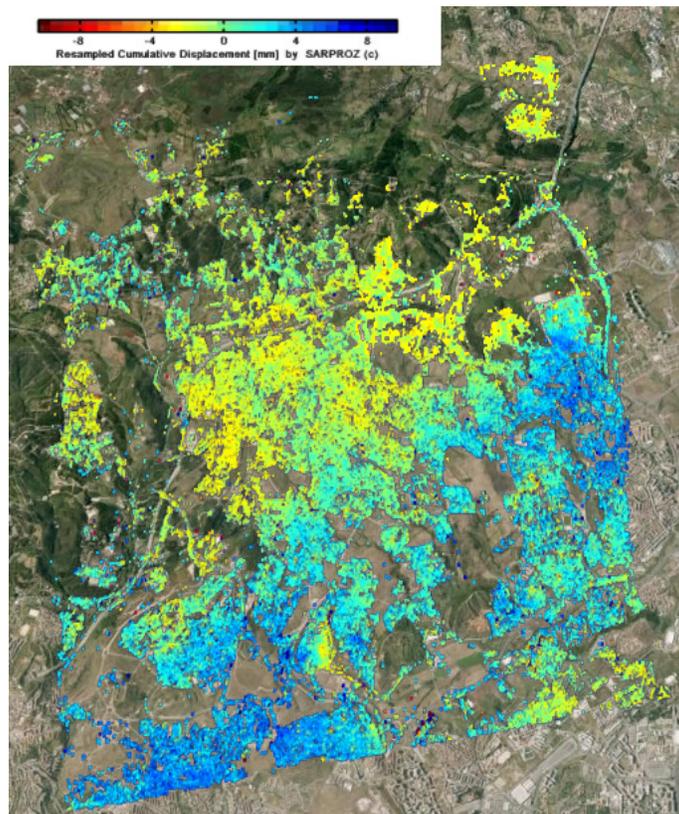


Figure 3 – Cumulative displacement along LOS map for the whole study area

PS with negative displacement values are moving away from the satellite, while positive cumulative displacements are associated to PS getting closer to the satellite. SAR technology only enables the observation of displacements along the sensor line-of-sight (LOS), which has an angle of 41.7° with the vertical. The displacement observed through InSAR may be a combination of vertical and horizontal displacements. Assuming most of the detected displacement is in the vertical direction, a large area close to CREL presented settlements of, approximately, 4 mm during the time interval considered in the study. Analysing the time series of a few PS (Figure 4), it can be verified that an oscillatory behaviour affects most points and that those oscillations cause the scatterers to move away from the sensor by the end of the time series.

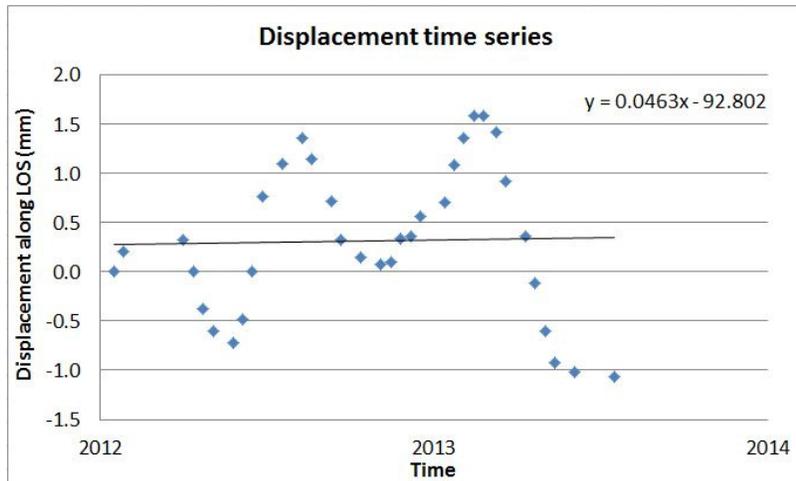


Figure 4 – Displacement time series for a PS from region 2

4.2 Linear and oscillatory approach

4.2.1 – Region 1

In order to check if the apparent displacement away from the sensor from Figure 3 is truly subsidence or just a side-effect of the oscillatory behaviour, linear velocity and correlation to the oscillation presented in Figure 2 were computed for each PS of regions 1 and 2. These results were compared to those obtained from the non-linear approach from the previous section. For region 1, Figure 5 shows a decrease of the number of PS for the linear and oscillatory approach (Figure 5b) with respect to the non-linear one (Figure 5a). The decrease is possibly due to the fact that some of the initial scatterers' motion does not follow the oscillatory behaviour being considered and thus their temporal coherence is low and they are not selected as PS. Comparing the cumulative displacement from the non-linear approach with the cumulative displacement caused by only the linear movement, it is observed that the first method leads to larger displacement magnitudes, which means that some of the movement away from the sensor observed with the first approach may be caused by oscillatory behaviour.

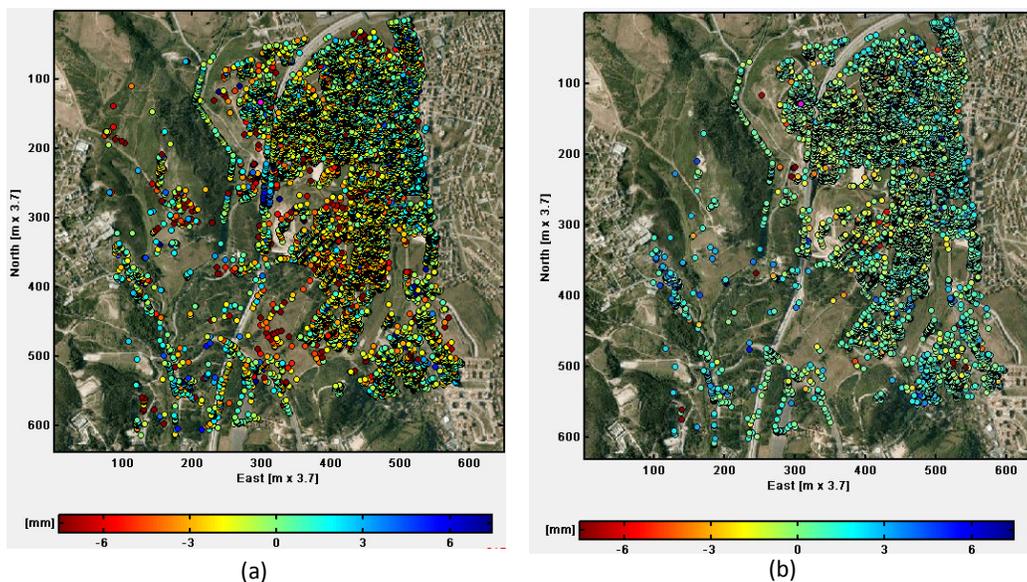


Figure 5 – Cumulative displacement maps considering non-linear (a) and linear (b) models for region 1

4.2.2 – Region 2

Similar to region 1, for region 2 the cumulative displacement when considering only linear motion is lower than for non-linear displacements. In Figure 6, it can be observed from the linear velocity map that the scatterers at region 2 present subsidence behaviour. Most PS are moving away from the sensor with an average velocity around 2 mm/year along LOS. The subsiding area occupies, approximately, 0.2 km² and is located south of CREL. A nearby region centred at CREL is highly correlated to the oscillatory reference time-series (PS with large values in Figure 6b). Possible explanations for this phenomenon will be researched in future work.

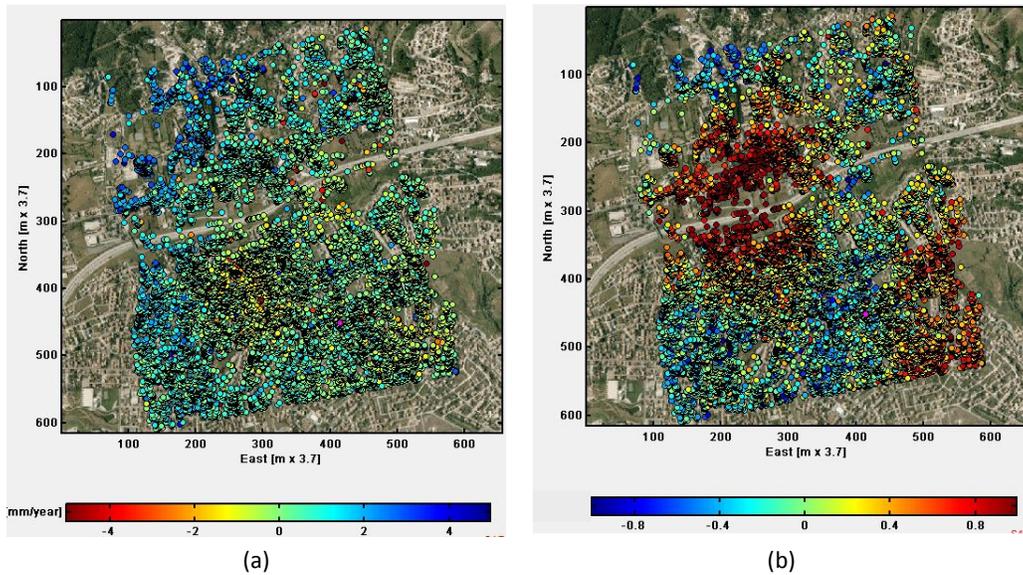


Figure 6 – Linear velocity (a) and correlation to oscillation movement (b) maps for region 2

4.2.3 – Region 3

For region 3, the Montemor tunnel, a few scatterers presenting cumulative displacement away from the sensor above 5 mm are found (Figure 7). However, these are isolated scatterers and it is possible that this behaviour corresponds to elements built on the tunnel and not to the tunnel itself. As the tunnel surface is covered by vegetation, a small number of scatterers is identified on it.

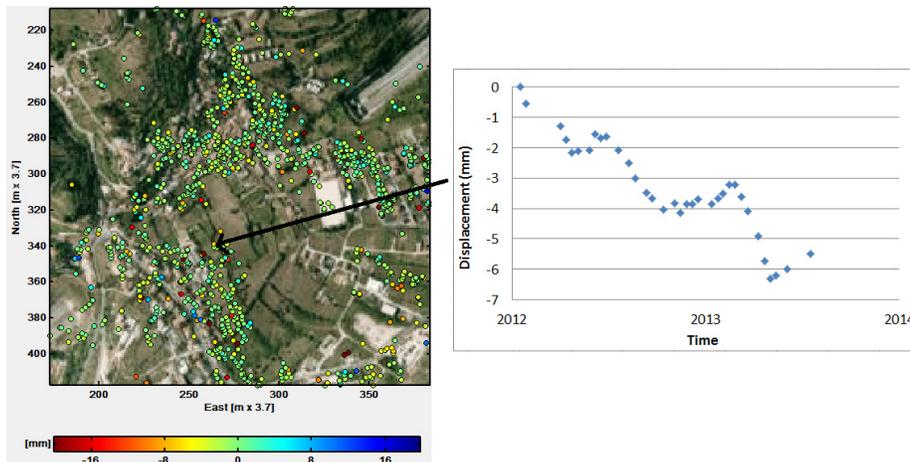


Figure 7 – Cumulative displacement along LOS map and time series for a scatterer on the tunnel

4.2.4 – Region 4

The study area for region 1 includes a bridge in the North-South direction and, approximately, 500 m length (region 4 from Figure 1). When processing this bridge using the non-linear displacements approach, the PS located on it present positive cumulative displacement values, meaning that the bridge is moving towards the sensor. As man-made structures are usually affected by phenomena such as thermal dilation, the behaviour obtained through the PSI processing may be explained by the temperature causing the bridge to dilate (going up or moving towards the sensor) in summer and to contract (going down or moving away from the sensor) in winter. As the studied time interval ends in summer, the last displacement observations are performed while the bridge is going up, thus the cumulative displacement observed is positive. Nevertheless, this result may be masking possible signs of instability. A small area around the bridge was processed considering linear and a seasonal trend related to air temperature.

It is observed that there is a high correlation between the displacement of the PS on the bridge and the air temperature time-series. When this seasonal behaviour is removed from the results, linear velocity shows that, unlike what results from the non-linear approach presented, the PS on the bridge are actually moving away from the sensor (Figure 8). It should also be noted that PS on the ground near the bridge present linear velocities away from the sensor that, for some scatterers, reach 10 mm/year, however a detailed analysis of the bridge structure is needed to assess the causes of the displacement measured.

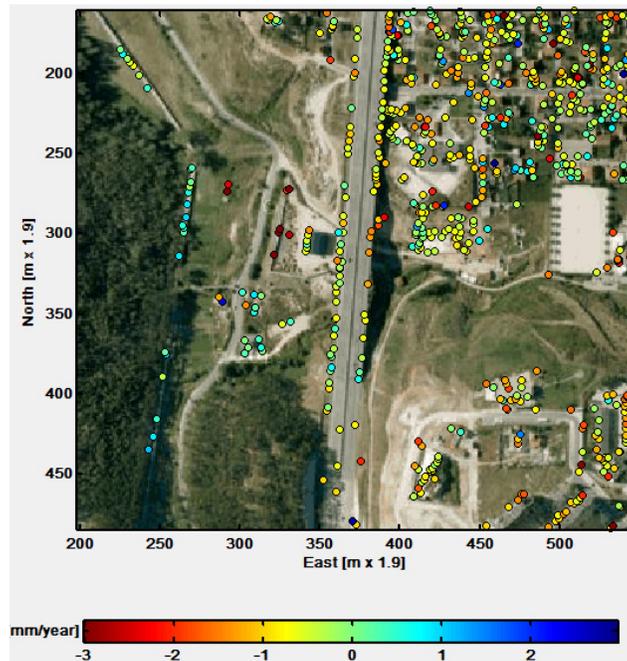


Figure 8 – Linear velocity along LOS map for the bridge

5. Conclusions

PSI enabled displacement measurement for an area of 50 km², for approximately, 67000 points located mainly at urban areas. This technology allowed the remote monitoring of a wide area around one of the most used roads to access Lisbon. Not only was it possible to measure displacements at CREL and at some of its elements such as a tunnel and a bridge, but also at its surroundings, which have a large influence on the infrastructure stability and safety. An area presenting subsidence behaviour was identified around CREL. However, the study presented at this paper showed that some of these displacements are caused by an oscillatory movement and, therefore, it is possible that the ground may return to its original state. After removing the oscillation from the displacement time series, the linear velocity maps show that region 2



presented subsiding behaviour between December 2011 and July 2013 around 2 mm along the sensor LOS. Signs of noticeable displacements were not identified neither for region 1, the tunnel or the bridge. Nevertheless, the PSI technique proved to be useful to measure displacements on these infrastructures and may provide information for early warning systems.

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