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A first approach for displacement analysis in Lisbon Downtown using PS-InSAR

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Abstract

Lisbon Downtown presents unique geomorphologic properties which makes it an area prone to terrain instability. Serious accidents have occurred there, namely, during the 1755 earthquake and a flooding event at the extension of a subway line, demanding a frequent monitorization for safety reasons and expense minimization. In this study, Permanent Scatterers technique is applied. The calculated displacement velocities are compared to those obtained from levelling operations. Possible causes for the discrepancy are presented in the paper. Besides a subsidence trend, a seasonal behaviour is also detected, probably related to aquifer recharge or tides.

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Keywords: Permanent Scatterers; subsidence; seasonal trend; Lisbon downtown

1. Introduction

Many cities around the world are located in unstable regions. Their susceptibility to landslide, subsidence or to the collapsing of man-made structures is high and therefore represents a risk for their inhabitants. Geomorphologic

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properties such as soft clay soils or the presence of groundwater are worsened by human activities like, for example, groundwater extraction or the construction of urban structures like subways or sky-scrappers, which increase the terrain load.

Geodetic techniques, such as levelling or GNSS surveys, are efficient for monitoring terrain displacements, however they only provide information for a reduced number of points. Differential SAR Interferometry is an alternative technique but, it is severely affected by geometric and time decorrelation as well as by atmospheric effects. The analysis of long time-series of SAR images allows the estimation of the Atmospheric Phase Screen (APS), which can reduce the influence of atmosphere in the displacement calculation. Included in the time-series techniques, Persistent Scatterer Interferometric SAR (PS-InSAR) approaches identify points that keep their scatterer properties for large space and time baselines, enabling the displacement analysis for a thick network of points. The Permanent Scatterers algorithm [1] was the first strategy of this kind to be proposed.

Many authors have recently applied time-series InSAR strategies to monitor subsidence in cities. Water extraction is considered, by the authors, to be the main cause for subsidence, as presented in [2,3,4,5,6], being that in [2,4,5] this phenomenon is associated to soft clay soils. The construction and maintenance of subway tunnels are also identified in [3,4,7] as a cause of subsidence. Seasonal effects are identified in [5,8], where it is suggested that they might be related to hydrogeological parameters and changes in groundwater level.

Persistent Scatterer technique has been previously applied to Lisbon, resulting in the identification of two subsiding areas - Laranjeiras and Vialonga [6,9] - mainly correlated to water extraction and proximity to seismic faults. For its heritage importance, the Lisbon Downtown area has been selected to be analysed in this study. Previous levelling surveys show that this area is prone to instability due to geomorphologic conditions. The validation of data obtained through PS-InSAR will be performed throughout a comparison with levelling data. Besides subsidence phenomena, seasonal trends are also searched for, since the knowledge about the region geomorphology suggests that they might be present.

Concerning this paper, the following section presents the area under study and the data used. Section 3 contains the methods for both processing and validation. Section 4 presents the results and discussion while the final Section shows the main conclusions.

2. Study area and data

Lisbon Downtown is located in the northern bank of the estuary of River Tagus (Fig. 1). This area was severely damaged during the 1755 earthquake and was reconstructed in the following years. As the built area is over the junction point of two underground streams, the existing groundwater leads to soil instability, turning Lisbon Downtown in a region which requires frequent and careful monitoring. Two subway lines cross each other in this region, at *Baixa-Chiado* station, and the recent expansion of one of the lines was marked by a flooding event in a tunnel under construction close to *Terreiro do Paço* station in 2000 [10].

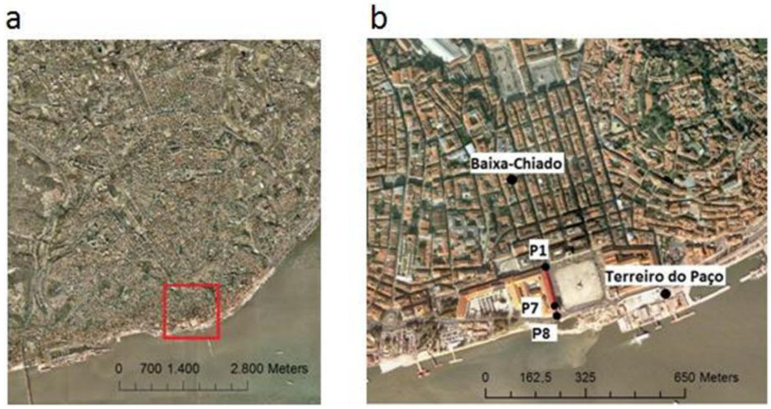

Fig. 1. (a) The city of Lisbon (Downtown study area in red square); (b) location of subway stations and levelling points.

For the PS-InSAR analysis, 19 ASAR images from an ascending pass of Envisat satellite acquired every 35 days between August 2008 and May 2010 are available. The images were obtained from the European Space Agency in Single-Look Complex (SLC) format. For altimetric information, a Digital Terrain Model (DTM) from Intermap NextMap with 5 m of spatial resolution was utilized. The data processing was performed in the SARPROZ software, developed by D. Perissin [11].

3. Methods

3.1. Data processing

Considering the acquisition time and perpendicular baseline of the SAR data, an image acquired in July 2009 was automatically selected as the master image for the processing. An area of 3.2 km x 3.2 km of the city of Lisbon was considered for the first step of the procedure. The slave images corregistration to the master image was performed using information from orbital data. The correct geocoding of the SAR data was guaranteed by selecting a ground control point located in the Downtown area, easily identifiable in a statue located in the middle of a square.

After the completion of the pre-processing operations, the estimation of the Atmospheric Phase Screen (APS) was performed. Permanent Scatterer Candidates (PSC) were selected through the thresholding of the Amplitude Stability Index, in which only points with an index value above 0.8 were used. The range values for linear trend, height and seasonal trend were selected, by performing a histogram analysis, in order to achieve a displacement model which would fit the PSC behaviour (Table 1). The residuals inversion was then performed in order to obtain values of APS for each PSC. The APS values were interpolated for all the study area. The Permanent Scatterers (PS) were selected over the Amplitude Stability Index but, using a threshold lower than for APS estimation in order to increase the number of available points (0.5). Both the displacement model and APS values determined in the previous step were applied to calculate displacement values for the points.

Table 1. Range values for APS estimation.

Parameter	Minimum	Maximum
Linear trend (mm/y)	-15	15
Height (m)	-20	20
Seasonal trend (rad/ºC)	-0.1	0.1

As the area of interest is the Downtown, a more detailed analysis was performed for this region, which involved the selection of a second study area with 1.2 km x 1.2 km. A new point selection was performed over Amplitude Stability Index where points with values above 0.5 were chosen. The displacement model parameters were adjusted in order to fit the data from the Downtown (Table 2), while using the APS values estimated from the larger area.

Table 2. Range values for the detailed processing of the Downtown area.

Parameter	Minimum	Maximum
Linear trend (mm/y)	-10	10
Height (m)	-20	30
Seasonal trend (rad/ºC)	-0.1	0.1

3.2. Quality assessment

A levelling line with eight points was established in the western wing of *Praça do Comércio* and has been surveyed since 1956 [10] by surveying teams from the Applied Geodetic Division of the *Laboratório Nacional de Engenharia Civil*. A subset of the surveying results between January 2009 and July 2009 was considered, as this is the time span common to the SAR images and levelling. The northern point of the line (P_1) is considered to be stable and is used as reference to the survey.

The number of PSs close to the levelling line is low. Therefore, the authors considered that performing an interpolation of deformation velocities for comparison to the levelling data would introduce considerable errors in the analysis. As high coherence PSs were identified close to point P_1 and to the two southernmost levelling points (P_7 and P_8), it was assumed that those PSs (PS_1, PS_7 and PS_8) would present velocities similar to those of the levelling points.

The PS velocities obtained from the PS-InSAR processing are referred to a PS considered as stable (PS_0) which is located in the Downtown neighbourhood. In order to compare the PS-InSAR results to the levelling ones, the PS-InSAR velocities of PS_7 and PS_8 must be known in relation to PS_1 and not PS_0, which can be achieved by subtracting the PS-InSAR velocity of PS_1 from that of the other PSs. However, the value calculated is the displacement velocity along the sensor line-of-sight (LOS). In order to achieve data comparable to the levelling, the vertical component velocity was determined. According to sensor geometry, an incidence angle of 23º was used for the conversion.

4. Results and discussion

The quality of the results obtained through PS-InSAR was assessed by the comparison with the data of levelling surveys of the western wing of *Praça do Comércio*. The surveys show that, from January 2009 to July 2009, the average vertical displacement for P_7 was -5.6 mm/yr and for P_8 was -12.0 mm/yr, in relation to P_1.

Displacement velocities for Permanent Scatterers PS_7 and PS_8 along LOS were calculated from the point heights in relation to PS_0 for the SAR images acquired at the beginning and the end of the considered time period. Table 3 presents the points' coherence, the vertical component of the displacement velocities of PS_7 and PS_8 in relation to PS_1, and the difference to levelling results. The comparison of vertical displacements from PS-InSAR and levelling are in Fig. 2 and Fig. 3 for PS_7 and PS_8, respectively.

Table 3.Vertical displacement velocities for PS_7 and PS_8 obtained from PS-InSAR.

Permanent Scatterer	Coherence	Velocity (mm/yr)	Difference to levelling (mm/yr)
PS_7	0.98	-6.4	0.8
PS_8	0.87	-13.1	1.1

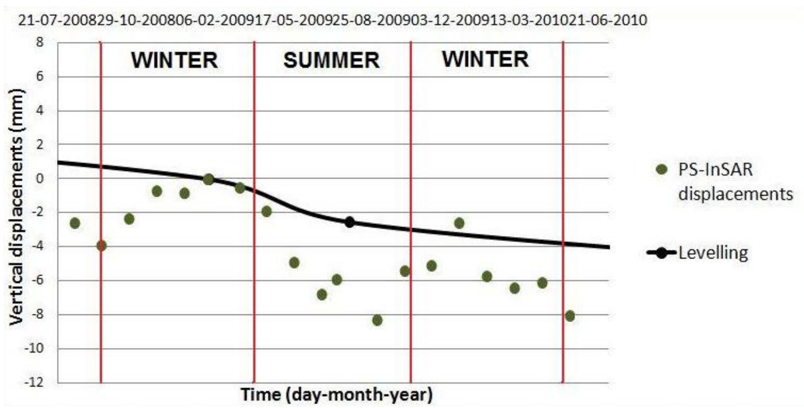

Fig. 2. Vertical displacement values for P_7 and PS_7.

A good agreement between the displacement velocities determined by PS-InSAR and levelling surveys was verified for both PS_7 and PS_8. Although the results only could be validated for two points, an average difference of 1.0 mm/yr was observed. It must be taken into account that the PSs are not in the same location of the levelling points, which may contribute to the observed discrepancy.

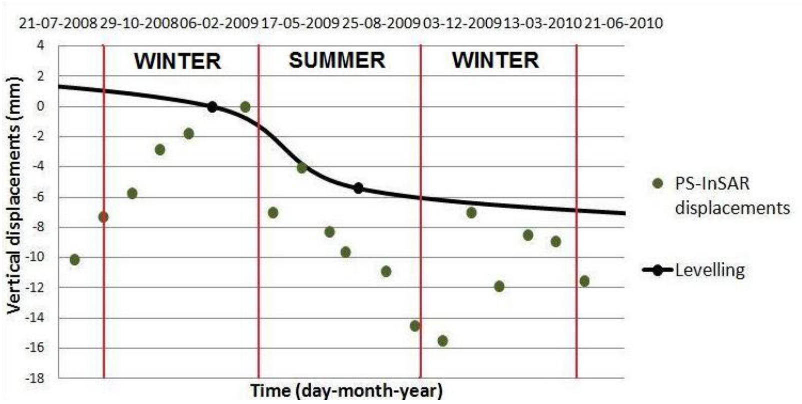

Fig. 3. Vertical displacement values for P_8 and PS_8.

PSs located in Lisbon Downtown show a distinct behaviour from those in other regions of the city. The geomorphology of the terrain implies that this area is prone to instability. PS-InSAR detected LOS displacement velocities from -9.7 mm/yr to 5.9 mm/yr, considering only PSs with coherence values above 0.8 (Fig. 4). At the western wing of *Praça do Comércio*, an increase in the subsidence velocity is observed towards the river. Soil compaction is suspected to be the main reason for the observed subsidence, which will be further investigated using geotechnical data from the study area.

Fig. 4. Displacement velocity for PSs in the study area.

Superimposed on this linear trend, there is a seasonal behaviour presenting a period of one year. Most PSs reach their maximum displacement value in reference to PS_0 in winter, which, according to [2], may be due to aquifer recharge during the rainy season. The authors also consider a possible influence of tides in the obtained results, which will be further investigated.

5. Conclusion

Lisbon Downtown is the most important area of the capital: it is an important business and commercial area, it has several ministries and public services, it is a very important historical place with 250's years old buildings. In the Downtown, PS-InSAR technique identified a subsidence trend, with LOS velocities ranging from -9.7 mm/yr to 5.9 mm/yr, and a seasonal behaviour. Soil compaction, aquifer recharge or tides are suspected to be the main causes for the phenomena. A good agreement was found between PS-InSAR and levelling surveys, where the average difference between the two methods is 1 mm/yr for coherence values higher than 0.87. In the future, the authors intend to analyse geotechnical and tidal data in order to explain the results and test other time-series InSAR algorithms, such as Quasi-PSInSAR [12] and Small Baseline Subsets (SBAS) [13].

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