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Subsidence and fault hazard maps using PSI and permanent GPS networks in central Mexico

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Abstract We present an example of an integrated displacement and horizontal subsidence gradient analysis derived from an ENVISAT-ASAR Persistent Scatterer interferometric analysis. The study area is the southeastern sector of the Mexico City Metropolitan Area that includes Iztapalapa, Ciudad Nezahualcoyotl and Chalco. Correlation of surface faulting gathered from direct field evidence and spatial distribution of subsidence show that the principal factor for constraining hazardous areas is best determined not by solely using the subsidence magnitude rates, but rather by using a horizontal subsidence gradient analysis. This analysis can then be used as the basis for subsidence and fault hazard mapping.

Key words InSAR; subsidence; fault; Chalco, Iztapalapa, Mexico

INTRODUCTION

Mexico City's subsidence has been documented since over a century ago, after the first well battery was drilled to supply water to the rapidly growing city at the end of the 19th century (Cabral-Cano *et al.*, 2008 and references therein). The consequences of the subsidence process are costly but the economic impact of subsidence in urban areas is hard to assess due to the fact that their costs are generally factored into yearly maintenance budgets rather than accounting for them as a unique natural disaster. It has thus become increasingly important to assess the extent and magnitude of damage in rapidly subsiding urban environments. This study describes the generation of hazard maps obtained from a horizontal subsidence gradient analysis using Persistent Scatterers InSAR (Synthetic Aperture Radar Interferometry) and continuously operating GPS data sets in the southeastern sector of the Mexico City Metropolitan Area (MCMA), which includes Iztapalapa, Ciudad Nezahualcoyotl and Chalco.

APPROACH

We present an example of a remote sensing approach using available ENVISAT-ASAR (Advanced SAR) archive data to create integrated displacement and horizontal subsidence gradient maps from Persistent Scatterer InSAR (PSI). This analysis can be used as the basis for a high spatial resolution subsidence and fault hazard zonation.

Satellite geodesy

Twenty-three ENVISAT-ASAR scenes acquired between 16 January 2004 and 14 August 2006 were used to generate interferograms with the Delft Object-oriented Radar Interferometry Software (DORIS; Kampes & Usai, 1999). Precise orbits from the Delft Institute were used to minimize orbital errors (Scharroo & Visser, 1998). The 29 July 2005 acquisition was selected as the master scene to minimize the effects of spatial and temporal baselines. The study area was cropped from each SAR scene acquisition and oversampled by a factor of two in range and azimuth to avoid under-sampling of the interferogram, especially during resampling of the slave acquisition. Further processing included stacking of interferograms relative to a single master image, a selection of strong scatterers visible in all interferograms and unwrapping of their phase changes through time. These strong scatterers were then filtered to detect and remove the atmospheric phase contribution. Data from three permanent GPS sites (Figs 1 and 4) were used as an aid to improve calibration of InSAR determined subsidence. Finally each scatterer point was georeferenced and its line of sight (LOS) displacement rate was generated and normalized for yearly rates (Fig. 2).

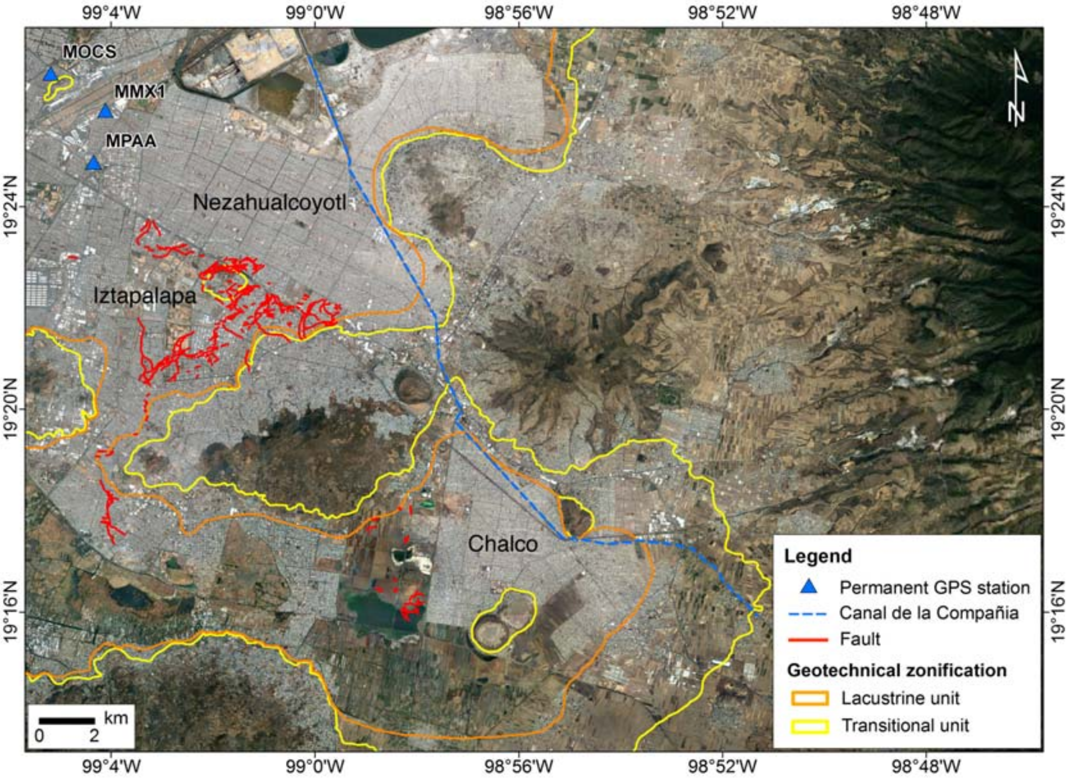

Fig. 1. Satellite image showing the location of study area. Faults in the Iztapalapa and Chalco areas are modified from CMFS (2008) and Ortiz-Zamora (2007) respectively. Geotechnical zonification after GDF (2004).

The resulting PSI data point cloud was interpolated using an Inverse Distance Weighted approach to generate a 100 × 100 m grid resolution in order to obtain a smoother map. The total displacement was then calculated for the whole PSI time interval spanned from SAR acquisitions, assuming that deformation rates are constant over time. Maximum horizontal subsidence gradients (Cabral-Cano *et al*., 2010) were evaluated by computing the difference in subsidence between cells divided by the horizontal distance between adjacent cells (Fig. 3).

Although spatial resolution of ENVISAT-ASAR based InSAR products is very good, its temporal resolution is variable, depending on the frequency of acquisitions. In order to provide better temporal resolution for selected areas and fully validate our results, we also used data from three permanent GPS sites. The coordinate time series for both GPS stations (Fig. 4) were determined using a standard precise point-positioning analysis of the raw code and phase data using GIPSY software from the Jet Propulsion Laboratory (JPL). Daily station coordinates were estimated in a non-fiducial reference frame and then transformed to ITRF2005 using daily seven-parameter Helmert transformations from JPL.

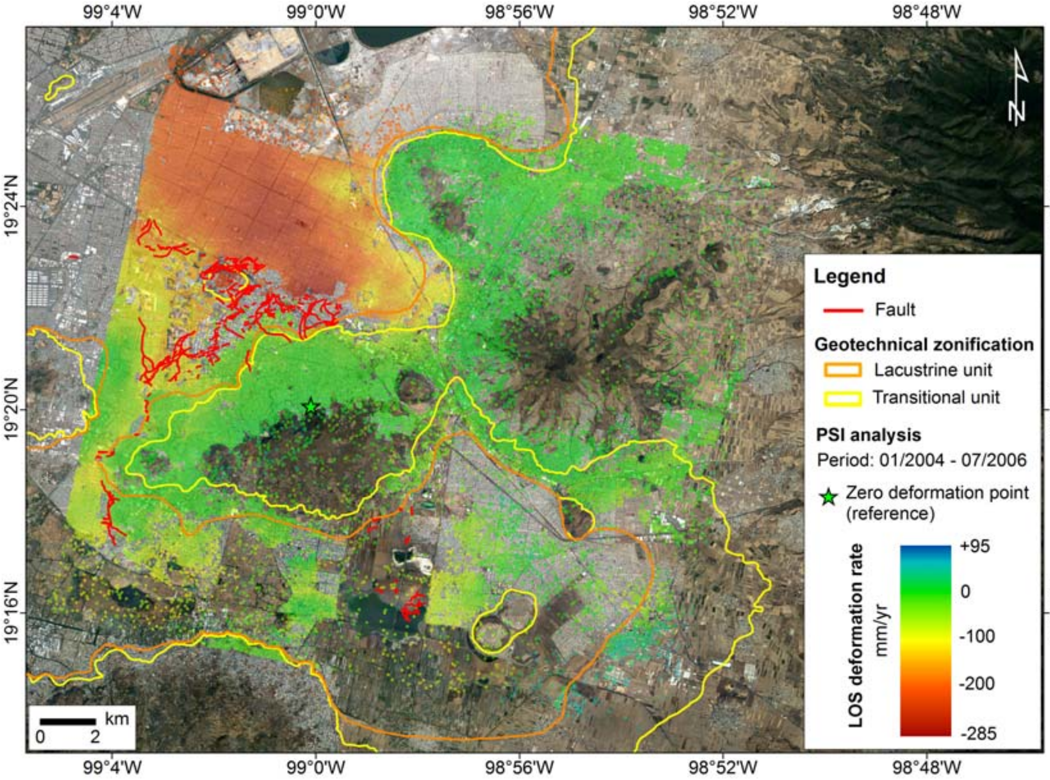

Fig. 2 Persistent Scatterer InSAR (PSI) displacement map of the southeastern sector of the Mexico City Metropolitan area overlapped onto high-resolution satellite imagery. Faults in the Iztapalapa and Chalco areas are modified from CMFS (2008) and Ortiz-Zamora (2007), respectively. Geotechnical zonification after GDF (2004).

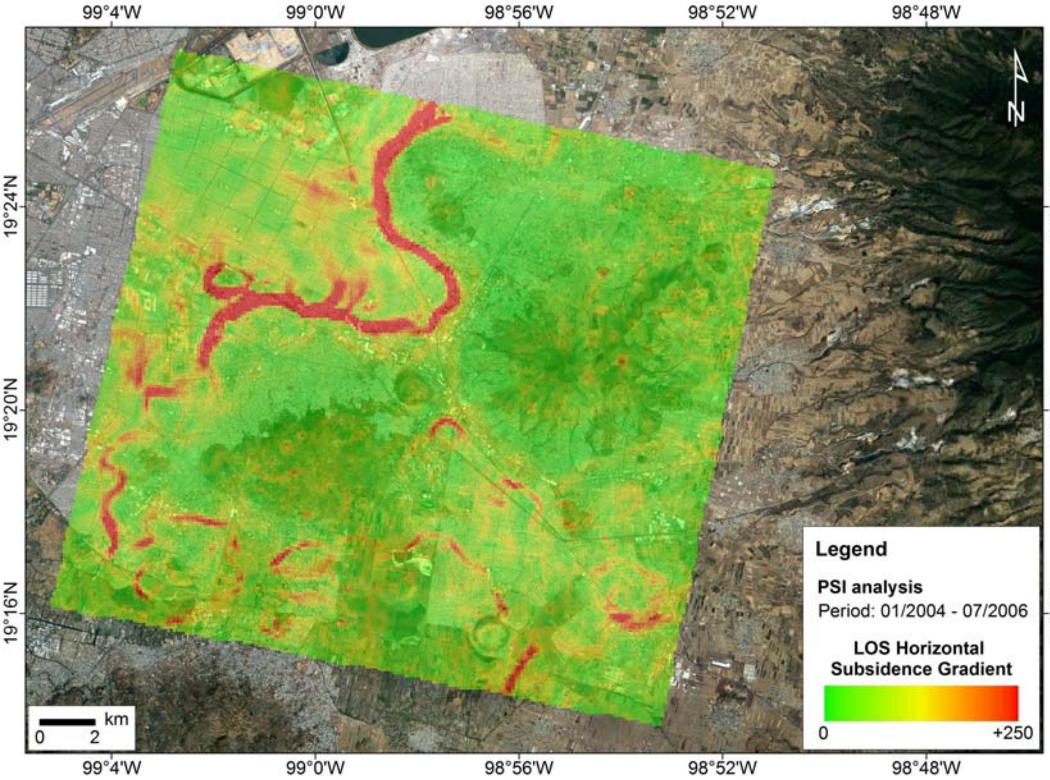

Fig. 3 Line of sight horizontal subsidence gradient map showing the potential for fault development in the study area. Compare to fault location on Figs 1 and 2.

DISCUSSION

The PSI-derived LOS displacement map (Fig. 2) shows that the Ciudad Nezahualcoyotl undergoes LOS deformation rates of more than –280 mm/year, while Chalco and selected areas in Iztapalapa subside at rates of –150 and –100 mm/year, respectively.

Figures 1 and 2 show the location of faults determined after visual reconnaissance and near-surface geophysical exploration in the Iztapalapa area (Ortiz-Zamora, 2007; CMFS, 2008; Ortiz-Zamora & Ortega-Guerrero, 2010). The location of these fault zones is well constrained by the high gradient zones derived from the PSI maps (Fig. 3). This correlation of surface faulting gathered from direct field evidence, urban infrastructure maintenance reports and the spatial distribution of subsidence strongly suggests that the principal factor constraining these hazardous areas is best determined not by solely using the subsidence magnitude rates but rather by using a horizontal subsidence gradient analysis. This product can then be used as the basis for the generation of subsidence-induced surface faulting hazard maps. Selection of high-risk threshold values of the horizontal subsidence gradient can be done empirically from field reconnaissance of fault damage (Cabral-Cano *et al.*, 2010), or alternatively based on the capacity of civil structures to resist shearing from the differential motion of their foundations. Both approaches can be successfully used to correlate the potential for surface faulting in high horizontal subsidence gradient zones. This approach produces high-resolution hazard maps that can be integrated with the decision analysis for land-use regulation, building and zoning codes, and other urban infrastructure maintenance projections.

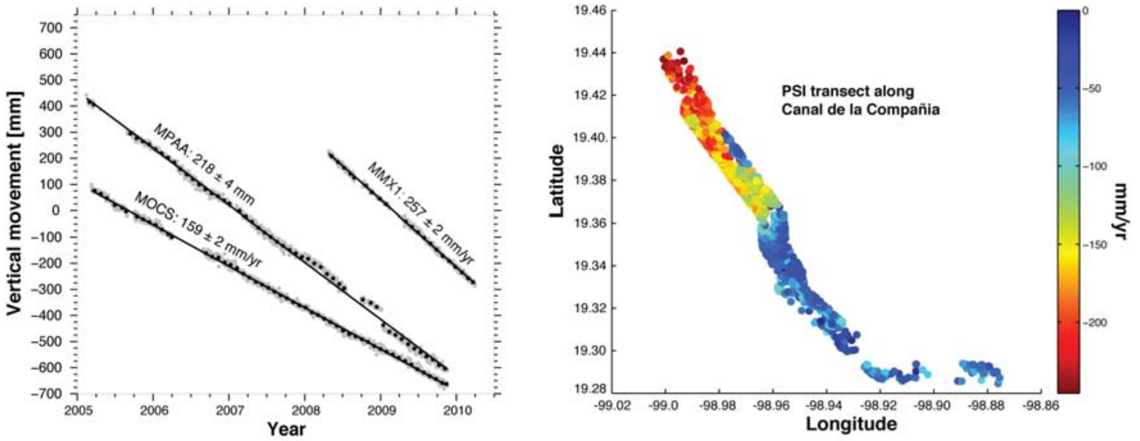

Fig. 4. Left: Vertical time series for MMX1, MRRA and MOCS permanent GPS sites; see Fig. 1 for site location. Grey dots are daily solutions and black dots averaged weekly solutions. Right: Retrieval of PSI points (Fig. 2) along a 250-m wide transect centred on the Canal de la Compañia (see Fig. 1 for location).

The Canal de la Compañia levee failure on January 2010

On January 2010 the Canal de la Compañia (Fig. 1) levee failed, flooding a large portion of the surrounding neighbourhoods near its intersection to Highway Mex-150D Mexico-Puebla. This canal is part of the sewage and drainage system for the MCMA, thus any failure in its integrity poses a serious health hazard for the surrounding communities. Figure 4 shows a 250-m wide transect of the Canal de la Compañia along the PSI map (Fig. 2). This plot illustrates the deformation of its substrate in its northwestern segment and explains the necessity to continuously increase the current height of the levee in order to maintain a proper slope for the canal. However, the height of the levee, several metres above the surrounding housing developments, imposes a high vulnerability to its nearby surrounding areas. This example illustrates the potential of PSI and horizontal gradient analysis for urban infrastructure hazard assessment.

CONCLUSIONS

Displacement and horizontal subsidence gradient analysis derived from Persistent Scatterer Synthetic Aperture Radar Interferometry can be successfully used as the base for subsidence and fault hazard mapping. Our example in the southeastern sector of the Mexico City Metropolitan Area documents an excellent correlation from our mapping products with independently surveyed faults in selected parts of the study area, and validates our approach.

The high density of the PSI point cloud in urban and suburban areas can be further exploited to obtain critical parameters for hazard assessment in a wide range of urban infrastructure elements such as the case of Canal de la Compañia.

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