CONVENTIONAL AND PS DIFFERENTIAL SAR INTERFEROMETRY FOR MONITORING VERTICAL DEFORMATION DUE TO WATER PUMPING: THE HAUSSMANN-ST-LAZARE CASE EXAMPLE (PARIS, FRANCE)

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ABSTRACT /RESUME

The St Lazare area in Paris (France) has undergone important water pumping for the construction of the underground Haussmann - St Lazare station for Eole subway line. This paper presents the monitoring of small surface displacements related to the pumping activity by both classical and PS SAR interferometry. Hydrogeolocial and geodetic data are also examined: piezometric measurements provided on 87 piezometers by SNCF and IGC, precise levelling done on 626 points by SNCF. Analysis and comparisons of all available data show first their good agreement and complementarity to monitor the small surface deformation of the studied area and second the potential operationnality of the classical and PS SAR interferometric approach in such study.

1 INTRODUCTION

Natural and anthropogenic hazards in urban areas will be a major concern in the next few years, and require a complete monitoring of cities in order to prevent possible deformation they may encountered, especially during construction works. Comprehension of these mechanisms is necessary to better prevent such urban risks and at least better protect population and buildings.

This study focuses on the construction of the Haussmann-St Lazare-Condorcet underground railway station (French railway company) for the EOLE line. The important water pumping, done to keep the works in dry conditions, affected slightly the sus-jacent topography, as it is usually observed with such water pumping. However, the magnitude and the extension of such vertical deformation are not easily detectable with classical geological and geotechnical methods such as levelling comparisons which are expensive, time consuming and with local results.

The technique of Synthetic Aperture Radar differential interferometry (DINSAR) [1] can bypass some of those problems. The advantage studying large urban areas such as Paris is that the coherence is preserved through long time scale, allowing to monitor slow motions [2][3][4]. The major disadvantage is due to the varying atmospheric conditions between the two radar images used to form an interferogram, which can introduce artefacts on the interferograms. The relatively new PS technique [5] [6] allows to compensate for the atmosphere, and to obtain a full description of the time evolution of single privileged radar targets (PS). In this study, numerous SAR images are used to established conventional differential interferograms, as well as Permanent Scatterers (PS) time series, in order to analyse the displacement related to the pumping. We also analyse piezometric measurements provided on 87 piezometers by SNCF and IGC, precise levelling done on 626 points by SNCF, as well as a cartography of deformation observed on the buildings. All the available data are then compared

2 CLASSICAL DFFERENTIAL INTERFEROMETRY

We used about 40 radar images acquired by the ERS-1 and ERS-2 satellites between 1993 and 1999, and processed differential interferograms, removing the topographic contribution with a 25m x 25m DEM provided by the Institut Géographique National. Interferometric pairs have been selected according to their perpendicular baseline (which might be small to avoid residual topographic effects and geometric decorrelation): they all have “good” baseline lower than 100 m. They have also been chosen according to the time period they cover, in order to examine the different temporal characteristics of the displacements.

ERS-1 and ERS-2 acquisitions allow a good temporal coverage of the construction work, except during the period of subsidence : no images are available between Jan 94 and March 1995, when the pumping starts, so that it is impossible to detect with precision the beginning of the subsidence phenomenon.

One major limitation of the DINSAR method is the variation of the atmospheric conditions between the two images acquisitions, which can introduce large phase variations in the resulting interferograms and can be misinterpreted as deformation.

Differential interferograms were computed for 4 different time periods. Fig. 1 gives an example of four differential interferograms on Paris corresponding to these periods. The first one (Fig.1a) corresponds to the period before the water pumping starts : no significant signal can be observed on it. On the second one (Fig.1b), one can easily detect a blue spot located near the St-Lazare station. The interferogram corresponding to the period of intense water pumping and underground works (Fig.1c) shows again no phase variation, confirming that no surface deformation occurred during this period of time. The last one (Fig.1d) reveals a red spot at the same place we already observed the blue spot.

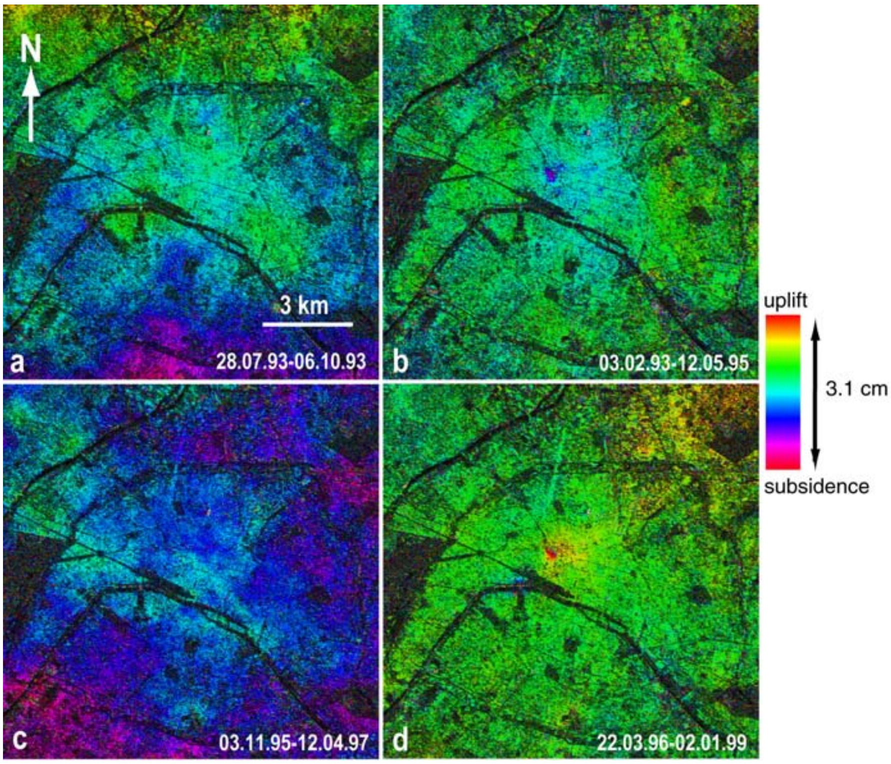

Fig. 1. (a) Differential interferogram in 1993 showing no vertical deformations before the construction work (28.07.93-06.10.93)- (b) Differential interferogram covering the period 1993-1995 showing the cumulate vertical deformation at the beginning of the construction work) - (c) Differential interferogram showing no vertical deformation during the water pumping and the construction work (03.11.95-12.04.97)- (d) Differential interferogram showing a vertical uplift due to the end of the construction work, and the slow recharge of the water tables (the water pumping stopped by mid 1997)(processing done by UMLV)

Maps of cumulate subsidence and uplift have been generated. For this, we unwrapped and stacked independent interferograms, for which atmospheric artefacts are already of low amplitude, in order to reduce again the noise [7].The spatial extension of the phenomena can be determined: the subsidence is about 800 m large and 1200 m long, whereas the uplift concerns an area of 1800 m x 2500 m. The general shape of the deformation zone is a WSW-ENE oriented ellipse, flattened on its eastern part. The area of maximum deformation (south of the station) is formed by 2 bowls, especially visible for the uplift period : one is elongated, oriented NNW-SSE. The other one, much smaller is situated eastward. The amplitude of these two displacements can also be obtained (assuming that all displacements are vertical, one fringe (complete cycle of phase) in a differential interferogram represents 28 mm of displacement along the radar line of sight, or 3.1 cm of vertical displacement). The maximum amplitude reached during the subsidence is 1.7 cm, whereas it is of the order of 1.6 cm for the uplift (Fig. 2).

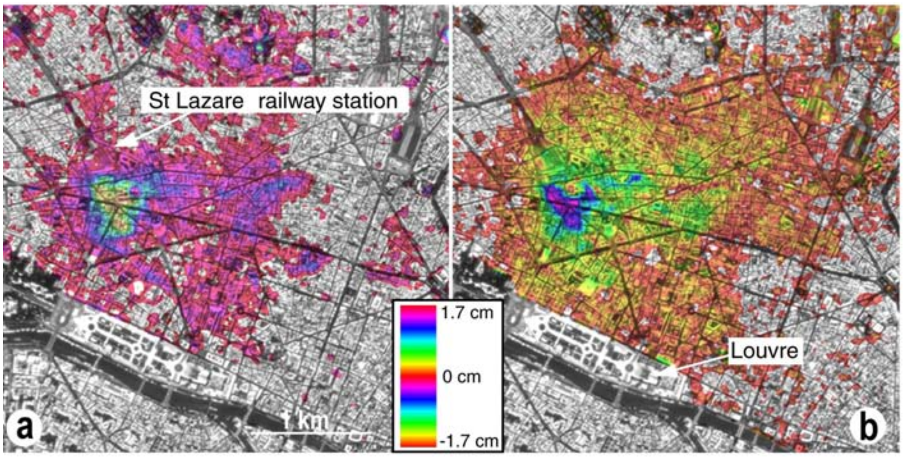

Fig. 2.(a) Map of cumulate subsidence due to the beginning of water pumping: Intensity Hue Saturation composition using an aerial photograph of IGN (©IGN Paris 2001. Poster Paris ISSN BD Ortho®) - (b) Map of cumulate uplift due to the end of water pumping and the slow recharge of the nappe (same HIS composition)(processing done by UMLV)

As mentioned before, no precise analysis of the subsidence can be done, due to the lack of data in 1994.

Concerning the uplift period, we can try to examine the temporal evolution of the uplift during the recharge of the water. Three phases can be observed for this uplift, with different areas successively reached. It appears that the uplift began between Nov 97 and Jan 98. Spatial extension of the deformation is quite small, localized above the pumping area. This signal seems to be stable until July 98, then propagates toward SW: we observe a rapid uplift, between July and Aug 98, of an area centered approximately at the intersection of rue Tronchet and rue Mathurins, and having the shape of a NNW-SSE ellipse. Surface of deformation grows again slightly until oct. 98 : the extend of the displacement seems to reach the final one.

3 PS TECHNIQUE

The major limitation of the classical interferometry technique in cities appears to be the atmospheric artefacts, which superimpose on displacement phase contribution : it is then difficult to discriminate displacement and atmospheric signature. This drawback can be overcome with the PS technique, since the atmospheric artefacts are compensated for. The technique allows for a full description of the time evolution of single privileged radar targets (PS). The PS density can reach values of several hundreds points/km2 in urban areas, even though, in this study, only a limited set of 76 PS time series has been exploited. The PS approach requires a sufficient number of SAR images (e.g. > 20) and in areas affected by time non-uniform deformation (like the selected test site) is rather computationally intensive.

The 76 PS time series we used here have been processed by TRE with 80 ERS images, in the framework of the RESUM project. Fig. 3 gives the time evolution of some of those PS. They present similar periods of variation : subsidence between 1993 and 1995, stability between april 95 and march 98, uplift between march and oct 98, and then again relative stability.

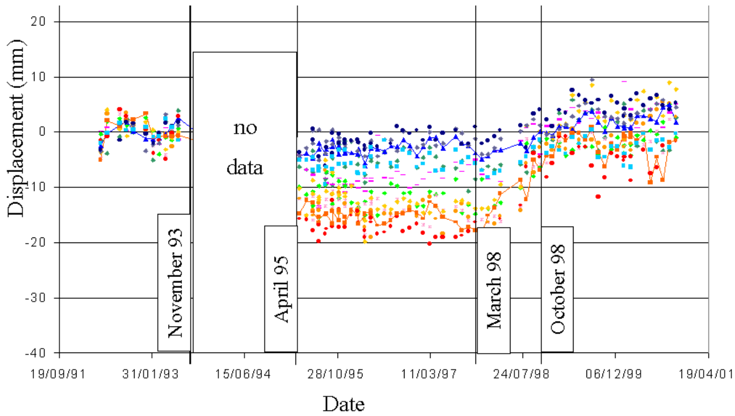

Fig. 3. Time series of different PS

A different time evolution can be observed from PS to PS, but the uplift takes place everywhere after march 1998. It appears also that for most of the PS, the major deformation takes place in the period july-aug. 98.

The amplitude of the variations depends on the location of the PS and corresponds to the one observed with classical interferometry : they are distributed in a concentric manner, with high values near the station (south of station), and low values going away (Fig. 4).

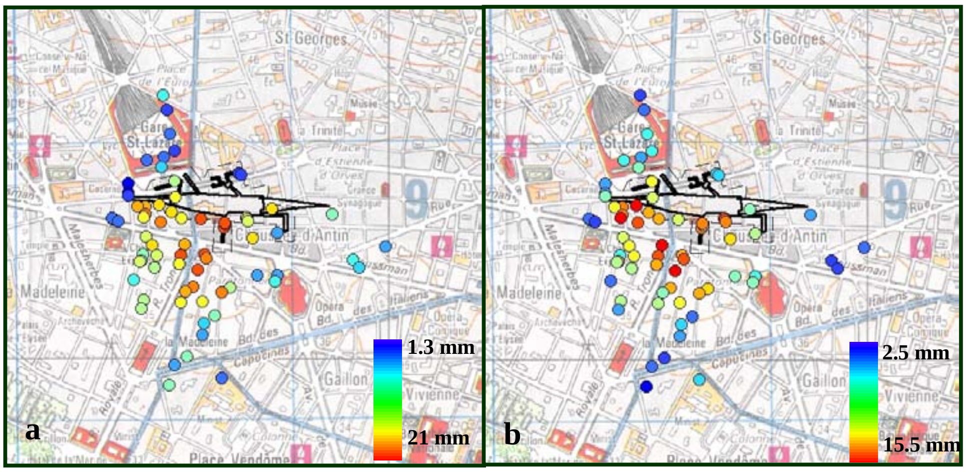

Fig. 4. Localisation of the PS with the amplitude of displacement for the subsidence (a) and the uplift (b)

4 COMPARISON WITH PIEZOMETRY AND LEVELLING

The precise monitoring of 87 piezometers (done by SNCF and IGC) between november 1990 and june 2000 reveals major fluctuations of the top of the different water levels (alluvial, Lutetian, and Ypresian nappes) during the underground works. The water pumping had been done in the Cuisian (Ypresian) nappe. Only the data of four piezometers are available in that aquifer. The piezometric monitoring is mainly done here using the high number of lutetian piezometers and the drainance effect that exists between both Ypresian and Lutetian aquifers.

The water level evolution through time indicates no vertical changes in the alluvial aquifer due to water pumping, which means no action of this aquifer on the topography. In contrast, the Lutetian and Ypresian aquifers show major modifications (more than 20 m of subsidence) in may 1994 and a rise or surrection of similar amplitude between march and july 1998 when the water pumping stops.

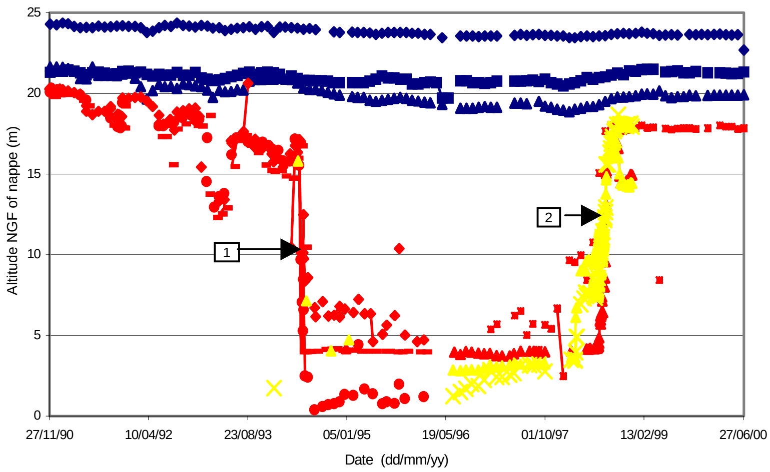

Fig. 5. Piezometric monitoring of the different aquifers from November 1990 to June 2000). In blue: alluvium, in red: Lutetian; in yellow: Ypresian. 1: may-june 1994, 2: june-aug. 1998.

Five major periods are distinguished from the piezometric point of view :

- May 1992 – may 1994 : three small decreases of the lutetian piezometric surface that correspond to the water pumping tests
- May 1994- june 1994 : major subsidence of the piezometric surface of Lutetian and Ypresian aquifers
- June 1994 – march 1998 : stability during the construction work and water pumpings
- March 1998- September 1998 : major rise of the lutetian and ypresian piezometric surface back to the pre may 1994 level
- September 1998- june 2000 : stability post underground work

These variations are clearly form anthropogenic origin as the observed small offsets of the lutetian piezometric surface in july 1991, june 1992 and april 1993 correspond to the three water pumping tests, and the period of major changes correspond to the beginning and the end of the water pumpings.

We also analysed 626 points of levelling comparison done by the SNCF. They clearly show the same period of variation. Concerning the amplitude, it appears that the reference point is localised in the influence area estimated by the SNCF : this influence area is clearly underestimated.

Analysis and comparisons of all available data show their good agreement and complementarity. Piezometric data, evidencing the fluctuations of the different water tables during the construction works, give quite similar periods of variation with interferometric data and levelling data.

The spatial extension obtained with the piezometric data and interferometry show their good agreement: the superimposition of the maps of deformation obtained with DINSAR and the piezometric surface variations show the excellent fit that exists between both.

Furthermore, the comparison between the levelling, piezometric data and PS time series allows to confirm which water nappe is responsible of surface deformation. It appears (Fig. 6) that a rise of the Lutetian nappe does not lead to a surface uplift (no influence of the levelling and PS), whereas a rise of Ypresian nappe leads to surface deformation, as observed by levelling and PS variations.

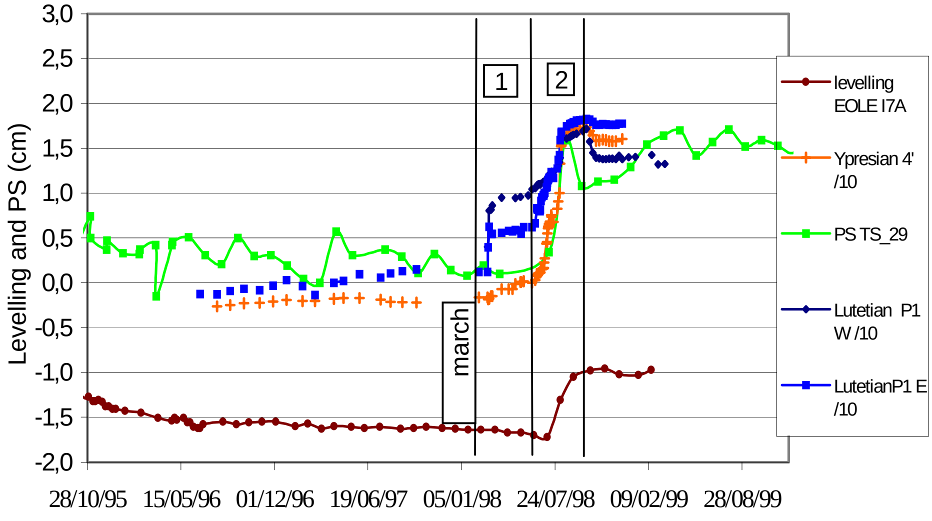

Fig. 6. Comparison between levelling, piezometry and PS.-1:Rise of Lutetian nappe- 2:Rise of Ypresian nappe

5 CONCLUSION

With the analysis of a series of radar images, used to established classical differential interferograms as well as PS time series, we were able to monitor slow ground deformations in both ways: subsidence and uplift in the city of Paris. We were able to separate the different phases of the underground construction works for the Haussmann-St-Lazare station of the Eole line, specifically before, during and after the water pumping.

We used independent piezometric measurements done by the SNCF and IGC which confirm the fluctuation of the multilayer aquifer due to water pumping during the construction period. It appears that the area affected by the deformation has been underestimated.

Comparison between the levelling, piezometric data and PS time series confirm which water nappe is responsible of surface deformation. It is then possible to propose some reasons of the mechanisms of the discharge/recharge of the multilayer aquifer of the Paris Bassin in the studied area, which may allow in the future to define new specifications for water pumping in order to reduce surface deformation. Combining conventional and PS SAR interferometry technique appears to be an efficient and operational tool for low-cost, large-coverage (compared with levelling) surface deformation monitoring.

6 ACKNOWLEDGEMENTS

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