REFLEXIONS AND INSIGHTS FROM URBAN 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 the small surface displacements related to this pumping activity, by conventional and PS SAR interferometry. Piezometric measurements provided on 87 piezometers by SNCF and IGC, and precise levelling data aquired on 626 points by SNCF are also examined. Their comparison with interferometric results show their good agreement and complementarity, as well as the potential operationnality of SAR interferometric approach in such urban environment.

1. INTRODUCTION

A major problem in cities is to locate, characterize, quantify and modelize the small amount of deformations linked for instance to urban works. The latter are difficult to monitor with classical field works methods (levelling …) which are expensive, time consuming and with local results. We herein develop the use of interferometry DINSAR, which allows to map small displacements [1], especially in cities such as Paris [2][3][4].

We focus our study on the St Lazare-Condorcet (Paris city) area, where important construction works have been done for the construction of the Haussmann-St Lazare-Condorcet underground railway station (French railway company) for the EOLE line. In order to settle this underground railway station, the French railway company undertook major water pumping (around 750m^3/hour) in the Ypresian water nappe during several years (1994-98). The aim was mainly to decrease the water pressure of the two aquifers in order to make the underground work easier. Of course due to the decreasing of the hydrostatic pressure, small vertical offsets appear at the topographic surface which might affect the overlying buildings. This paper presents the monitoring of those surface deformation related to the pumping activity by classical and PS SAR interferometry. Piezometric measurements and precise levelling are also examined.

2. PIEZOMETRIC SURVEY

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 (Fig. 1). 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.

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

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- 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

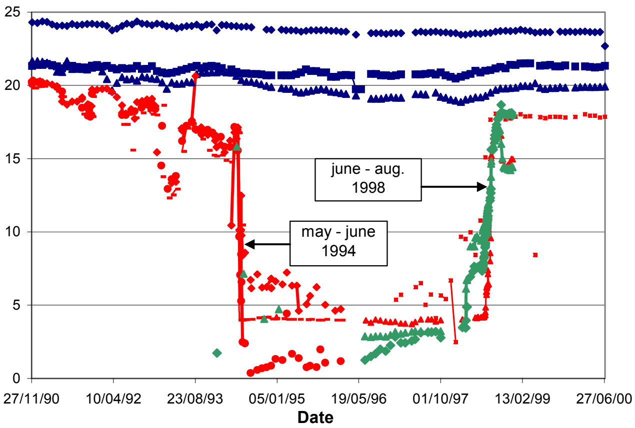

Fig.1. Monitoring of the different aquifers from November 1990 to June 2000). In blue: Alluvium, in red: Lutetian; in green: Ypresian.

These variations are clearly from 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.

3. LEVELLING COMPARISON

Monitoring on 626 points (Fig. 2) has been done for the SNCF straight above the working site and in an enlarged perimeter of 50 m (estimated area of influence).

3 periods, globally homogeneous can be observed on the graph of evolution of the points (Fig. 3).

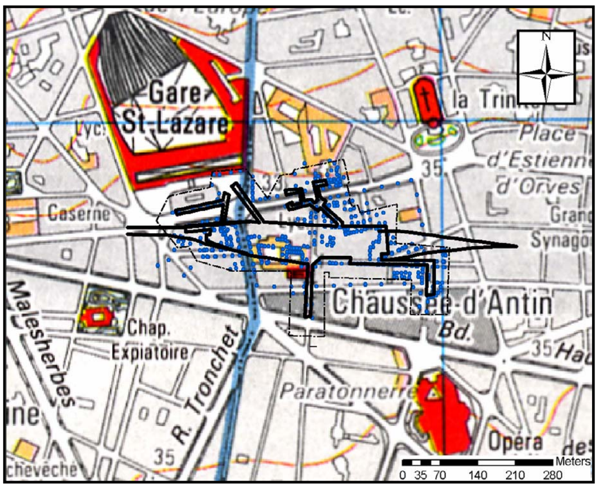

Fig. 2. Localization of the different points of leveling

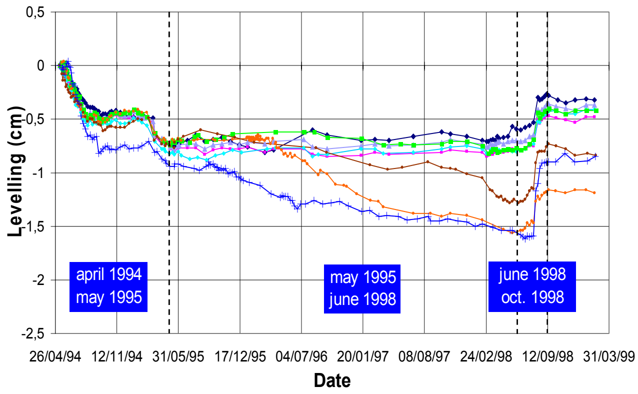

Fig. 3. Time evolution of different levelling points

4. RESULTS OBTAINED BY SAR INTERFEROMETRY

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.

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 [5] [6].

- We processed a series of differential interferograms using 40 ERS-1 and ERS-2 images acquired between 1993 and 1999 .

The topographic contribution in the different interferograms was removed using a 25m x 25m DEM provided by the Institut Géographique National.

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.

Three phases are revealed:

- a subsidence of 1.7 cm from late 1993 to mid 1995,

- then a stable phase during the intense water pumping (no changes from 1995 to late 1997),
- finally a topographic surrection (1.6 cm) due to the end of the water pumping, from march 1997, with a rapid uplift, between July and Aug 98.

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. 4).

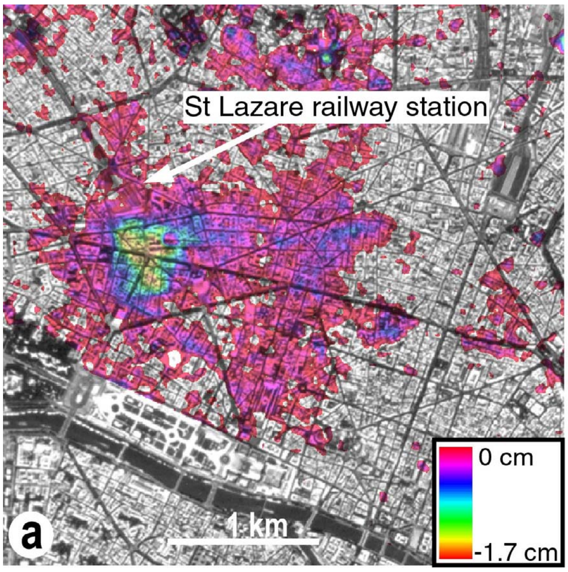

Fig. 4. (a) Map of cumulate subsidence due to the beginning of water pumping: Intensity Hue Saturation composition using an aerial photograph of IGN (©IGN Paris 2001. Poster Paris ISSN BD Ortho®)

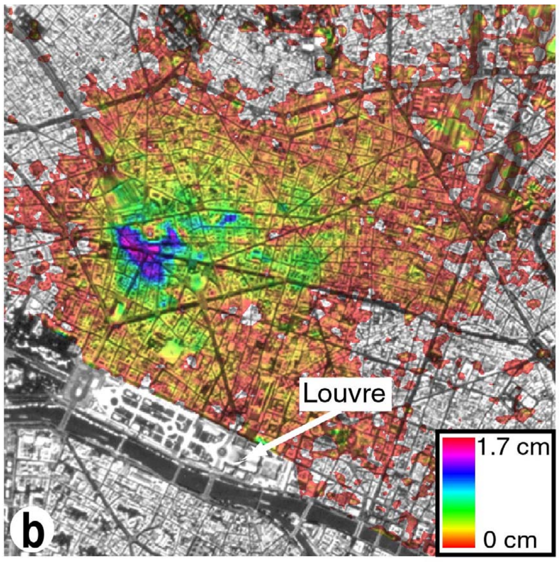

Fig. 4. (b) Map of cumulate uplift due to the end of water pumping and the slow recharge of the nappe (same HIS composition)(processing done by UMLV)

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, localised 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.

It is important to notice here the importance to avoid filtering or smoothing the different interferograms as the anomaly seen on the subsiding depression is located above the open pit of the underground works.

▪ The PS time series we used here have been processed by Altamira Information using 74 images, but only from april 95. They present similar periods of variation: stability between april 95 and march 98, uplift between march and oct 98, and then again relative stability.

5. COMPARISON BETWEEN PIEZOMETRY AND INTERFEROMETRY

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 (Fig. 5).

Fig. 5. Superimposition of interferometric and piezometric data for the subsidence

6. COMPARISON BETWEEN LEVELLING, PIEZOMETRY AND PS

The comparison between the levelling, piezometric and PS data allows to confirm which water nappe is responsible of surface deformation (Fig. 6). It appears 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.

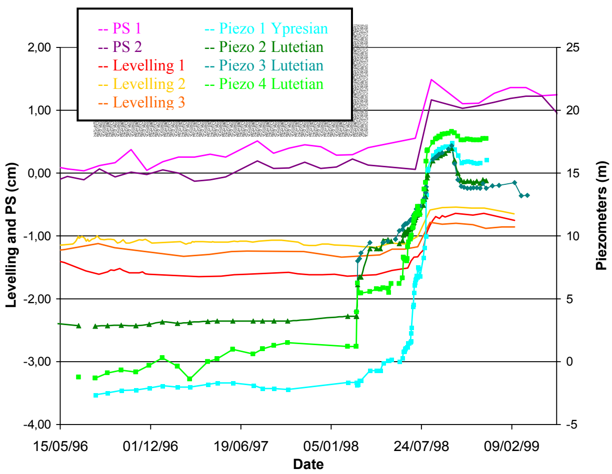

Fig. 6. Comparison between levelling, piezometry and PS .

7. 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. Effectively, the (re)loading of the artesian Ypresian nappe corresponds to the surrection of the topography. 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, even if more validation and research/development are still needed.

8. AKNOWLEDGEMENTS

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