SAR interferometry reveals ground water induced surface deformation around Tehran

N. Gourmelon, M. Peyret, J.F. Ritz, J. Chery
Laboratoire de Geophysique, Tectonique et Sedimentologie
Universite de Montpellier II, France

ABSTRACT

Tehran (Iran) area experiments strong natural and anthropic-induced ground water dynamics. This causes a major problem for irrigation of cultivated land and for water supply of the 15 millions of inhabitants of the city. This ground water motion may lead to surface deformation. Therefore, the monitoring of this surface deformation provides helpful information to better understand aquifer system processes. InSAR (Interferometric Synthetic Aperture Radar) provides dense and precise deformation measurements which are essential for mapping complex heterogeneous deformation fields. We used acquisitions of ERS that span 9 months between September 1998 and June 1999. They reveal wide areas of surface uplift (by as much as 9 cm). This vertical deformation has probably no tectonic meaning but is rather the ground response to ground water recharge. These zones are all located downstream of large alluvial fans like the one of Karaj. The variation of effective stress caused by interstitial water draining could explain such phenomenon. The seasonal survey of this deformation may be relevant for ground water monitoring and urban development management. It can also be noticed that some faults act as barriers for these deformation zones and related fluid motion. In the future, new set of images will allow to map tectonic deformation on a longer period of time and to monitor in a more continuous way the deformation due to groundwater evolution. This would allow to quantify the tectonic and hydrogeological part of this signal.

1. INTRODUCTION

Tehran (Iran) region is a sensitive area regarding to hydrogeological processes. The city is built on multiple aquifer systems made of unconsolidated detritic materials. The outlets of some big alluvial systems of the Alborz mountain range are situated close to the city. These alluvial systems are the main supplies of ground water table and experiment a strong seasonal flow rate contrast. The increasing rate of anthropic exploitation needed by the consumption of the 15 millions of inhabitants from Tehran and by the irrigation of cultivated lands, lead to a depletion of ground water level. The Tehran area experiments seasonal wide surface of collapse events that suggest a surface expression of ground water processes. This means that surface monitoring around Tehran is able to provide information on aquifer processes [1,2,5,6]. We used Differential SAR Interferometry (DInSAR) [8] to measure the temporal height variation of ground surface around Tehran. DInSAR measures the line of sight component of the displacement with a precision of a few millimeters. The high density of measurement (one point every 20 meters) reveals the shape of the displacement field. This gives information on the probable cause of the movement and reveals some details of the process. We describe and discuss the results of DInSAR measurement from 1998 to 1999, during ground water recovery period, covering Tehran, surrounding cultivated area and a part of the Alborz mountain range.

2. GEOLOGICAL SETTINGS

Tehran is built on a Plio-Quaternary foreland basin. These formations are distributed in front of the east-west Alborz mountain over about 50 km from north to south with a maximum thickness of 1 km. A gravimetric study near Tehran indicates an alluvial formation thickness of about 600 meters. The alluvial basin is composed by the lateral succession of alluvial fans which have been formed since quaternary time. There is a strong spatial complexity of the deposit due to alluvial sedimentation process and surimposed tectonic. The lithology is composed for the main part by gravels and sand in which are interbedded conglomerate and silt lens. Moreover, tectonic has mainly affected the older formation which causes faulting and large wavelength east-west folding with vertical dip locally [4]. The complex structure of alluvial deposit leads to multiple aquifer system which consists of unconfined, semi-confined and confined aquifers in lateral and vertical succession. The precise location as well as the thickness of each of these aquifers are not known. The main ground water recharge of Tehran alluvial basin is done during the snowmelt in the springtime. This type of recharge causes strong amplitude variation: for example the flow rate of the most important river, the Karaj river, is triple between the dry period in autumn and the wet period in spring. The surface runoff is generally small and the most part of the water that comes from Alborz supplies the ground water runoff downstream of the piedmont slope. The main free-water table groundwater level is a few tens of meters below the surface, deeper in the piedmont slope than in center part of the alluvial deposits. The 40 meters isopieze of the main free water table is roughly known (Fig 1). Although the average watertable fluctuation is not precisely known, [4] reports amplitude from 3 to 8 meters in external part of the main alluvial fans. In addition to this natural dynamic, anthropic exploitation plays an important role in ground water table fluctuation. An average long term fall of 5 meters in 8 years of the ground water table as well as drying out of swampy terrain are reported in high alluvial exploitation zone.
3. INSAR DATA

We analysed 10 interferometric pairs constructed from 5 archived ERS data (12 Sept 98, 13 Sept 98, 11 Apr 99, 16 May 99 and 20 Jun 99) acquired in 1998 and 1999 in descending orbits. Their temporal separations vary from 1 day to 9 months while their altitudes of ambiguity range between 15m and 80m. The last images acquired by ERS-2 could not be combined with the former acquisitions, due to the lack of attitude control of the satellite since February 2001.

We used a set of stereo Spot couples for constructing a 20m-resolution digital elevation model. This DEM was used for removing most of the topographic contribution to the phase signal. The elevation errors are believed to be smaller than 30 meters. The topographic phase signature on the central iranian plateau is removed while some residuals remain on the Alborz slopes. The DEM improved the coherency upon the northward and southward slopes of the Alborz range but we observed heavy time decorrelation in the nine months interferogram. As a result, the use of this DEM leads to Differential SAR Interferograms that are likely to reveal ground surface deformation over Tehran and on the northern reliefs bordering the main faults (North Tehran fault, Mosha fault).

4. INSAR OBSERVATIONS

We detect two main fringes systems both located in alluvial formations, downstream of the two major alluvial fans in the Tehran neighbourhood: the ones of Karaj and Djadjroud. The persistance of these patterns on all the interferograms rules atmospheric effects out as a cause of these fringes systems.

The most important amplitude and the most detailed movements are observed near the Karaj fan (Fig 1). The east-west elongated eggshaped area (Fig 2) is by 20 km from north to south and by 35 km from east to west. Almost all of the area consists of cultivated land which explain local little signal coherency. Only its most eastern part is on the west Tehran suburbs.

Fig 1: Tectonic and Hydrogeology around Tehran
Fig 2: Fringe system of Karaj. ERS differential interferogram spanning one month [May 99-June 99]

Assuming that the ground displacement is purely vertical, we found an uplift that reaches a maximum of 9 cm in 9 months between September 1998 and June 1999 (Fig 3). The vertical north-south gradient is higher in the northern part of the uplifted zone (3 fringes in about 2 km), than in the south (3 fringes in about 8 km). In order to access the temporal variation of the upward ground displacement, we zoom in time, computing interferograms spanning 1 or 2 months with images acquired in April, May and June 1999. The global shape remains the same, while the better coherence of the signal shows the spatial continuity of the deformation area. In the two 1 month interferograms, the maximum amplitude of the uplift is about 3 cm (Fig 2).

Fig 3: a) West part of Karaj fringe system between September 1998 and June 1999
White dashed lines: iso-displacement curves with values in centimeters; Black dashed lines: piezometric surface (40 m deep); Yellow line: external limit of Karaj fan; Black arrow: direction of ground water flow; White lines: location of profiles.
b) Vertical displacement (cm); dots are values with coherence > 0.7
Fig 4: a) East part of Karaj fringe system. Measurement between September 1998 and June 1999
Kj : Karaj river (white sinuous line); Black lines : faults (NRF : North Rey Fault;
SRF : South Rey Fault; KzF : Kharizak Fault); Others : see Fig 3.
b) See Fig 3. Green lines : position of faults and river.

The figure shows faults and river control of the deformation.

The interferogram that spans nine months reveals two zones with particular features in the eastern part of the fringe system of Karaj (Fig 4):
Along the Karaj River, the profiles show a drop of displacement by about 1 and 2.5 cm respectively in the May-June 1999 and September 1998-June 1999 interferograms. The fringes of deformation are lined up along the north-south river bed, in contrast with the general orientation which is roughly east-west.

There is a drop of displacement in the south-east part of the system. Surrounding this zone, Quaternary faults of North Rey, South Rey and Kharizak may play a main role in this deformation. Fringes are lined up along the South Rey and North Rey faults, while, in the south, the ground deformation stops suddenly at Kharizak fault.

5. INTERPRETATION

Knowing the present rate of tectonic deformation near Tehran [7], which is of a few millimeters per year, it is unlikely that deformation observed has a tectonic origin. We also exclude a consequence of change in dielectric property of ground surface. On the other hand, there is a wide continuous extension of the Karaj deformation zone spatially correlated with the main free ground water and also a strong spatial correlation between the gradient of ground water flow and the one of deformation. There is a close connexion of the north part of the deformation zone with the external part of Karaj fan. Moreover, the gradient of deformation is generally stronger near the source of ground water supply. The upward movement of the ground is temporally related with seasonal increasing river flow rate. Therefore, we propose that the uplift is caused by the natural ground water recharge. The flow coming from Alborz during high flow rate supplies the ground water run-off, as a consequence the aquifer volume tends to increase especially by an increase of its height. Quaternary faults of North Rey, South Rey and Kharizak act as barriers for ground water flow: deformation is less important south of North Rey and South Rey faults and no longer occurs south of Kharizak fault. Karaj river, as a ground water draining zone, smooths the ground water variation and so makes weaker the ground water dynamics induced uplift. The data show an apparent maximum uplift rate for the period of April-May and May-June relatively to September 1998 - April 1999, either because uplift rate is really lower during the September-April period or because subsidence also occurred during this period. Continuous monitoring of the phenomenon is needed to conclude. Unfortunately, due to the lack of attitude control of satellite ERS2 since February 2001, the last images acquired could not be combined with the former acquisitions.
In order to explain how ground water motion can induce surface deformation, we study the hypothesis that thickness variation of sub-surface reservoir is related to variation of effective stress [3,10]. The effective stress $\sigma_\text{e}$, equal to the lithostatic stress $\sigma_\text{lith}$ minus the hydrostatic stress $\sigma_\text{hydro}$, is the stress acting on the soil skeleton in a water saturated porous media. In the case of an increase of water table, the hydraulic head inside the aquifer increases, and so does the pore pressure. Because pore pressure increase has a negative effect on the mean effective stress, that is to say of the lower stress on the soil skeleton, the latter expands by elastic relaxation. A stress-strain relation for unconsolidated sedimentary material is established in soil mechanics by the oedometric test. The oedometric test consists in laboratory measurement of thickness variation of a drained soil sample induced by change in effective stress for maximum pressure equivalent to few hundred meters in depth. Over a maximum stress called consolidated stress, the thickness sample response to effective stress change is reversible. Results of the test are represented by a void ratio $e$ versus $\log\sigma$ linear curve. For each kind of material, there is a constant called swelling indice $Cs$ such as:

$$\Delta e = -Cs \cdot \Delta \log \sigma$$

(1)

where

$$\Delta e = \Delta V_{\text{vol}} / V_{\text{rock}}$$

(2)

What is measured during oedometric test is in fact $\Delta H/H$ where $H$ is the thickness of the sample. It is assumed that variation of thickness $\Delta H$ is only due to change of void ratio. So $\Delta e$ is obtained by the relation:

$$\Delta e = \Delta H \cdot (1+e) / H$$

(3)

Using Eqs 1-3, we calculated a swelling indice $Cs$. We assumed $h_{a1}$ to be 40 meters from the position of isopieze. In order to minimize the possible horizontal component caused by horizontal gradient of vertical displacement, we used the InSAR measurement of $\Delta H=9$ centimeters from the central part of deformed zone where horizontal gradient of vertical deformation roughly equals to zero. A mean void ratio of 0.7 is assumed. Given the uncertainty of aquifer thickness and water table variation, the aquifer thickness is treated as a variable and we made the computation with several water table fluctuations $h_{a1}-h_{a2}$: 3, 5 and 10 meters.

Fig. 6 shows the resulting diagram. For an expected range of alluvial formation near Tehran (lower than 600 meters), the values of the swelling indice are consistent with a mixed aquifer of sand ($Cs=0.01\rightarrow0.03$) and clay ($Cs=0.03\rightarrow0.6$) [9]. From this result, the variation of effective stress, so the variation of ground water table, may explain the observed deformation.
6. CONCLUSION

InSAR measurements near Tehran between September 1998 and June 1999 have revealed two areas of tens kilometers wide of surface displacement field, located west and south of Tehran, downstream of large alluvial fans, in the foreland alluvial basin of South-Alborz. There are close relationships between deformed areas and hydrogeological data during period of ground water recharge. Moreover, a comparison between oedometer test results shows that the drop of effective pressure caused by the increase of ground water table classically observed in the region of interest is able to explain this vertical deformation. This leads us to propose that surface motion measured is an uplift caused by an increase of aquifer volume during ground water recharge. Precise hydrogeological studies as well as continuous geodetic measurements of the area are needed to better constrain the phenomenon. This, together with GPS, gravimetric and seismologic measurements, will allow us to discriminate between tectonic and non-tectonic surface field displacement, and will lead to a better evaluation of both underground dynamic and seismic hazard on the Tehran area.

7. REFERENCES