Characterization of regional land subsidence induced by groundwater withdrawals in Tehran, Iran

Masoud Mahmoudpour[1], Mashalah Khamehchiyan[1]*, Mohammad Reza Nikudel[1], Mohammad Reza Ghassemi[2]
[1] *Engineering Geology Division, Department of Geology, Faculty of Basic Science, Tarbiat Modares University*
[2] *Research Institute for Earth Sciences, Geological Survey of Iran (GSI)*
**Corresponding author, e-mail: Khamechm@modares.ac.ir*
(*received: 19/06/2013 ; accepted: 26/11/2013*)

Abstract
Generally, alluvial basins of arid and semiarid zones are the places with excessive groundwater withdrawal, and also they have a high potential for land subsidence. Excessive groundwater withdrawals have caused severe land subsidence in Tehran, Iran. At present, the maximum land subsidence rate is 36 cm/year, covering an area of nearly 530 km^2. In the 2000s, as a result of economic and population growth, the area of groundwater withdrawals expanded to both the west and the east. Over the past 28 years, groundwater level has decreased 11.65 m. As a result, the impacts of land subsidence, such as major drop in groundwater level, damage and tilting of buildings and civil structures, and rupture of well casings, have increased in the southwest of Tehran. In accordance with the field and laboratory data, we have constructed a new conceptual model for alluvial basin recognition of the study area. This model describes various hydro-geological units according to their physical properties. Based on this model, a multi-layered aquifer system in southwest plain of Tehran includes three aquifer units and three aquitard units.

Keywords: *Groundwater withdrawals, InSAR, land subsidence, Multi-layered aquifer system.*

Introduction

The term of land subsidence includes both gentle down warping and the sudden sinking of discrete segments of the ground surface. Displacement is principally downward, and the associated horizontal deformation often has significant damaging effects. The extraction of groundwater plays a direct role in land subsidence by causing the compaction of susceptible aquifer system. Subsidence accompanying the extraction of fluids such as water, crude oil, and natural gas from subsurface formations is considered the main cause of land subsidence, anthropogenic and natural. Subsidence phenomena cause disturbances in lifelines (roads, railway, pipelines) and sustainable water management (Galloway & Burbey, 2011).

Land subsidence is considered a worldwide problem, due to a long-term excessive groundwater withdrawal. This phenomenon is often observed in semiarid and arid environments. There are more than 150 major cities in the world where subsidence is substantial. The wide distribution of land subsidence and its severe consequence for the environment and economy, and technology transfer at the international level (Hu *et al.,* 2004). As a widespread geohazard, land subsidence caused by excessive pumping of groundwater has been widely reported in many areas, such as Mexico city (Carreon-Freyre *et al.,* 2011; Calderhead *et al.,* 2011); Shanghai (Hu *et al.,* 2004); Tianjin (Yi Lixin *et al.,* 2011); Antelope Valley, California (Galloway *et al.,* 1998), Bangkok (Phien-wej *et al.,* 2006), Rafsanjan (Mousavi *et al.,* 2001), Mahyar, Nayshabour and Kashmar (Lashkaripour *et al.,* 2010, 2007, 2006), Mashhad (Motagh *et al.,* 2007).

The principle of effective stress, first proposed by Karl Terzaghi in 1925, is often used to explain the occurrence of land subsidence caused by groundwater withdrawal (Galloway *et al.,* 1999). Excessive groundwater withdrawal from aquifer systems causes the pore water pressure to decrease and the normal effective stress to increase. The increasing normal effective stress results in the compaction of hydrostratigraphic units, including aquitard and aquifer units, which in turn results in land subsidence. It is often thought that aquitard units, primarily consisting of clays and silty clays, have higher compressibility and greater compaction than aquifer units consisting primarily of sand (Calderhead *et al*., 2011). In aquitards, when the applied stresses due to extraction are stronger than the preconsolidation stress (the stress prior two water pumping), soil particles rearrange to carry the additional load and may undergo weak chemical bonding, leading to irreversible compaction (Sneed *et al*., 2003).

The role of the engineering geologist is clearly defined in land subsidence studies; it is to supply and correct ground model. The ground has to be divided into layers and zones that can be ascribed typical values for their mechanical and hydraulic properties. This means the vertical profile has to be known, especially the presence and thickness of potential confining layers, which requires the sensible location of boreholes based on the existing knowledge of local geology, good drilling, and meticulous core logging (Price, 2009).

On the other hand, Rui Ma *et al*. (2006) showed that the formation heterogeneity is the major reason of land subsidence at Taiyuan (northern China). Factors such as clay layer thickness, stratigraphy, and physical properties of clay soils (at different places and depths) affect the occurrence of this phenomenon.

Budhu and Adiyaman (2013) demonstrated that two factors affect the ground surface subsidence profile: 1. the presence of low hydraulic conductive geological materials in aquifers, 2. the presence of the clay zones (their amount and location). It is worth mentioning that the presence of low hydraulic conductive geological materials in aquifers influences the shape of the ground surface subsidence profile by affecting the amount and rate of the subsidence.

In Iran, land subsidence, as a result of the withdrawal of groundwater, has occurred in cities such as Tehran, Mashhad, Kashmar, Varamin, Kashan, Rafsanjan, etc. (Sharifikia, 2010).

Tehran and its surrounding cities have more than 15 million inhabitants. There are a lot of agricultural and industrial activities in the area.

This paper presents land subsidence caused by groundwater exploitation in the southwest of Tehran (Tehran-Shahriyar subsiding zone, which has the largest size and is the most populated city of Iran). This zone is also the most documented area for leveling, geology, hydrogeology, geophysics, remote sensing, and geotechnics. The objectives of the present study are:

1- to find a relationship between land subsidence characteristics and groundwater withdrawal in the aforementioned area, and

2- to characterize the stratigraphic heterogeneity and the effects of their characterization on land subsidence.

Geological and hydro-geological settings

In Tehran, land subsidence has been observed since the 1960s. Today, the population of Tehran exceeds 15 million inhabitants. Tehran plain, with an area of 2250 km^2, is located in the north of Iran, between the Alborz Mountains to the north and the Arad and Fashapouye mountains to the south. The southwestern part of the basin is subject to land subsidence, caused mainly by withdrawal of groundwater. The subsidence was first revealed by geodetic observation from precise leveling surveys across the area between 1995 and 2002 (Amighpey *et al.,* 2006). The subsidence area of 714 Km^2 is between 35° 30′ N - 35° 42′ N latitude and 50° 55′ E - 51° 23′ E longitude (Fig. 1). This is a semiarid to arid region.

From the stratigraphy point of view, Tehran Alluvial deposits consists of four stratigraphic units (Rieben, 1955): The alluviums of (A) Unit (Hezardareh Formation), (B) Unit (Kahrizak Formation), (C) Unit (Tehran Alluvium), and (D) Unit (Recent Alluvium). This section of the Hezardareh Formation is located in the north of Tehran and central Alborz. This formation consists of the conglomerate rock masses (with low porosity). The Kahrizak Formation is heterogeneous early Quaternary Formation, which makes up a flat-lyring sheet of alluvial sediments outcropping between the Hezardareh anticlinal folds and Alborz Margin. This formation consists of clayey silts.

Tehran Alluvium is the sub-recent alluvium of late Quaternary deposits that exist between Alborz and Anti-Alborz. This unit is predominantly exposed in the southern part of the Tehran plain. In the northern part, this unit mainly consists of irregularly layered gravels, imbedded with silty loam deposits that are progressively increasing towards the south. The river deposits consist of the young alluviums.

Tehran Alluvium and Kahrizak Formation, dominating the central part of the Tehran plain, represent potential aquifers with good hydraulic conductivity, while the folded beds of the Hezardareh Formation, dominating the northern part of the plain, show poor aquifer characteristics with low conductivity.

The conceptual model preparation is one of the most important parts for numerical modeling. Drawing a hydro-geological cross section requires large sets of data. Identifying the ground layers and its features can be useful in the interpretation of sedimentary basin. These features may be the characteristics of hydraulic, geotechnics, and hydrodynamics. The results obtained from the field and laboratory tests play an important role in model preparation. The first step in this method is drawing a hydro-geological cross section.

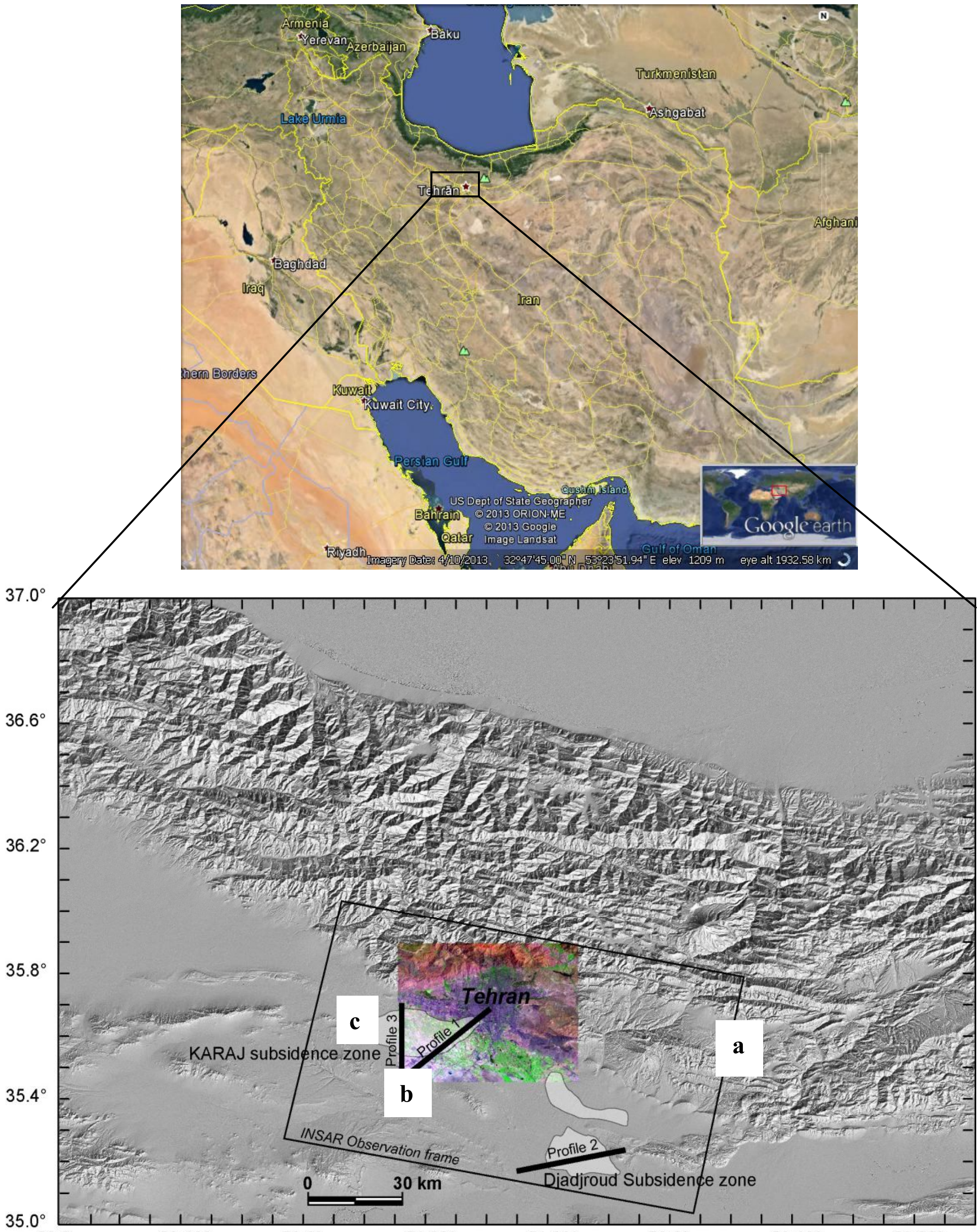

Figure 1: Shaded DEM around Tehran, a) black box: area of the InSAR study, b) black thick line: location of subsidence profiles derived from InSAR data, c) light grey area: subsidence zone of Tehran southwest.

The hydro-geological units of this area may be divided into the aquifers and aquitards systems. In this study area, six boreholes with a depth of 600 m were drilled. Based on the geotechnical data, from land surface downward, hydro-geological units consist of three aquifers and three aquitards. Figure 2 shows the hydro-geological cross-section in the southwest of Tehran (Rockworks software was used to show this cross section). The aquifer units consist primarily of silty sands and fine sands with gravel.

The following data were used for this work (GSI, 2007, 2008):

- *6 borehole geological logs,*
- *399 tests of grain size distribution and Atterberg limits,*
- *18 consolidation tests,*
- *42 Geophysical sections, and*
- *seismological study (microtremor analysis).*

The following data were used to calculate the correlation of aquifers and aquitards units (Table 1):

- *atterberg limits,*
- *unified classification,*
- *shear wave velocity and soil density, and*
- *consolidation index.*

Impervious deposits including clays and silty clays formed the aquitards. In this area, the groundwater's depth was from 30 m to 78 m. The maximum thickness of fine-grained soils (clay, silty clay) was observed in the south region of subsidence zone (Sabashahr, Eslamshahr and Saveh road regions). Currently, aquifer unit (1) is dry, and groundwater level is lower than 80 meters. The excessive withdrawal of groundwater has led to a severe decline of water in this aquifer. In figure 2, it can be seen that the aquifer and aquitard units are the main elements that form the study area. Because the fine-grained soil units (aquitard units) are exposed among the coarse-grained soil units (aquifer units) occurred differential settlement.

The thickness of hydro-geological units in the southwest of Tehran is different. In general, the thickness of the third aquitard in BH2 and BH3 locations (Sabashahr and Eslamshahr) is the thickest (Table 1). In addition, the clays of Sabashahr area are high plasticity clays (GSI, 2008). Increase in these parameters is impressive on the land subsidence rate in this area. The thickness of the third aquitard ranges between 9.5 and 41.5 m. In Sabashahr, the thickness of this unit is 41.5m. The clay with high plasticity (CH) has been reported only in Sabashahr area. In borehole 2 (BH2), CH layers from 34.90 to 36.60 m (1.70 m), 43.65 to 44.70 m (1.05 m), 65.64 to 70 m (4.36 m) and 74.30 to 76.95 (2.55 m) have been reported (GSI, 2008). The characteristics of these units are shown in tables 2 and 3. The atterberg limits (LL, Pl, PI) of aquitard units in Sabashahr and the toll gates of the Saveh road are higher than other regions (Table 2).

Table 1: Thickness of hydro-geological units in the boreholes (m)

BH No. / Unit	BH1	BH2	BH3	BH4	BH5	BH7
Fill materials	0-0.6 (0.6)	0-0.7 (0.7)	0-2 (2)	0-2 (2)	0-0.5 (0.5)	0-0.5 (0.5)
Aquitard 1	0.6-7.80 (7.2)	0.7-16.2 (15.5)	2-16.50 (14.5)	2-29.5 (27.5)	0.5-18.55 (18.05)	0.5-14.40 (13.9)
Aquifer 1	7.80-14 (6.2)	16.20-19.40 (3.2)	16.50-25.90 (9.4)	29.5-41.60 (12.1)	18.55-25.30 (6.75)	14.40-21.95 (7.55)
Aquitard 2	14-36.36 (22.36)	19.40-36.60 (17.2)	25.90-53.30 (27.4)	41.60-58.10 (16.5)	25.30-54.70 (29.4)	21.95-37.70 (15.75)
Aquifer 2	36.36-54 (17.64)	36.60-50.50 (13.9)	53.30-59.80 (6.5)	58.10-71.45 (13.35)	54.70-67.70 (13)	37.70-47.30 (9.60)
Aquitard 3	54-63.50 (9.5)	50.50-92 (41.5)	59.80-92.60 (32.8)	71.45-89 (17.55)	67.70-98 (30.3)	47.30-80 (32.70)
Aquifer 3	63.50-68.40 (4.9)	92-100 (8)	92.60-100 (7.4)	89-100 (11)	98-100 (2)	80-90 (10)

The fine grained soils from west to east of this area (Fig 2) showes increasing in plasticity properties (Table 2). In the south of this area, the compressibility level is high. Based on the proposed cross-section, southwest region of Tehran included a multi aquifer-aquitard system.

The transmissivity in the central plain is estimated at 2500 m^2/day (near Ahmadabad Mostofi). In the north, the transmissivity reduces steadily. In the southwest, the transmissivity reduces as well. In the south of Shahriyar to Andisheh town, values are less than 200 m^2/day. There are two reasons for the low transmissivities in the southern and southwestern Tehran plain; 1- the reduction of saturated layer's thickness (in the north and northeast of the study area), and 2- the reduction of hydraulic conductivity (in the south and southwest of the study area). Storage coefficient (main value) of Tehran plain is 5%, (GSI, 2005).

The northern limit is controlled by the change in lithology between coarse grain of the fan to the north and finer grain (Thickness is similar). As the change in lithology is rapid, the northern limit of the subsidence zone shows a high gradient of subsidence rate.

Table 2: Plasticity properties of aquitard units

BH No. / Unit	BH1	BH2	BH3	BH4	BH5	BH7
Aquitard 1	LL=28.1-30.6 PL=17-19.5 PI=11.1-12.3 CL	LL=33.5-39.8 PL=18-21 PI=15.1-16.4 CL	LL=30.3-43.8 PL=18-23.16 PI=12.3-21.7 CL	LL=31.5-39.5 PL=18.2-21.7 PI=13.3-20 CL	LL=32.2-36.3 PL=20.9-22.6 PI=12.6-13.7 CL	LL=30.9-44.6 PL=19.5-22.8 PI=11.3-21.8 CL
		LL=46.3-44.1 PL=24.3-29.3 PI=16-19.8 ML	LL=24.7-28 PL=18.9-21 PI=6.2-7 CL-ML		LL=27.9-32.8 PL=24.5-25.2 PI=4 -7.7 ML	
Aquitard 2	LL=27.1-36 PL=20-22.6 PI=8-13.5 CL	LL=37.5-45.3 PL=22.7-25.3 PI=15.4-20.1 CL	LL=28.7-31.8 PL=14.8-19.2 PI=15-12.5 CL	LL=30.7-37.7 PL=19.1-22.6 PI=11.7-15.1 CL	LL=32.3-38.7 PL=22.3-23.7 PI=10.8-14.9 CL	LL=31.5-46.8 PL=19.7-24.8 PI=12.8-22 CL
Aquitard 3	LL=27-31.9 PL=18.5-18.8 PI=8.2-13.4 CL	LL=36.1-48.8 PL=20.2-27 PI=15.9-21.5 CL	LL=23.3 PL=9.5 PI=13.8 CL	LL=34.5-48.5 PL=16.7-26.4 PI=18.6-22.1 CL	LL=29.7-37.4 PL=14.6-22.8 PI=14.5-15.1 CL	N/A
		LL=41.2- 49PL=26.3-32.4 PI=14.8-16.6 ML	LL=23 PL=16.4 PI=6.6 CL-ML	LL=46 PL=27.2 PI=18.8 ML	LL=47.7 PL=29.2 PI=18.5 ML	

Table 3: Some parameters of the Hydro-geological units

Parameter / Unit	LL (%)	PL (%)	Vs (m/s)	γ (KN/m^3)	Cc	Cs
Aquitard 1	30.6-45.2	17-37	228-348	16.19-16.90	0.26-0.35	0.18-0.21
Aquifer 1	21.9-30.8	16-20	266-297	16.39-16.53	-----	-----
Aquitard 2	27-38	21.6-25.5	235-754	16.22-17.54	0.16-0.34	0.11-0.24
Aquifer 2	29-35.6	18.4-20.8	626-830	18.86-20.88	-----	-----
Aquitard 3	31.9-46	16.6-29.3	794-907	20.15-20.89	0.14-0.52	0.10-0.46
Aquifer 3	24-40.6	24.4-26.3	-----	-----	-----	-----

In contrast, the southern limit seems to be controlled mainly by the thickness of the sediment; since the thickness changes slowly, the gradient of subsidence rate is low (dissymmetric V shape).

The main water uses in the Tehran plain are for agricultural, drinking, and industry purposes. In 2012, about 1.9 billion m^3 of water was extracted from the Tehran aquifer (annually). In 2003, the number of permitted wells within the Tehran plain was 26070. In 2012, their numbers rose to 32518 (Table 4).

Figure 3 shows the mean hydraulic head for the time period between October 1984 and March 2012. A drop of 4 m between the years 1984 and 1991, 6 m between the years 1995 and 2004, and 1.65 m between the years 2007 and 2012 is evident. Between the years 1991 and 1995 and 2005 and 2006, there is a small increase in the groundwater level. In March 2012, the groundwater level was 1056.5 m. The total decrease in groundwater level over 28 years is almost 11.65 m, an average of 42 cm/year. In a decade, there is a 4.56 m decline in groundwater level.

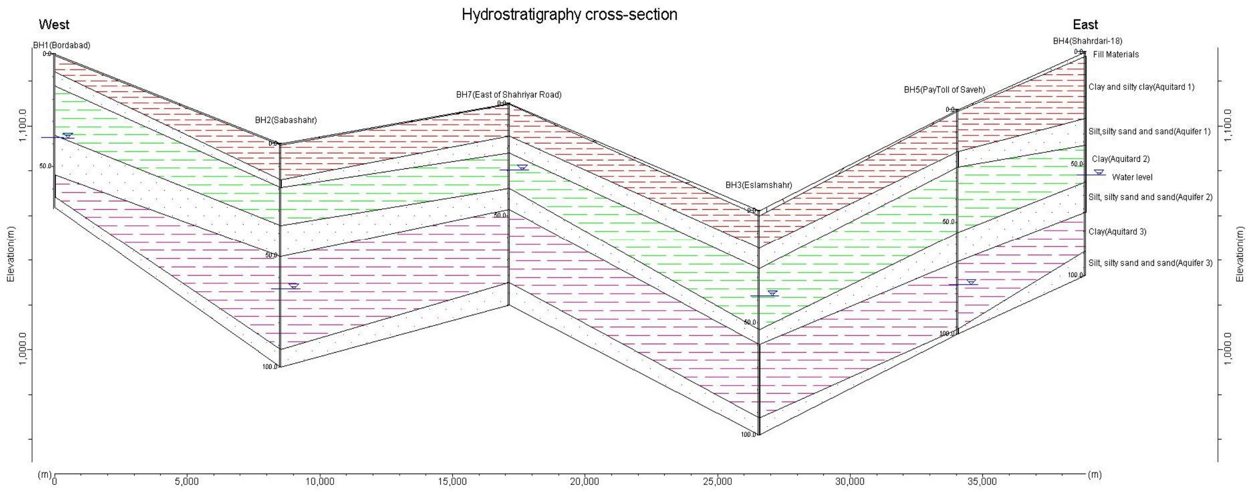

Figure 2: Conceptual hydro-geological cross-section of study area

Table 4: Discharge of wells and Infiltration galleries (Tehran Regional Water Authority, 2012)

Total discharge (million m^3)	Number of Infiltration galleries	Discharge of Infiltration galleries	Number of wells	Discharge of wells	Year
1031.8	522	393	3906	638.8	1968
_	_	_	7304	985.7	1983
1233.9	286	272	8950	961.9	1994
972.4	76	71	26076	901.4	2003
1907.8	167	26	32518	1881.8	2012

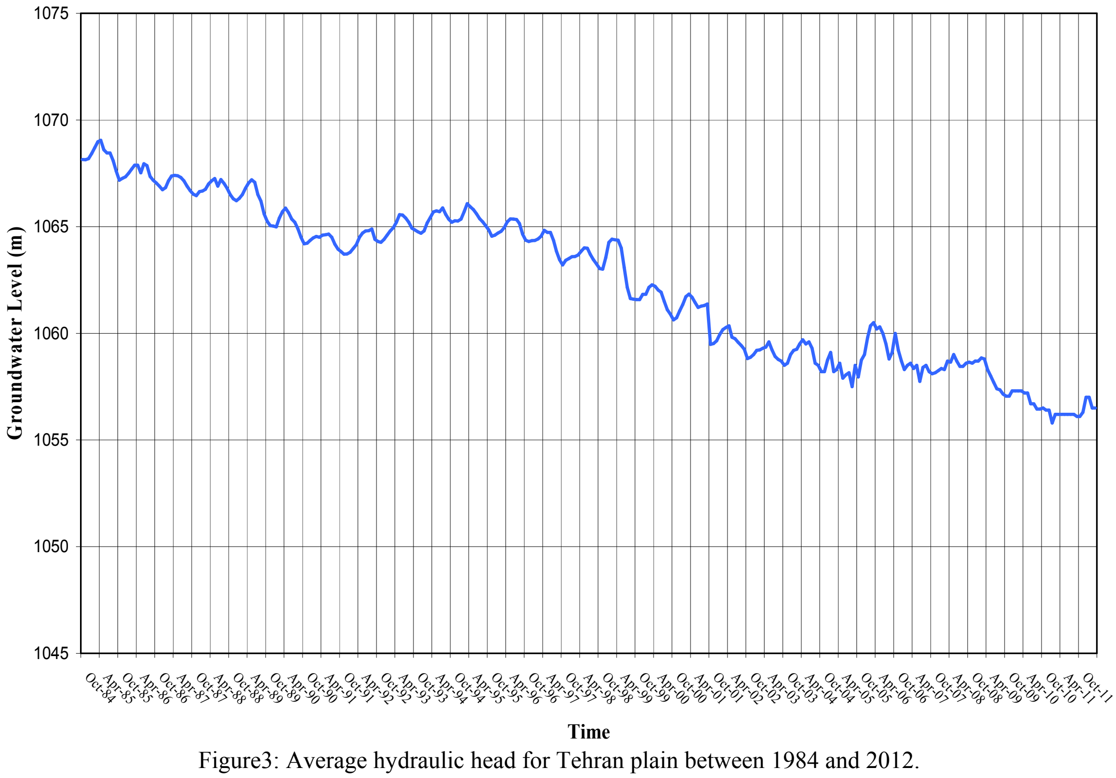

Figure3: Average hydraulic head for Tehran plain between 1984 and 2012.

Leveling Data

Land subsidence has been detected over the years by using surveying techniques such as differential leveling, high accuracy Global Positioning System (GPS) surveying, and InSAR method. Subsidence phenomena in Tehran basin have been studied using the GPS survey method, differential leveling, and also InSAR.

Leveling measurements of 3 lines across the zone have been done by the National Cartographic Center of Iran (NCC). The two lines are located in the southwest of Tehran (Fig 4). In 1989, NCC showed reducing groundwater level in the southwest of Tehran (Fig 5). The first Tehran subsidence zone is along the Tehran ring road (station 2009 to 2015). This line, with a length of approximately 16.36 km, and maximum land subsidence rate of 1.86 m, in the period from 1995 to 2004 AD (20.7 cm/year) was located in this zone. The second area of subsidence is located along the Ayatollah Saeidi highway (the old Saveh road) with a 38 km length approximately. The maximum amount of the land subsidence in the route and the time interval is 1.52 m (17 cm/year).

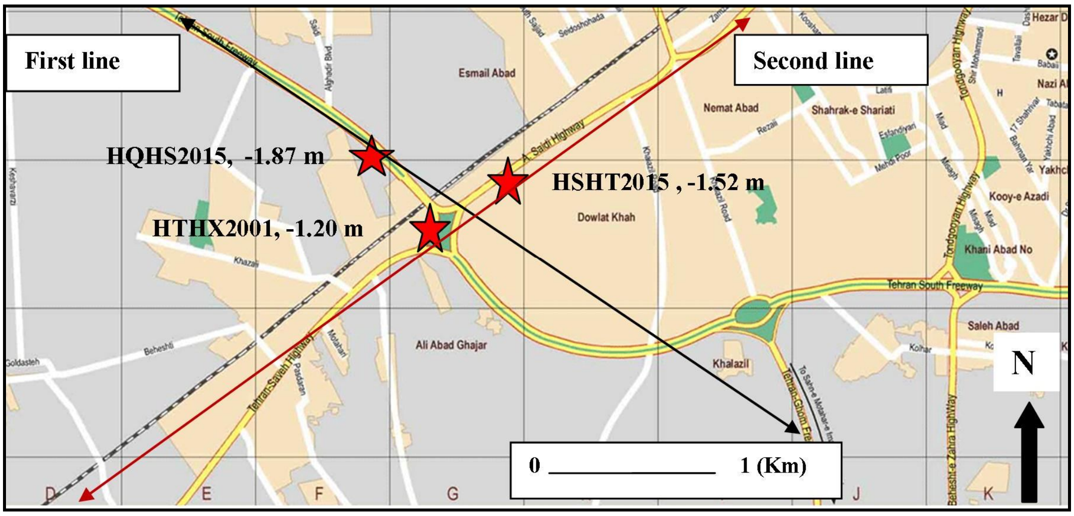

Figure 4: Distribution of leveling routes in southwest of Tehran

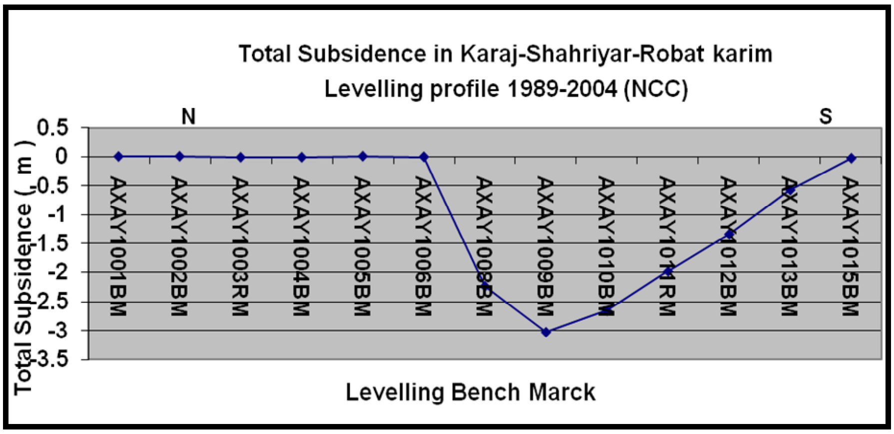

Figure 5: Leveling profile (1989 – 2004)

GPS data

Ground level changes have been studied using the time series method. Two GPS stations (SAFA and AVRZ) were located in the southwest of Tehran (Sabashahr and near the Saveh road toll gates, Fig 6). They are a portion of the geodynamics network (the local network) of the Tehran province (NCC, 2007). Local networks are created for specific purposes, and they are mostly temporary. The study was conducted from 2006 to 2008. At present, the two stations are not there anymore. The GSP data obtained are shown in Figure 7. The GPS data indicates that the southwest of Tehran is subsiding at a high rate, and there is a rapid decline in surface land.

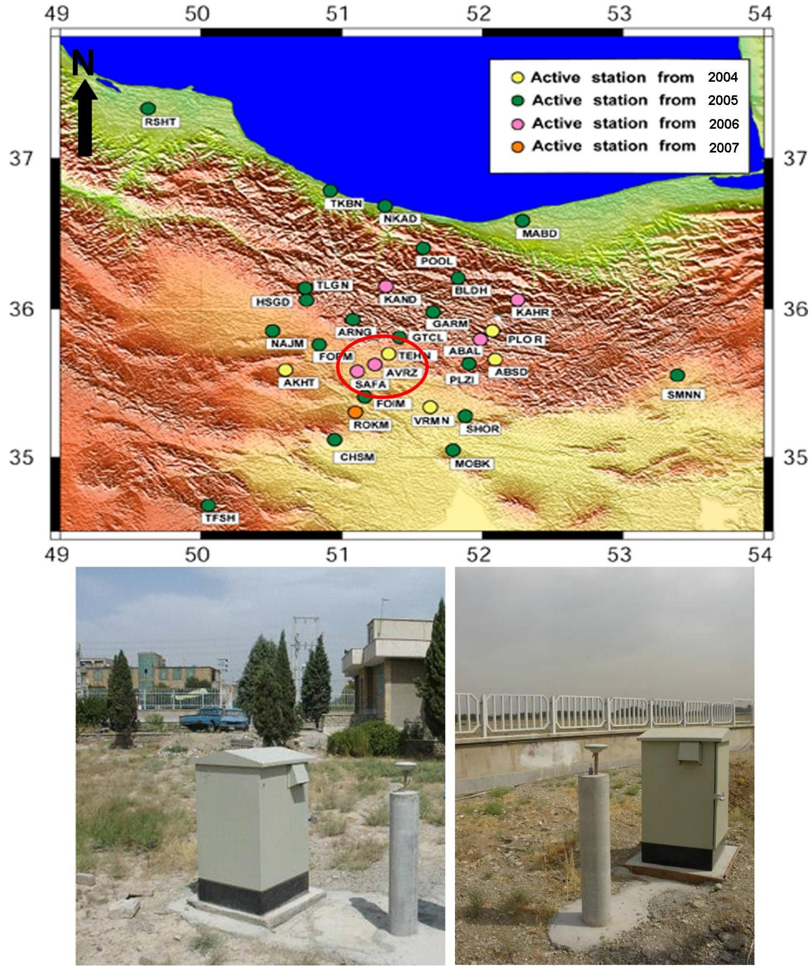

Figure.6: top: Distribution of GPS station in North Iran for studying of ground leveling and bottom: The GPS station (local network),, (left) Sabashahr (SAFA), (right) Toll of saveh road (AVRZ).

InSAR data

An interferogram can be formed between two images acquired at the same time from different positions; however, if the aim is to measure the data simultaneously from different positions. But if the aim is to measure deformation of the ground, the images must be acquired at different time intervals. A change in the position of the satellite between the two acquisitions leads to a geometric contribution to the phase change, which can be approximately corrected for knowing the positions of the satellite and the surface topography. Differential interferometric synthetic aperture radar (DIn-SAR) is a well known space geodetic technique due to its capability for regional scale subsidence measurement. DIn-SAR has been successfully demonstrated in many applications, such as land subsidence (Hooper, 2012).

Based on the satellite data, using the InSAR method, subsidence area in southwest of Tehran is known. Fig. 8 shows profiles 1, 3, and a subsidence bowl that is elongated in east-west direction. In the interferograms shown below (Fig. 9), one typical subsidence zone, where the number of fringes (transition from blue to pink) increases with the time interval, can be detected. In first approximation, fringes in this zone can be read as contour lines of subsidence (with a space of about 3 cm). In the preliminary analysis, we assumed that all the InSAR's signals are related to displacement, neglecting other effects like atmospheric perturbations (note that long wavelength signal has been removed from the unwrapped interferograms). This assumption implies a centimetric accuracy of the results. Data processing has been conducted for 2 months, 3 months, 4 months, 6 months, 12 months and 18 months periods (Sep 2004 to Mar 2006). These data gathered in a 6-month period (Sep 2004 to Mar 2005, indicates a subsidence region of 415.64 km2 (GSI, 2005).

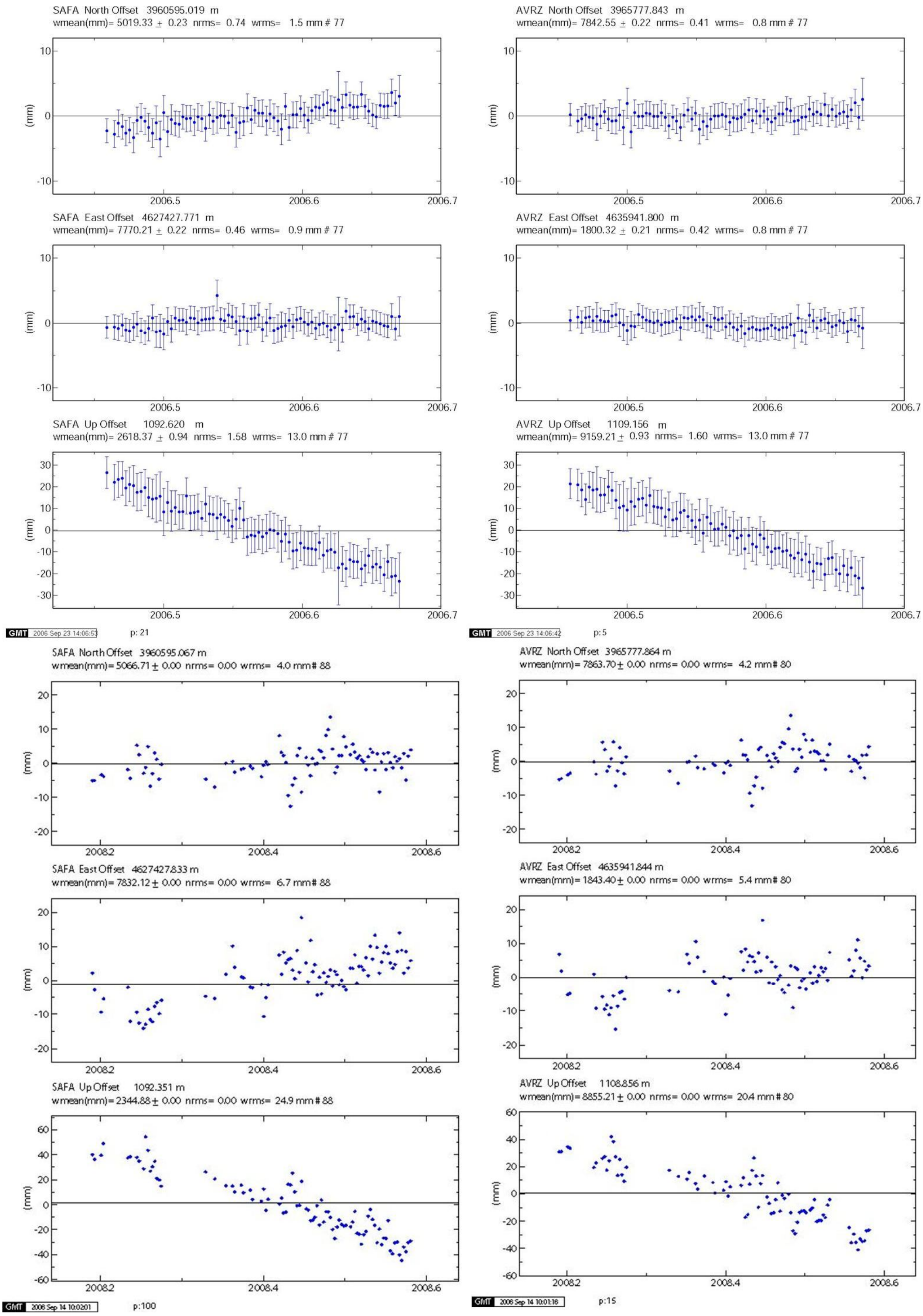

Figure 7: North, East and Vertical components of motion observed by the GPS stations (Time series), left- upper: Sabashahr station (Apr to Jun 2006), left-bottom: Sabashahr station (Feb to Jun 2008), right-upper: Avarezi station (Apr to Jun 2006), right-bottom: Avarezi station (Feb to Jun 2008). Note the rapid subsidence observed in two sites.

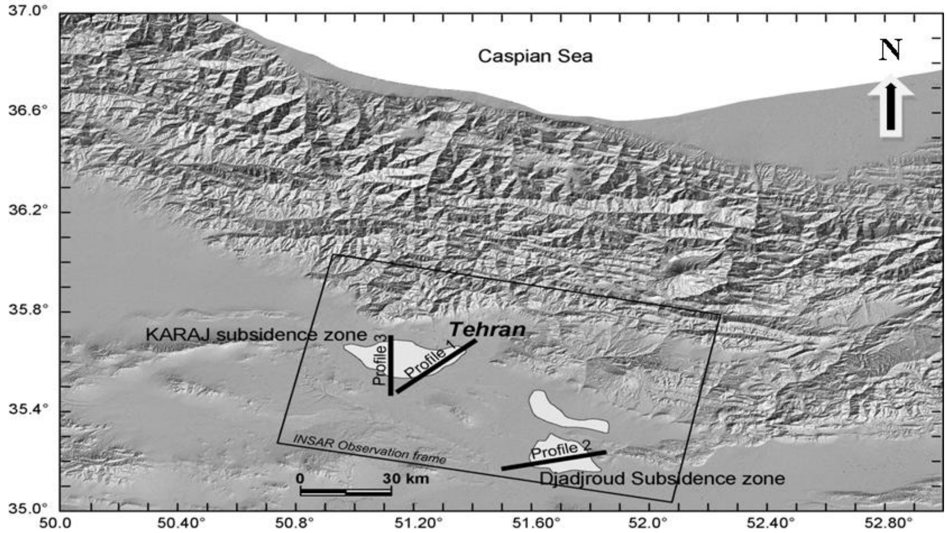

Figure 8: Distribution of InSAR profiles (profile 1 and 3) in southwest of Tehran.

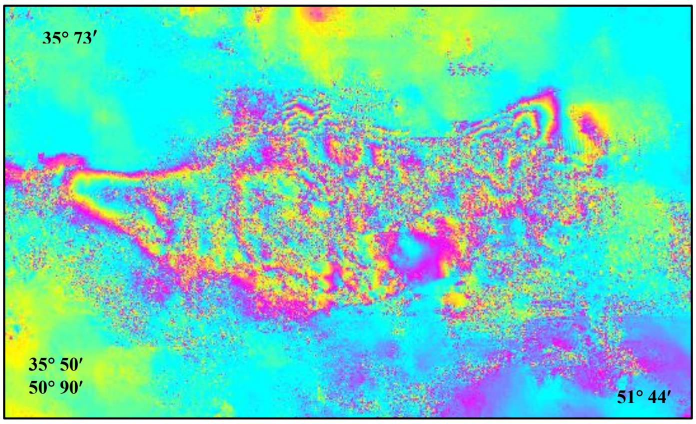

Figure 9: Interferogram image of southwest and south of Tehran. The major subsiding zone of Tehran southwest region (v- shape) is clearly visible on this interferogram (The temporal decorrelation noise is increasing in agricultural area).

On the other hand, the new satellite data analysis shows that the maximum subsidence rate in a 110-day period (from spring to summer, 2010) is about 110 mm (Fig. 10, Sharifikiya, 2010).

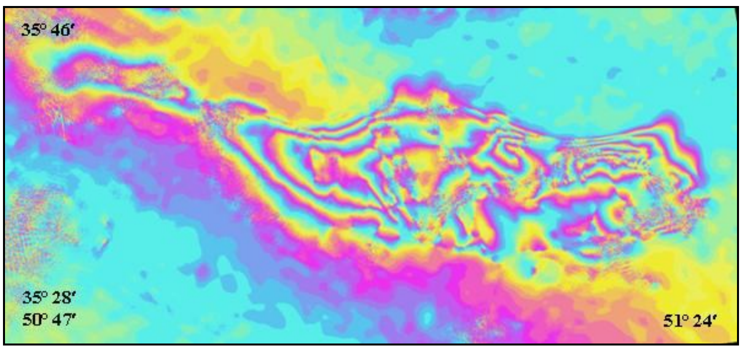

Figure 10: Interference image (D-InSAR technique) of southwestern Tehran (From 10 January 2007 to 17 January 2010) - Each color fringe indicated subsidence rate is 11.8 cm.

This means that the land subsidence rate is about 1 mm/day (about 36 cm/year). Comparison of these figures shows the development of land subsidence zone in the past 5 years. This development can be seen in the northern, western, and eastern sections of the area.

In the following figure (Fig 11), unwrapped interferograms are superimposed on a shaded DEM.

Black lines show the location of the profiles. The coloured scale gives the amount of displacement (dark line: 10 cm or more toward the satellite, green: 0 cm, dark red: 10 cm or more away from the satellite).

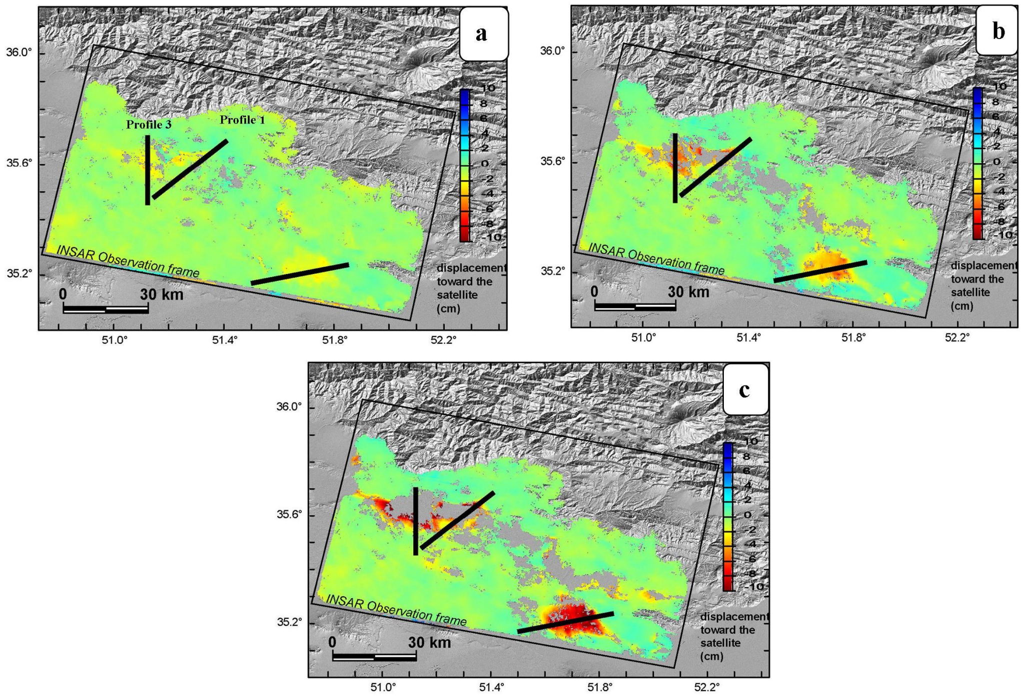

Figure 11: Unwrapped and geo-referenced interferogram a) CD. 70 days (9 January 2005 – 20 March 2005), b) BD. 175 days (26 September 2004 – 20 March 2005) and c) AD. 315 days (9 May 2004 – 20 March 2005).

Subsidence map was studied for periods of 70, 175, and 315 days. Coloured spectrum of satellite data processing and displacement values was detected for two profiles (profile 1 and 3) with NE-SW and N-S strikes. Land subsidence pattern in this area is (V) shape (Fig. 12). The maximum rates of land subsidence in the profiles 1 and 3 are 15 and 16 cm, respectively (GSI, 2005).

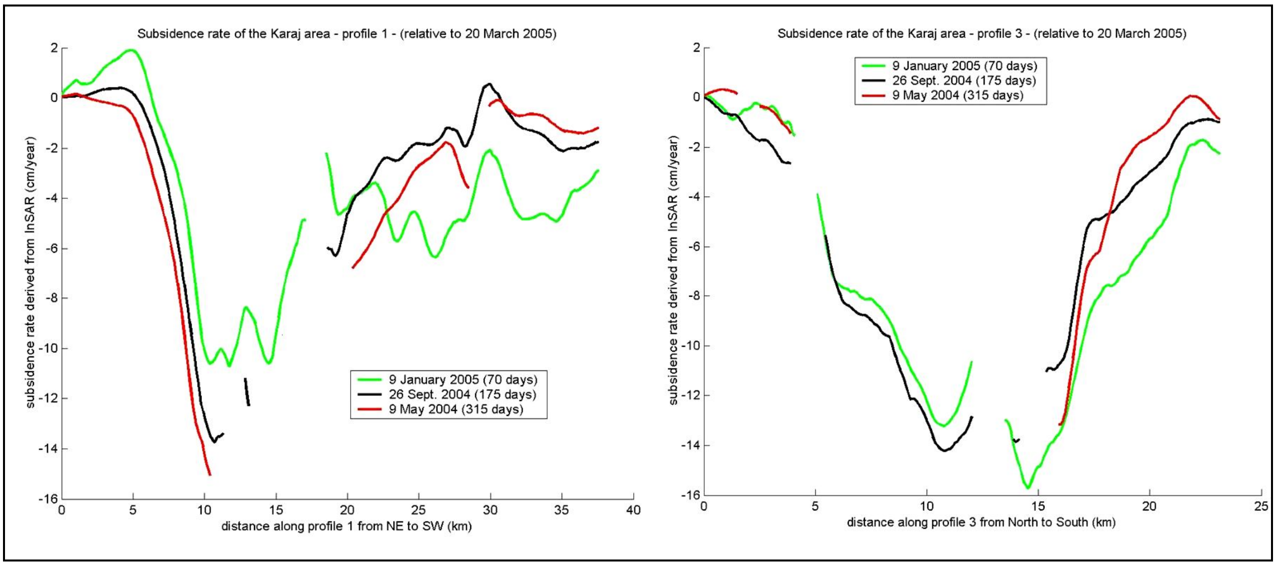

Figure 12: Left: subsidence rate along profile 1. This NE-SW profile shows an asymmetrical 'V' shape pattern with the highest gradient of displacement affecting the SW of the city of Tehran. The maximum estimated rate is about 15 cm/year. right: subsidence rate along profile 3. This profile shows a 'V' shape subsidence pattern. The maximum estimated subsidence rate is about 16 cm/year. (Gaps in the curves correspond to missing data that have not been unwrapped because of signal decorrelation in the interferograms).

Both of these profiles have shown a rapid drop in ground surface in 70, 175, and 315-day periods (2004- 2005). Note that subsidence values have been derived from the range-change values provided by InSAR, assuming a pure vertical displacement (Fig. 12).

Impacts of Land Subsidence in the Area

Land subsidence has negative impacts in the southwest of Tehran. In general, the impacts of land subsidence in the southwest of Tehran basin could be seen in several forms, such as: elevation of groundwater resources loss, damage and tilting to buildings and civil structures (cracking of permanent constructions and roads), rupture of well casings and other water transport facilities, and erosion of agricultural lands. These impacts were induced by differential settlements. In the past few years, with the development of land subsidence zone in this area, the losses have been growing. Another factor that adds to the development of the damages is the increasing rate of land subsidence in this area (more than twice, approximately). Fig 13 shows some representation in the field caused by land subsidence phenomena from several years ago and recent times. This figure also shows that most damages occurred in the areas showing high subsidence and also those that have spatially differential subsidence.

Figure 13: Evidence of progressive land subsidence at southwest of Tehran, a,b) coming up piezometric well and tilting of electrical tower (Sabashahr) ,c,d) cracks in building (Eslamshahr and Ahmadabad) , e,f) coming up well's casing (Shahriyar and Ahmadabad).

Conclusions

1. In this study, leveling, GPS, and InSAR technique were used to detect land subsidence in the southwest of Tehran. The InSAR result points out that in 2004 the area of subsidence was about 415.64 km^2, with a maximum rate of 16 cm/year. The land subsidence pattern in this area is in the shape of a (V).
2. The development of industrialization, intensive agriculture, and growth of the population of Tehran led to the exploitation of groundwater resources; in order to meet the water demands of the increasing population and industrial expansion. This situation causes groundwater depletion, compaction of aquifer system, and land subsidence of this area. Therefore, overpumping the groundwater is the main cause of land subsidence in this area.
3. Land subsidence has been widespread in the study zone from 2004 to 2010, with settlements up to 36 cm/year.
4. The increased withdrawals from wells and groundwater resources in the period from 2003 to 2012 are consistent with the development to land subsidence zone.
5. The aquifer system is categorized into three aquifers and three aquitards layers. Therefore, the aquifer system in the southwest region of Tehran is a multi-layered system (multi aquifer-aquitard system). The third unconfined aquifer, which is the main aquifer under pumping, and the third soft layer (third aquitard layer), which has the largest thickness and is closest to the main aquifer of all the aquitards. Soil layers constituting the aquifer system have the main role in the amount of compaction. The thickness of the fine-grained interbeds is the main factor that controls the timing of the land subsidence.
6. Several factors affected the subsidence rate of this area: heterogeneity of the layers of aquifer system, variation of layer thickness, and water pumping rate. Subsidence rates increase in the south of the subsidence basin (Sabashahr and Eslamshahr) where the clay–rich sediment package is thickest. The north limit of land subsidence zone is mainly controlled by changes in the layers (their heterogeneity). The south limit is mainly controlled by the thickness of fine-grained soils.
7. The negative impacts of subsidence in this zone are evident in buildings, civil structures, wells, and agricultural lands. These impacts are visible in areas such as: Sabashahr, Eslamshahr and the toll gates of the Saveh road.
8. The heterogeneity of fine-grained soils, their plasticity properties, and compressibility in different places at different depths is also an important factor controlling the spatial pattern of land subsidence in the southwest of Tehran.

Acknowledgments
The authors wish to thank the Geological Survey of Iran (GSI) for providing large amounts of data for this study.

References

Amighpey, M., Arabi, S., Talebi, A., Djamour, Y., 2006. Elevation change of the precise leveling tracks in the Iran leveling network, Scientific report, National Cartographic Center (NCC) of Iran, Iran.

Budhu, M., Adiyaman, I., 2013. The influence of clay zones on land subsidence from groundwater pumping, Ground Water, 51: 51-57.

Calderhead, A.J., Therrien, R., Rivera, A., Martel, R., Garfias, J., 2011. Simulating Pumping-induced regional land subsidence with the use of InSAR and field data in the Toluca Valley, Mexico, Journal of Advanced in Water Resources, 34: 83-97.

Carreon-Freyre, D., Cerca, M., Ochoa Gonzalez, G.H., Ortiz- villasenor, I., Gamez-Gonzalez, J., Gutierrez-Calderon, R., 2011. Land subsidence and ground fracturing affecting major cities of central Mexico and related groundwater management, Pan-Am CGS, Geotechnical conference, 7pp .

Galloway, D.L., Burbey, T.J., 2011. Review: Regional land subsidence accompanying groundwater extraction, Hydrogeology Journal , 19: 1459-1486.

Galloway, D., Jones, D., Ingebritsen, S., 1999. Land subsidence in United States, U.S., Geological Survey, Circular 1182, 175

Galloway, D., Hudnut, K., Ingebritsen, S., Phillips, S., Peltzer, G. F., Rosen, P., 1998. Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California, Journal of Water Resource Research, 34 (10): 2573-2583.

Geological Survey of Iran (GSI), 2008. Geoelectric study in southwest plain of Tehran; 5: 185. (in Persian).

Geological Survey of Iran (GSI), 2008. Geotechnical study in southwest plain of Tehran; 543 pp., (in Persian).

Geological Survey of Iran (GSI), 2008. Seismology study in southwest plain of Tehran; microtremor analysis with array method, 4: 426, (in Persian).

Geological Survey of Iran (GSI), 2007. Seismology study in southwest plain of Tehran; microtremor analysis with single station method, 2: 205, (in Persian).

Geological Survey of Iran (GSI), 2005. Land subsidence study in Tehran-Shahriyar plain, 84 pp., (in Persian).

Hooper, A., Bekaert, D., Spaans, K., Arikan, M., 2012. Recent advances in SAR Interferometry time series analysis for measuring crustal deformation, Journal of Tectonophysics 54-517:1-13 .

Hu, R.L., Yue, Z.Q., Wang, L.C., Wang, S.J., 2004. Review on current status and challenging issues of land subsidence in China, Engineering Geology, 76: 65- 77.

Lashkaripour, G., Ghafouri, M., Salehi, R., 2010. Land subsidence of southern Mahyar plain and effects of induced fissures on residential, industrial and agricultural, Fifth National Conference of Geology and the Environment, Islamic Azad University of Eslamshahr, Iran, (in Persian).

Lashkaripour, G., Ghafouri, M., Kazemi, R., Damshenas, M., 2007. Land subsidence due to groundwater decline in Neyshabur plain, Fifth Conference of Engineering Geology and the Environment, Natural Disaster Research Institute, Tehran, Iran, (in Persian).

Lashkaripour, G., Rostami barani, H., Kohandel, A., Torshizi, H., 2006. Decline in groundwater levels and land subsidence in the kashmar plain, Proceeding of the International Conference on Earth sciences, Tehran, Iran, (in Persian).

Motagh, M., Djamour, Y., Walter, T.R., Wetzel, H.V., Zschau, J. and Arabi, S., 2007. Land subsidence in Mashhad valley, Northeast of Iran, results from InSAR leveling and GPS, Journal of Geophysics, 168 (2): 518-528.

Mousavi, S.M., Shamsai, A., Naggar, M.H.Z., Khamehchiyan, M., 2001. A GPS-based monitoring program of land subsidence due to groundwater withdrawal in Iran, Canadian Journal Civil Engineering, 28(3): 452-462.

National Cartographic Center of Iran (NCC), 2007. Global Geodynamic Network of Iran, 16 pp., (in Persian).

Phien Wej, N., Giao, P.H., Nutalaya, P., 2006. Land subsidence in Bangkok, Thailand, Engineering Geology, 82: 187-201.

Price, D.G., 2009. Engineering geology, Principles and practice, Springer- Verlag, 460 pp.

Rui, M.A., Yanxin Wang, Teng Ma, Ziyong Sun, Shilony Yan, 2006. The effect of stratigraphic hetrogenity on areal distribution of land subsidence at Taiyuan , northern China, Journal of Environmental Geology., 50, 551-568.

Sharifikia, M., 2010. Evaluation of land subsidence related disasters in plains and residential areas of Iran, Iranian Association of Engineering Geology, Vol.3, No. 3 & 4, 43-58 (in Persian.(

Sneed, M., Ikehara , M. E., Stork, S.V., Amelung, F., Galloway , D.L., 2003. Detection and measurement of land subsidence using interferometric synthetic aperture radar and global positioning system, San Bernardino Country, Mojave Desert, California Tech. Rep. Water- Resources Investigations Report 03-4015, U.S. Geological Survey, Sacramento, California.

Tehran Regional Water Authority, 2012. Detailed data collection from peizometric wells , Tehran Province.

Yi Lixin, Zhang Feng, Xu He, Chen Shijie, Wang Wei, Yu Qiang, 2011. Land subsidence in Tianjin, China, Journal of Environmental Earth Science, 62: 1151- 1161 .