# MONITORING LAND SUBSIDENCE USING GPS AND INSAR

Parul Patel*, Madhav Kulkarni
Department of Civil Engineering,
Indian Institute of Technology Bombay, Mumbai-India
*p5parul@iitb.ac.in

**Abstract**

Land subsidence is one of the most varied forms of ground failure with devastating effects, ranging from broad regional lowering of the land surface to local collapse. Geological reasons like tectonic and volcanic activities affect at regional scale while localized phenomena can be mainly attributed to either human activities or natural activities like sink holes, fissures etc. With the increase in population, demand of natural resources like water, oil and gas has also increased, resulting in the extraction of these important natural resources in a haphazard manner. Such unplanned extraction of natural resources is one of the major reasons for land subsidence. Uniform settlement of ground does not create any major problem; however, uneven settlement causes lots of damage to infrastructure built over the affected area. There is a significant financial loss in repair of such the infrastructure. Hence attention should be paid to this man-made hazard.

To monitor and measure land subsidence, many techniques are available, like conventional levelling, Global Positioning System (GPS), Synthetic Aperture Radar Interferometer (InSAR), in situ techniques like Bore hole extensometer and Radio Active Marker method, etc. With the advancement of space technology, land subsidence is increasingly being measured and monitored with GPS. GPS has proven to be a reliable technique for monitoring the land subsidence with the precision of few mm levels, using geodetic dual frequency receivers, precise ephemeris and processing the data in post processing mode with scientific software.

To measure subsidence near Surat in Gujarat state, India, GPS survey has been carried out by the Indian Institute of Technology Bombay (IITB) GPS team. A total of 10 GPS field campaigns have been carried out during the period: February 2004 to October 2006, at an interval of 3-4 months. A GPS monitoring network was established in February 2004 with four reference stations and 27 deformation stations. Geodetic dual-frequency GPS receivers have been used for these observations. The reference station GPS receivers were continuously observing during the entire field campaign, and at each deformation station, minimum five hours of continuous GPS data was collected. The collected data and base lines were processed with scientific GPS data processing software: Bernese v 4.2. IGS data files as well as precise ephemeris were downloaded from IGS data bank, which were used for post processing the data. The data was processed considering saastamoinen troposphere model and ionosphere free solution combining L1 and L2 frequencies. In this paper, the results of ten campaigns are compared to understand land subsidence phenomena in the area of study. During a period of two years, 67 mm subsidence has been measured within the gas reservoir area. It has been confirmed that the rate of subsidence is more within reservoir boundary compared to that out side the reservoir boundary. Estimated subsidence is also correlated with the parameters responsible for land subsidence like gas extraction rate, pressure depletion, water level. It is established that, gas extraction is one of the main causes of subsidence over the study area. It was planned to compare the GPS results with InSAR method, but the results of INSAR method could not get due to limitations of INSAR method in highly vegetated area with changing in the crop pattern with time. (Key Words: Land Subsidence, GPS, InSAR)

## Introduction

Land subsidence is most challenging task in the field of geology. Since the rate of land subsidence is very law and often it goes unnoticed. Hence there must be an effective technique, which can measure even the small change with great accuracy. Many techniques are available to measure and monitor the land subsidence. Most common technique used to measure the land subsidence till last decade was geodetic levelling. The accuracy of geodetic levelling is very high, but it is time consuming, tedious, labour intensive and expensive operation. So with the development of new space technology, land subsidence is now being measured with GPS technology. The Global Positioning System (GPS), a satellite based navigation and surveying system for determination of precise position and time using radio signals from the satellites, is very widely used for numerous applications, including the study of crustal motion and subsidence (kulkarni et al., 2005). The accuracy of GPS derived coordinates is 4-5 mm in the vertical direction and 1-2 mm in the horizontal direction (Kulkarni and Patel, 2007). This accuracy is adequate to detect and monitor subsidence rates that are generally measured in the centimeters per year. Due to advantages of GPS survey over conventional methods, currently the most convenient method for measuring land subsidence is GPS. For this study, GPS technology has been used to monitor and measure the land subsidence.

The study area is shallow gas reservoir and located in the South Gujarat in India, along the Gulf of Cambay. Gas is being extracted over this study area. Hence, gas extraction is one of the main causes of subsidence over this area. It is found from the literature that, the major reason for land subsidence is water extraction in the world, a very few numbers of land subsidences have been observed due to gas extraction. However, at many places in the world, subsidence was found due to hydrocarbon production. Over the study area, there is no permanent depletion in water level has been found so the observed subsidence is not due to the extraction of water. The mechanism of land subsidence over the gas/oil reservoir is very simple. Initially the load of overburden area is partially supported by soil and partially supported by gas presence in the pores. As the gas is extracted from the pores, pore pressure declines and weight of overburden mass is slowly transferred to the adjacent soil mass, and soil mass compacts, if the soil mass is compressible. This compaction slowly reaches to the surface of the earth and bowl shaped subsidence takes place on the surface of the earth. The land subsidence process is taking place below the surface and very complex phenomenon. One can not visualize the mechanism of land subsidence. It is very difficult to predict subsidence; because predicted subsidence is mainly based on the laboratory measured value of soil compressibility and other parameters. The laboratory measurements have consistent tendency at overestimating soil compressibility, if compared to the evidence from in-situ measurements (Cassiani & Zoccatelli, 2000). Hence, to get the actual idea about the land subsidence, it is most important to measure land subsidence at the site itself. In this study, land subsidence is being measured with GPS during hydrocarbon production itself. ENVISAT InSAR data were processed with DORIS software and results are described. Consistently the data regarding pressure depletion and cumulative gas extraction have been collected and compared with the observed subsidence, and correlation coefficients were found out. Good correlation has been observed between them.

**Land Subsidence monitoring with GPS**

***GPS Network, Data Collection and Processing Methodology for Land Subsidence Monitoring***

To monitor land subsidence in area of 19 km2, a precise GPS network of total 31 subsidence monitoring stations was established in February 2004. Out of 31 stations, 4 stations have been established as reference stations. Five more stations were added in May 2006 campaign. Reference stations are comparatively stable. Out of 27 deformation stations, 10 deformation stations are within the reservoir boundary and rests are out side the reservoir boundary as shown in Figure 1. To study land subsidence, total study area has been divided in three zones, critical zone, deformation zone and reference zone. Critical zone is a reservoir area, from which, gas is being extracted and more liable to subside. Critical zone is surrounded by the deformation zone, which is likely to be deformed but deformation would be less compared to critical zone. The reference zone is a zone, in which all the four reference stations are located. This zone is stable and very far from the study area. For This study IITB permanent GPS station has been also used with the other reference stations.

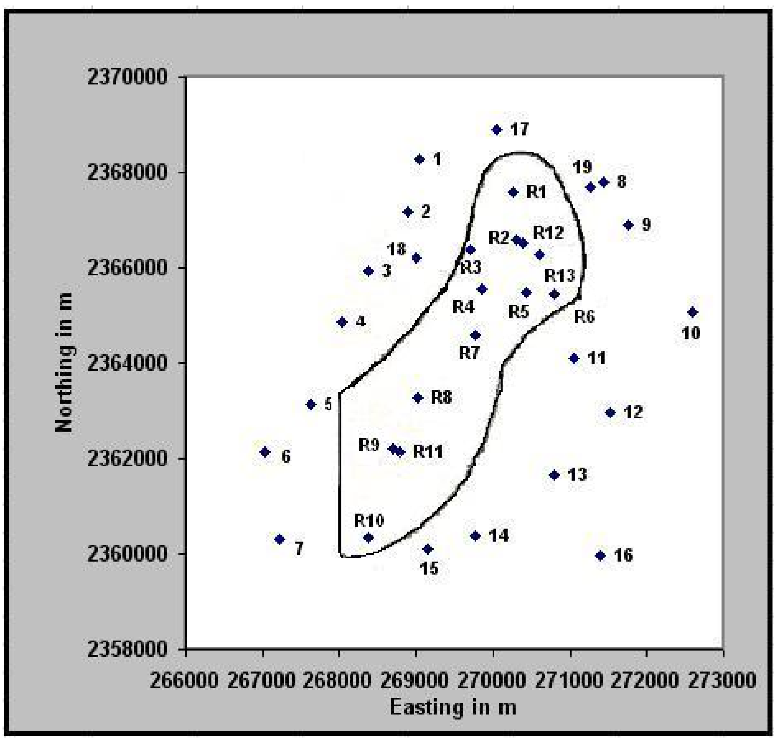


**Figure 1** Deformation Stations along with Reservoir Boundary

Total ten campaigns have been carried out to study land subsidence during February 2004 to October 2006 at a span of 3 to 4 months. The observations at the selected stations at Surat were taken using dual frequency geodetic GPS receivers: Trimble 4000SSi with Choke Ring antenna and Trimble 5700 with Zephyr Geodetic antenna. The data was collected for a period of minimum 5 hours with a sampling rate of 15 seconds for the deformation stations and 24 hours with a sampling rate of 30 seconds for the reference and permanent stations IITB, and satellite elevation mask of 15°. The data collected at respective stations at IITB and Surat were processed using Bernese v4.2 software (Hugentobler et al., 2001) to yield single baseline solutions and coordinates in both Cartesian rectangular and geodetic coordinate systems. Apart from the data files for the station points, three reference stations of International GNSS Service (IGS), belonging to different continental plates, were considered for the purpose of tightly constraining the coordinates of the GPS station points from these reference sites in ITRF2000 reference frame. The reference sites selected were BAHR (Baharin) on the Arabian plate, LHAS (China) on the Eurasian plate and IISc (a permanent station set up at Indian Institute of Science, Bangalore) on the Indian plate. The location of the following IGS stations is shown in Figure 2. The geodetic coordinates obtained for the stations (latitude, longitude and height) were projected onto a UTM grid to give results in Northing (m), Easting (m) and Height (m). To improve vertical accuracy of the GPS derived coordinates, special care has been taken for ionospheric correction, tropospheric correction, monument design, data collection time etc.

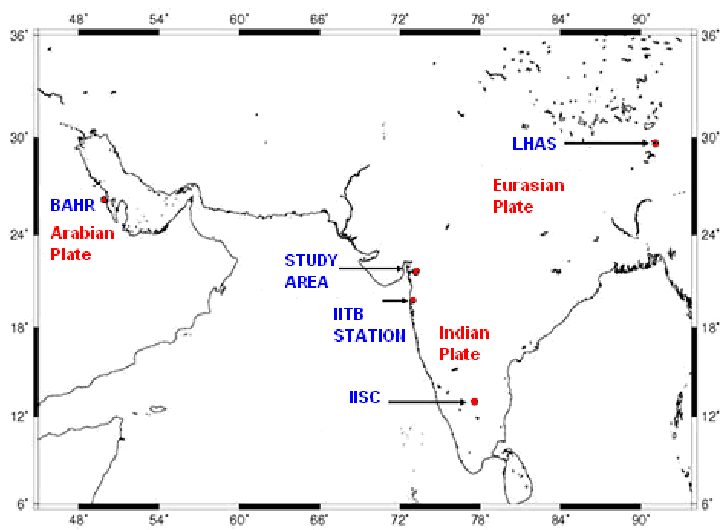


**Figure 2** Locations of IGS Stations, IITB & Study Area

The processing was done in two stages. In first stage, Precise coordinates were obtained from IGS website for three nearby IGS stations, namely LHAS in the Eurasian plate, BAHR in the Arabian plate and IISC in the Indian plate. By tightly constraining these three stations, the precise coordinates of all the four reference stations along with IIT Bombay permanent reference station were calculated. In second stage, all 27-deformation stations were processed with two reference stations and IITB permanent reference station. Here the coordinates of IITB and two reference stations were tightly constrained to get the coordinates of all deformation stations.

***Results and Discussion***

**Vertical Deformation of Station Points**

Precision estimated for GPS derived latitude and longitude is 1 to 2 mm and for height 4 to 5 mm respectively for this study. To monitor land subsidence in the study area, elevations of all deformation stations between two campaigns are compared. For land subsidence study only difference in elevations between two campaigns are enough to monitor changes in elevation. GPS derived heights are ellipsoidal, and enough to monitor land subsidence. Hence for this study, ellipsoidal height has been used (Abidin et al. 2001).

Effective (relative) subsidence is the difference between the average elevation difference of all deformation stations and average elevation difference of reference stations. Total ten campaigns have been carried out during February 2004 to October 2006. Average elevation changes with respect to first campaign February 2004 are calculated for all campaigns. It is found from the GPS results, that the stations within reservoir are showing significant subsidence compared to the subsidence of station points outside the reservoir boundary. The subsidence results obtained for station points within reservoir boundary and outside the reservoir boundary are shown in figure 3. It reveals that, average elevation change of deformation stations within the reservoir boundary are changing from positive to negative during February 2004 to October 2006. The effective elevation change of deformation stations within the reservoir boundary between two campaigns February 2004 and October 2006 is 63 mm downward. It is clearly seen from Figure 3 that, changes in elevations of deformation stations outside the reservoir boundary are fluctuating and not showing consistent subsidence. Thus it can be determined that deformation stations within the reservoir boundary are showing significant vertical deformation compared to deformation of stations outside the reservoir boundary.

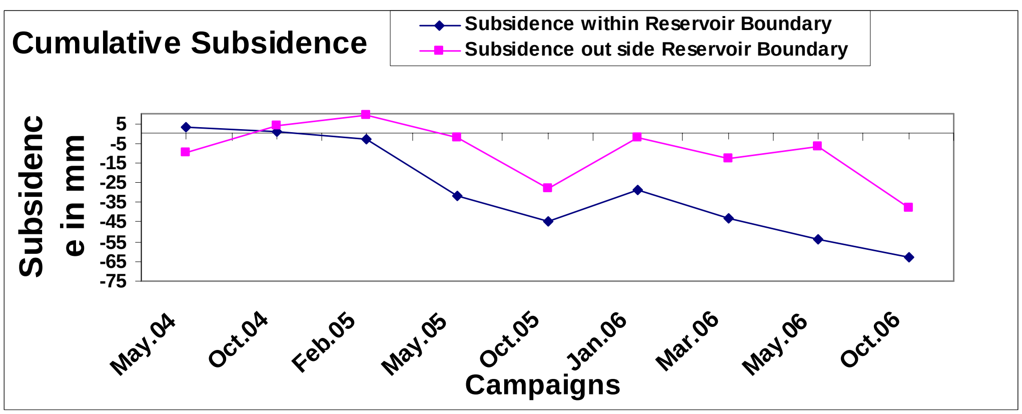


**Figure 3** Cumulative Subsidences from February 2004- October 2006

Contours have been prepared to see the change in elevation during February 2004 to October 2006. Figure 4 shows contour map, showing change in elevation during February 2004 to October 2006, deformation stations, approximate reservoir boundary and horizontal deformation vectors. Contours have been also prepared for height difference during February 2004 to May 2004, i.e. before the hydrocarbon production started. There was no significant change in elevation observed during February 2004 to May 2004. During this period almost all deformation stations have gone up. No subsidence was observed before the hydrocarbon production started. Hence, it can be concluded that subsidence was experienced only after the production of hydrocarbon. From the contour map, it is clear that northern and southern parts of the study area have subsided in October 2006, which was higher in February 2004. Total, two bowl-shaped depressions have been created, one is on north side and another is on south side of the reservoir boundary. Hence from the ground profile it can be concluded that area within the reservoir boundary is showing downward movement compared to area out side the reservoir boundary.

## Land Subsidence Monitoring with Differential InSAR Method

Conventional Levelling and Global Positioning System give point based land subsidence information, which is sometime not suffice to give overall picture of the study area. In this situation Differential Synthetic Aperture Radar Interferometry (DINSAR) method proves to be an important technique for monitoring land subsidence. It gives idea about the overall subsidence the study area. It provides better resolution and high accuracy within short duration. However, spatial and temporal decor relation and atmospheric signal reduces accuracy in repeat-pass SAR interferometry. For this study, three ENVISAT images were acquired for January 2004, before gas extraction started and May 2004, when gas extraction started and one year after the production of gas i.e in May 2005. These three pairs of data were used for mapping the ground subsidence during May 2004 to May 2005. The interferometric suitability of the available SAR data is tested by computing the base length. In order to construct the interferogram, ENVISAT satellite data are processed using Delft Object Oriented Radar Interferometric software (DORIS). The Delft Institute for Earth-Oriented Space Research (DEOS) has developed Doris software. DORIS is freely available at official site of the Delft University (http://enterprise.lr.tudelft.nl/doris/). Two pairs of interferograms (topographic interferogram and Deformation interferogram) are generated first and thereafter filtration is carried out (deformation interferogram subtracted from the topographic interferogram) to get the deformation fringes. Fringes are calculated to estimate the deformation over the study area.

From the results of InSAR data processing, it has been found that topographic interferogram was generated clearly but deformation interferogram was not generated due to poor correlation. Hence the final interferogram was not generated. This poor correlation may be due to heavily vegetated area. The study area is vegetated area, with changing pattern with time. Thus, this can be concluded that Differential InSAR method is not suitable for highly vegetated area. This conclusion is also supported by some past scientific paper (Chang et al., 2005).

## Study of Various Parameters Responsible for Land Subsidence

From the pressure depletion data of the gas reservoir, it is observed that reservoir pressure is consistently depleting with increase in extraction of hydrocarbon production. The correlation coefficient between cumulative gas extraction and pressure depletion was found to be very high 0.99. Hence it can be concluded that there is good correlation between these two parameters and pressure is decreasing with increase in gas extraction. From the locations of the well points, it is clear that, gas is being produced from two regions, which shows more subsidence compared to surrounding area. It is confirmed from the literature, that the central area of the reservoir generally shows more subsidence compared to surrounding region (Gambolati et al. 2005). The same results have been observed with GPS over the study area. Hence, it is confirmed that GPS is efficient and effective technique to measure and monitor land subsidence.

An attempt has been made to find out correlation between land subsidence and cumulative gas extraction. Correlation coefficient was found to be very high 0.93 between them. Hence, it can be concluded, the gas extraction is one of the major causes of subsidence over the study area. Mayuga and Allen had also found out close correlation between cumulative subsidence and hydrocarbon production over California’s largest oil field (Mayuga and Allen, 1969).

The abnormal reduction in ground water level besides seasonal level changes is responsible for land subsidence. Hence to study the change in water level, water level measurements have been taken over 30 points. Rate of change in water level and rate of change in elevation between two campaigns are calculated and plotted, from the statistical test; it has been found that the linear regression model is found to be suitable for these parameters. Fairly good correlation coefficient 0.78 has been observed between them. But no permanent depletion in water level has been observed during February 2004 to October 2006, only seasonal fluctuations have been observed. From the GPS derived elevations, it has been observed that, during pre monsoon period, all deformation stations are showing subsidence compared to previous campaign, while in post monsoon period, all deformation stations are showing uplift compared to previous campaign. This change in elevation and water level are hence seasonal. In general, the study area is waterlogged, and no permanent water depletion is observed over the study area. The use of ground water is very less in this area. Canal water is being used to irrigate the field as well as for other purposes. The rate of ground water extraction is very less in this area. Hence, there is very less chance to have subsidence due to ground water extraction. The subsidence measured by GPS or any geodetic technique represents a total subsidence associated with hydrocarbon production and other contributors like natural causes: water table changes, tectonic activities; and man-made causes: changing infrastructure, ground water withdrawal, mining, landfill etc. Therefore in future land subsidence due to hydrocarbon will be separated out from the total subsidence.

**Conclusions**

The accuracy of GPS derived coordinates is quite good, about 4-5 mm for height and 2-3 mm for latitude and longitude. This accuracy is adequate to detect and monitor land subsidence. The advantage of providing positions simultaneously at all sites, automated data collection and no line-of-sight requirement makes GPS technology more suitable, economical, efficient and convenient over the conventional methods.

From the results of this study, it has been established that, deformation stations within the reservoir boundary are showing significant vertical deformations (67 mm) compared to the stations outside the reservoir boundary (57mm). Two subsidence bowls, one on the north side and other on south side of the study area were observed. Convergence horizontal movement of all station points except at few stations, towards the centre of the reservoir confirms the subsidence over the study area. InSAR technique is not suitable for land subsidence measurements particularly over the highly vegetated area. Due to poor coherence, generation of interferogram is difficult.

It has been experienced that, reservoir pressure is consistently decreasing with increase in hydrocarbon production. A close correlation has been established between the subsidence and hydrocarbon production. A high correlation coefficient (0.93) was observed between cumulative subsidence and cumulative gas extraction. Hence, it is confirmed that, hydrocarbon production is one of the major parameters responsible for subsidence within the study area. Water extraction plays a major role in the land subsidence. But in the study area, the rate of water extraction is very less, no permanent depletion in water level is observed in the study area. Fairly close correlation 0.78 is observed between the water level and GPS derived elevation. In general, the deformation stations are showing subsidence before the monsoon campaign and uplift after the monsoon campaign, these results might be due to seasonal effect on black cotton soil available in the study area.

To study and monitor subsidence and to find the rate of subsidence, extensive monitoring for longer duration is required. These are the preliminary results of the studies; hence the rate of subsidence in this area has not been established. In future, rigorous monitoring will be carried to find the rate of subsidence.


**Acknowledgements**

This is a research project undertaken through Research and Development (R&D) cell, IIT Bombay. Late Prof. Madhav N.Kulkarni is a principal investigator of this project. We are thankful to R & D, for providing us infrastructure and financial support for this research work. Thanks are also due to Mr.Shashank Shekar and Mr.D. Borgohain for extending their help during data collection for this research work. We are sincerely thankful to Dr.Y.S.Rao and Dr.A.B.Inamdar, CSRE, IIT, Bombay for helping us, in getting and processing InSAR data. We are also grateful to entire IIT Bombay GPS team, V.S.Tomar, Pravin Pillai, Deepa Rai, Sagar Deshpande, Deepankar Vaidya, Narendra Ozha, Mahendra Kamath, Amruta Pathak and Anand Hiroji for Field work for ten campaigns.


**References**


1. Abidin HZ, Djaja R, Darmawan D, Hadi S, Akbar A, Rajiyowiryono H, Sudibyo Y, Meilano I, Kasuma MA, Kahar J, Subarya C (2001) Land Subsidence of Jakarta (Indonesia) and its Geodetic Monitoring System. Natural Hazards 23: 365-387.
2. Cassiani, G. and Zoccatelli, C. (2000). Towards a Reconciliation between Laboratory and In Situ Measurements of Soil and Rock Compressibility. Proceeding of 6$^{th}$ International Symposium on Land Subsidence, Italy, Vol. 2, 3-15.
3. Chang, H.C., Ge, L. and Rizos, C. (2005). Radar Interferometry for Monitoring Land Subsidence due to Underground Water Extraction. Proceeding of SSC2005, Spatial Intelligence, Innovation and Praxis: The National biennial Conference of the Spatial Science Institute, Melbourne, INBN 0-9581366-2-9.
4. Gambolati G, Teatini P, Ferronato M (2005) Anthropogenic Land Subsidence. Encyclopaedia of Hydrological Sciences, John Wiley & Sons.Ltd: 2443-2459
5. Hugentobler, U., Schaer, S., Fridez, P., (2001). Bernese GPS Software Version 4.2 Documentation, Astronomical Institute University of Bern, Switzerland.
6. Kulkarni M.N., Rai Deepa , Patel Parul , Study of Land Subsidence and Horizontal Crustal Motion in South Gujarat Using Global Positioning System" , MAP India International Conference , New Delhi (2005).
7. Kulkarni, M.N., Patel, P.R., 2007. Preliminary Results of GPS Studies for Monitoring Land Subsidence over the Shallow Gas Reservoir in India, Survey Review, UK (press).
8. Kulkarni M.N., Patel, P.R., 2007. Application of GPS for Monitoring Land Subsidence, ICFAI, Journal for Earth Science, India (press).
9. Mayuga and Allen DR (1969) Subsidence in the Wilmington oil field, Long Beach, California, USA. Proceedings of Tokyo Symposium on Land Subsidence 1: 66-79.
10. Radhakrishnan, N., (2007). Geodetic Monitoring of Deformation of Large Engineering Structures, Ph.D. Thesis, Indian Institute of Technology, India, 77-96.