Application of GPS for Monitoring Land Subsidence

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ABSTRACT

Monitoring land subsidence due to various causes is a challenging task in Geodesy. This paper deals with the monitoring land subsidence with Global Positioning System (GPS) in the South Gujarat, India. In this area, hydrocarbon is being extracted since many years. Hydrocarbon production is one of the main causes of land subsidence over the study area. Land subsidence studies have been carried out by GPS team, Indian Institute of Technology, Bombay with dual frequency GPS receivers. Total nine field campaigns have been completed. The collected GPS data have been processed in post processing mode using scientific GPS data processing software using precise ephemeris. To achieve mm level accuracy, ionospheric correction and tropospheric corrections were estimated and applied during data processing. Statistical testing was done to check the significance of the GPS data. The results of statistical testing confirm that there is significant subsidence within the reservoir boundary than the subsidence outside the reservoir boundary. It is established that gas extraction is one of main causes of subsidence over the study area. In this paper the findings of nine GPS campaigns are depicted.

I. Introduction

The term subsidence is used to indicate a slow downward change in ground elevation with little or no horizontal motion. Land subsidence arises either from regional or local phenomena. On the regional scale, geological reasons including tectonic or volcanic activities are the main causes of land subsidence. On the other hand, localized phenomena are caused by either natural or man-made reasons. Land subsidence induced by natural reasons are sink holes in lime stone areas, while man-made reasons are associated with the removal of subsurface material such as, under ground mining operations, underground construction and withdrawal of natural resources like water, oil, and gas. Over the last several decades, subsidence has caused problems in urban, rural and unpopulated areas of the world. Most of the major subsidences areas around the world have developed in the past half-century at accelerated rates due to rapidly increase the use of natural resources like ground water, oil and gas with increase in population. The type of hazards associated with subsidence is different from that caused by sudden and catastrophic natural events like floods and earthquakes, because surface sinking is a slow event. Uniform subsidence of the whole area does not create much problems but the heterogeneous subsidence in urban areas damages buildings and man-made structures such as bridges, canals, highways, electric power lines, railroads and underground pipes etc. Subsidence is considered as a one of the major problems because of financial loss due to costly repair of urban infrastructure and property damage. Hence accurate measurement and monitoring of land subsidence is required, to predict land subsidence in future and to protect infrastructure lying over the surface. It also helps in designing infrastructures, by viewing possible effects of land subsidence in future and to recommend methods for a sustainable use of the underground resources.

Many techniques are available to measure and monitor land subsidence. Most commonly used techniques are geodetic levelling, Global Positioning System and Synthetic Aperture Radar Interferometry. Other methods for monitoring land subsidence are Acoustic emission, Photogrammetry and in situ compaction/expansion measurement techniques like Borehole Extensometer and Radioactive Marker method. 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 widely used for numerous applications, including the study of crustal motion and subsidence (Kulkarni, 2002). GPS derived coordinates give mm level accuracy both in horizontal and vertical directions. The vertical accuracy of GPS derived results are less than the horizontal accuracy but enough to monitor land subsidence as subsidence is generally measured in centimeters (Mousavi et al. 2001). Due to advantages of GPS survey over the conventional survey, now a day GPS technology becomes very popular amongst the surveyors.

In India, the importance of subsidence research was realized in the beginning of the 20th century but the systematic investigations were started in the 1960's decade by Central Mining Research Institute (CMRI), Dhanbad. The research gained impetus after nationalization of coal mines in 1971. Many research works have been done to monitor land subsidence over the coal mines (Saxena or Singh). The most important case study of land subsidence in India was Sudamdih project. Research showed that, a railway main line at the Sudamdih in Jharia coal field had been subsided gradually by a maximum of 672 mm in a controlled manner without affecting its normal operation (Sinha and Singh, 1996). In past, no extensive research work was reported in literature, in India on land subsidence due extraction of natural resources like water, oil and gas. Recently land subsidence of Kolkata city was measured during 1990's by Chatterjee et al. (2006) using DInSAR techniques. They have used ERS data, to measure land subsidence over the Kolkata city. The main reason for land subsidence was over-drafting of ground water. Results indicate that an area in Kolkata city surrounded by Machhua Bazar, Calcutta University and Raja Bazar Science College had been undergone subsidence during the observation period, i.e., 1992-1998 with an estimated rate of 5 to 6.5 mm/year.

Mechanism of land subsidence over the gas reservoir

The compaction/subsidence of petroleum reservoir is one of the most spectacular, frequently, costly and dangerous manifestation of the poromechanical behaviour of rocks. The basic mechanism of reservoir compaction and surface subsidence is very simple. The weight of overlying sediments in gas producing reservoir is supported partially by the rock matrix and partially by the oil/gas pressure in the rock pores. Due to extraction of gas/oil, pore pressure declines and overburden load is transferred to the rock matrix, if the reservoir soil/rock is compressible, then volume of the reservoir compacts. Compaction is the process, in which the compressive strength of the rock is exceeded and plastic deformations resulting in reduction of porosity and permeability. This reservoir compaction is transmitted slowly to the surface and causes subsidence of the ground (Gambolati et al. 2005). The actual land settlement depends primarily on depth, volume and compressibility of the reservoir and adjacent formations. Other major factors, which affect surface subsidence, are porosity, permeability, fluid properties and production volume (Whittaker and Reddish, 1989).

Land subsidence has been studied intensively in the past. Different phenomena were addressed. But an accurate characterization of subsidence due to oil and gas production is rare due to various reasons, one of which is the difficulty of measuring surface subsidence precisely, with high resolution, over a larger area, and in a timely fashion. Subsidence caused by ground water extraction and hydrocarbon production has certain similarities, but they occur in distinct geologic condition. Water extraction generally takes place at lower height, where the porous media are soil or soft rock. This media has large porosity and permeability. Whereas oil & gas extraction take place at greater depth, where the porous media are consolidated or unconsolidated rocks. This is less porous and permeable than those mediums at shallower depth. There is also difference in temperature and pressure at shallow depth and at higher depth. At higher depth temperature and pressure are high compared to shallow depth (Xu, 2002).

Typically settlement above gas/oil fields is smaller than the reservoir compaction, because gas/oil reservoir placed at more depth, but it spreads over a larger area than the extent of the field itself. Aquifer system is shallower and has a much large area than gas/oil fields. Over a gas/oil fields, the subsidence usually takes on a bowl-shaped appearance with largest displacement occurring near the centre of the field. The border of the bowl may roughly resemble the shape of the field although it may extent up to twice or more area encompassed by the outline of the underlying reservoir (Gambolati et al. 2005; Xu 2002). The shape of the subsidence depression resembled the size and general shape of the underlying reservoir some 3 km below.

Oil and Gas extraction has given very less contribution compared to extraction of water to the list of case history of land subsidence. Subsidence over oil and gas fields has been widely reported and occurred in several countries. Surface subsidence probably occurs over all oil and gas field where pressure difference decline is experienced, even though subsidence seems to have been detected at only a few of the many thousands of oil and gas fields, which have been developed. But large settlement above gas and oil fields have been reported from Long Beach- Willington , USA; Goose Creek , USA; Groningen, Netherlands; The river Po delta , Italy; Bolivar Coast ,Venezuela; and Niigata , Japan. In Ekofisk oil field, the subsidence survey was carried out in 1984-85, and maximum subsidence depression of 2.6 m was observed up to mid-1985 and subsidence rates of 0.4 to 0.46 m/year with up to 0.7 m/year centrally occurred since 1979-80(Whittakar and Reddish, 1989).

In general, supporting evidence says that, there are fairly good correlations between the subsidence rate and production rate, namely faster the production, faster the subsidence is. In Goose Creek field near the head of Galveston bay, and the Saxet oil and gas field near Corpus Christi, close correlation between rates of hydrocarbon production and the rates of subsidence was found (Gibeaut et al. 2000).

II. Study Area

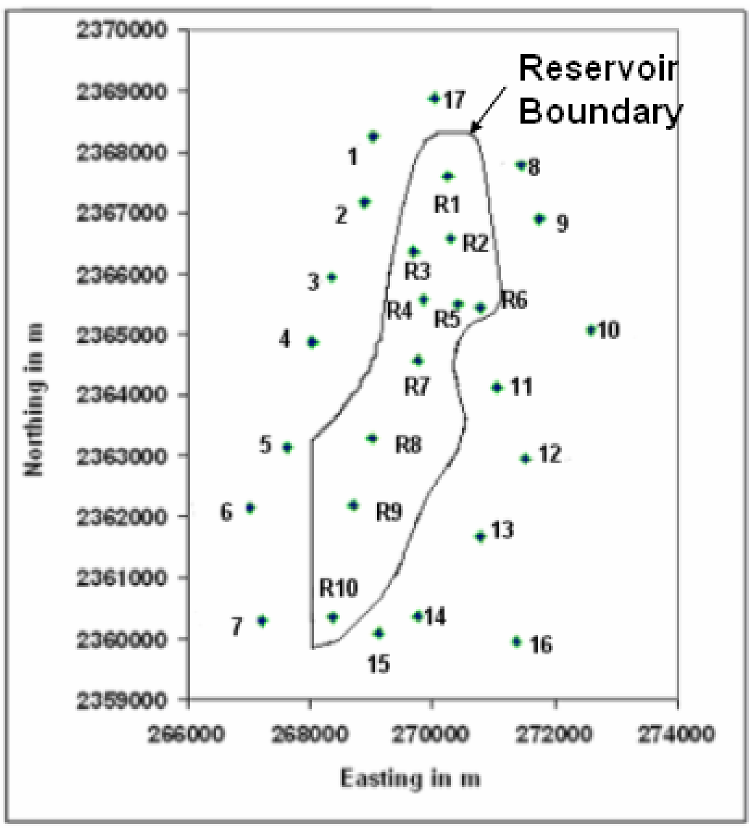
Olpad province of Surat district is situated on north side of Surat city. Study area is located in the Cambay basin, elongated in north-south direction. The Cambay basin rests on the basement of late Cretaceous. Thick sediments have accumulated during late Palaeocene to late Miocene in this basin. Initially, thick black shale referred as Cambay shale, was deposited in a marine transgression. Finally, multiple thin sandstone bodies within mudstone, clay and shale were deposited during late Miocene to Pliocene in an estuarine environment (Geological map of Gujarat, 2002). These sandstones form the reservoir units in this shallow gas field. The topographical area of the shallow gas reservoir is about 19.9 km². Total length of the reservoir is about 7.5 Km and width is about 2.5 km. The potential producing horizon constitutes of two main sands located between 180 m and 240 m depth from the surface. These two shallow gas reservoirs are named as "A" sand and Gamma sand. Two sands are separated by mudstone /clay stone. Based on the core samples obtained from the reservoir, the reservoir sand can be characterized as unconsolidated, weak sediment that exhibits nonlinear stiffness. The overlying shale and mudstones form the cap of the shallow gas field of Cambay basin. The variation in porosity and permeability of the shallow gas reservoir are 26 to 38% and 29 to 1500 mD respectively. Productions from the shallow gas reservoir were started in April 2004 from five wells and from sixth and seventh wells were started in June 2004 and May 2005 respectively. Total gas production and average pressure depletion are recorded 1818461129 m^3 and 0.654 N/mm^2 respectively during May 2004 to May 2006.

III. Data Collection and Processing

Total 31 subsidence monitoring stations were established. Out of 31 stations, 4 stations have been established as reference stations. Reference stations are comparatively stable and running through out the field campaigns. Remaining 27 stations are deformation stations and minimum five hours of data were collected from each deformation stations. Out of 27 deformation stations, 10 deformation stations are within the reservoir boundary and others are outside the reservoir boundary as shown in Figure 1. In March 2006, five new deformation stations were added to strengthen the GPS monitoring network. 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 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.

To achieve mm-level precision in detecting land subsidence, distinct care was taken to design and erect monumentation at GPS station. To construct GPS monuments at station, iron rod of 12 mm diameter was lowered up to 20-22 feet below the ground level. Concrete column of 1 m height was constructed below the ground level and about 0.75 m above the ground level. Pipe fencing is erected around the station for security of the GPS station point. Force centring devices are provided at each GPS station, over which GPS antenna is placed during the data collection.

Keeping in mind the possible effect of season, GPS data were collected by repeated observations, which includes data collection in dry season, usually in May, and after monsoon in October. Usually water level rises up after the monsoon. The water levels remain close to maximum up to December and January then start to drop. During May usually water level is observed to be minimal. Total nine field campaigns have been carried out over this network to study land subsidence during February 2004 to May 2006 at an interval of 3 to 4 months. Each fieldwork period is spanning approximately one week. Geodetic dual-frequency GPS receivers, Trimble 4000 SSi with choke ring antenna and Trimble 5700 with zephyr geodetic antenna were used to collect data. Reference stations were continuously running during the entire field campaign of GPS data collection. At each deformation station, minimum five hours of continuous GPS data was collected. The data were collected with a 15 second interval and elevation mask was kept 15 degree. Position Dilution of Precision (PDOP) Cut-off was set as 4.



R1 to R10 Deformation Stations within Reservoir Boundary

1 to 17 – Deformation Stations outside the Reservoir Boundary

Figure : 1 GPS Stations along with approximate Reservoir Boundary

Collected data and base lines were processed in the WGS 84 (World Geodetic System 1984) reference system. In addition to these, IITB reference station data is also used. Three IGS (International GNNS Service) stations were selected for constraining the solutions in the ITRF 2000 (International Terrestrial Reference Frame 2000). IGS data files as well as precise ephemeris files were downloaded from IGS data bank, which were used for processing the data in post processing mode. The data was processed considering saastamoinen troposphere model and ionospere free solution combining L1 and L2 frequencies. 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 their calculated values in step 1. The processed data gives coordinates and base lines both in Cartesian rectangular and geodetic coordinate system. The geodetic coordinates were projected on to the UTM grid to give results in Northing (m) and Easting (m).

Table 1. Precision Estimated for the Coordinates

	Estimated rms (mm)		
	Maximum rms	**Minimum rms**	**Mean rms**
Height	6.9	0.6	2.8
Latitude	0.2	0.1	0.3
Longitude	0.6	0.1	0.3

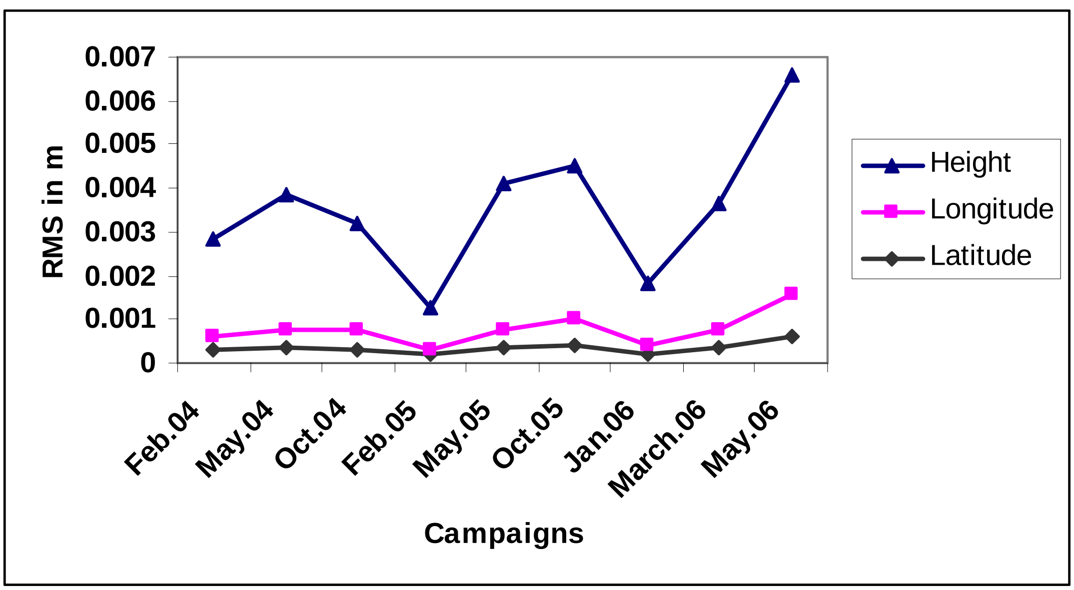


Figure: 2 RMS values for Latitude, Longitude and Height

IV. Results and Discussion

The precision estimated for the coordinates obtained with GPS is shown in Table 1. It shows maximum, minimum and mean 'root mean square' (rms) values for latitude, longitude and height. Mean rms value is the mean of all rms of observed points during all nine campaigns. From the Table 1 and Figure 2, it is observed that the vertical component (Height) is comparatively less precise than horizontal components. Precision estimated for latitude and longitude is 1 to 2 mm and for height 4 to 5 mm for this study.

Statistical Testing for Significance of observed subsidence

For this study, out of nine campaigns, two campaigns have been selected to monitor subsidence over the study area. Two campaigns are May 2004 and May 2006. Based on GPS derived elevation, the elevation differences between two campaigns are calculated and tabulated in Table 2 along with its standard deviation. Negative values are showing subsidence. In order to check the significance of the subsidence values measured by GPS surveys, the congruency test (Abidin et al. 2006) was performed. The null hypothesis H_0 of the test is that the elevation difference between two campaigns (e.g. i and j) are stable, i.e. there is no subsidence and alternate hypothesis H_1 of the test is that the elevation difference between two campaigns (i and j) are not stable (subsidence is taking place).

So

Null Hypothesis $H_0: dh_{ij} = 0$,
Alternative Hypothesis $H_1: dh_{ij} \neq 0$,

The test statistics for this test is:

$$\mathbf{T = \frac{dh_{ij}}{\sigma of dh_{ij}}} \qquad \textbf{(5.1)}$$

Where **dh_{ij}** = Elevation difference between two campaign
σdh_{ij} = Standard Deviation of elevation difference between two campaign

Which has student's t-distribution, if H_0 is true (Points are stable). The region, where the null hypothesis is rejected (Points are not stable) is, where the value of **T** is greater than the value $\mathbf{t_{df,\alpha/2}}$ (from Statistical table).

$$\mathbf{|T| > t_{df,\alpha/2}} \qquad \textbf{(5.2)}$$

Where df is the degree of freedom and α is the significance level used for the statistical test. GPS base lines are derived using 5 hours of GPS data with 15 seconds interval, so the degree of freedom is infinitive. T distribution with infinite degree of freedom is identical to normal distribution. If the confidence level is of 99 % then the value of α is 1%. Hence, the value of $t_{\infty, 0.995}$ is 2.576 from the statistical table (Mikhail and Gracie, 1981). This value is adopted for test and testing results are summarized in Table: 2. The statistical testing is only applied to the negative value of elevation difference. From Table 2, it is clearly seen that calculated values of $\mathbf{T_{12}}$ are greater than the value obtained from table (2.576) except in few cases. Hence Null hypothesis is rejected (No subsidence) and alternate hypothesis (significance subsidence) is accepted at almost all stations. Based on the results, it can be concluded statistically that at 99 % confidence level there were subsidence observed by GPS survey at most of the stations over the study area during May 2004 to May 2006. All stations within reservoir boundary are showing significant subsidence.

Table 2. Estimated Precision of Coordinates and Statistical Testing

Station ID	**Standard Deviation of h_1 in m**	**Standard Deviation of h_2 in m**	**Standard Deviation of Elevation Difference in m**	**Elevation difference in m between two campaigns**	**Calculated Test Statistics**	**Significant Subsidence**
	σh_1	σh_2	$\sigma dh_{(12)}$	dh_{12}	T_{12}	
01	0.0038	0.0044	0.0058	-0.032	-5.50	yes
02	0.0021	0.0030	0.0037	-0.009	-2.46	No
03	0.0020	0.0032	0.0038	-0.007	-1.86	No
04	0.0039	0.0043	0.0058	-0.062	-10.68	yes
06	0.0031	0.0026	0.0041	-0.033	-8.16	yes
07	0.0029	0.0110	0.0114	-0.004	-0.35	No
08	0.0034	0.0042	0.0054	0.027	-	-
09	0.0043	0.0040	0.0059	-0.019	-3.24	Yes
10	0.0038	0.0032	0.0050	0.012	-	-
11	0.0043	0.0028	0.0051	0.035	-	-
12	0.0031	0.0028	0.0042	-0.035	-8.38	yes
13	0.0033	0.0031	0.0045	-0.032	-7.07	yes
14	0.0031	0.0031	0.0044	-0.039	-8.96	yes
15	0.0037	0.0039	0.0054	-0.017	-3.16	yes
16	0.0034	0.0057	0.0066	-0.012	-1.81	No
R1	0.0031	0.0039	0.0050	-0.086	-17.26	yes
R2	0.0020	0.0097	0.0099	-0.129	-13.02	yes
R4	0.0023	0.0033	0.0040	-0.058	-14.42	yes
R5	0.0022	0.0062	0.0066	-0.061	-9.27	yes
R8	0.0023	0.0052	0.0057	-0.062	-10.90	yes
R9	0.0023	0.0051	0.0056	-0.059	-10.55	yes
R10	0.0037	0.0094	0.0101	-0.112	-11.09	yes

Change in Elevation during February 2004 to May 2006

To monitor general trend over the study area, elevations of all deformation stations between two campaigns are compared. For land subsidence study only difference in heights 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. Effective (relative) subsidence is the difference between the average elevation difference of all deformation stations and average elevation difference of reference stations.

From the consistent monitoring of deformation stations over nine campaigns, it has been observed that, in general land is showing downward movement before monsoon and upward movement after monsoon. This is attributed to seasonal water level changes and due to presence of deep black cotton soil in the study area. Black cotton soil is fine-grained clay and subject to significant swelling and shrinkage. It expands, if it is wet and shrinks, if water expel out. Hence these changes in elevation are seasonal. No permanent depletion is observed in water levels.

The effective elevation change of deformation stations within the reservoir boundary during February 2004 and May 2006 is 54 mm downward while for the deformation stations out side the reservoir boundary is only 7 mm. During February 2004 to May 2006, average changes in elevation of stations outside the reservoir boundary are varying from +9 mm to -13 mm, except -59 mm in October 2005. In October 2005, there was an unusual heavy rain fall over the study area. While the average change in elevation of stations within reservoir boundary are varying from + 3 mm to -54 mm during February 2004 to May 2006. Hence, the change in elevation is insignificant out side the reservoir boundary while average elevation change of deformation stations within the reservoir boundary is consistently showing subsidence except in January 2006. The subsidence estimated over the reservoir boundary is significant. Thus it can be said that deformation stations within the reservoir boundary are showing significant vertical deformation compared to deformation of stations outside the reservoir boundary.

Results show that, there is effect of seasons on the GPS derived elevations, so the elevations for the same seasons have been compared to get the real picture of land subsidence over the study area. The elevations of same seasons May 2004, May 2005 and May 2006 have been compared. Results are shown in Table 3. Effective local subsidence is estimated during May 2004 to May 2005 is 41 ± 5 mm and 26 ± 5 mm during May 2005 to May 2006. The precision estimated for vertical height is 4 to 5 mm for this work. So the subsidence calculated may be erroneous by ± 5 mm. The change in elevations during May 2004 to May 2006 is found to be 67 ± 5 mm over reservoir boundary and overall subsidence including deformation stations outside the reservoir boundary is found to be 34 mm. This study was started in February 2004 and to study and monitor land subsidence, two years data are not enough. Hence to predict rate of land subsidence over the study area, extensive study and consistent monitoring will be carried out in future.

Table: 3 Effective Local Subsidence

Campaigns	May 05 - May 06	May 04 - May 05	May 04 - May 06
Effective Local Subsidence for points within Reservoir Boundary	**26 ± 5 mm**	**41 ± 5 mm**	**67 ± 5 mm**

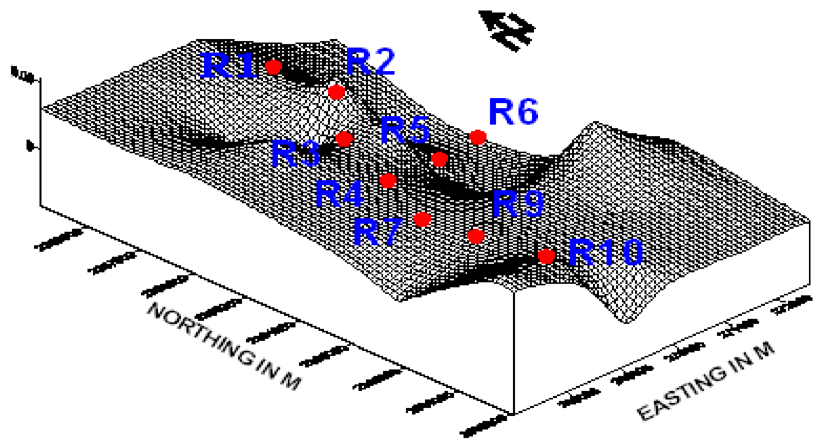


Figure: 3 Three D View of Change in Elevation during Feb 2004 to May 2004

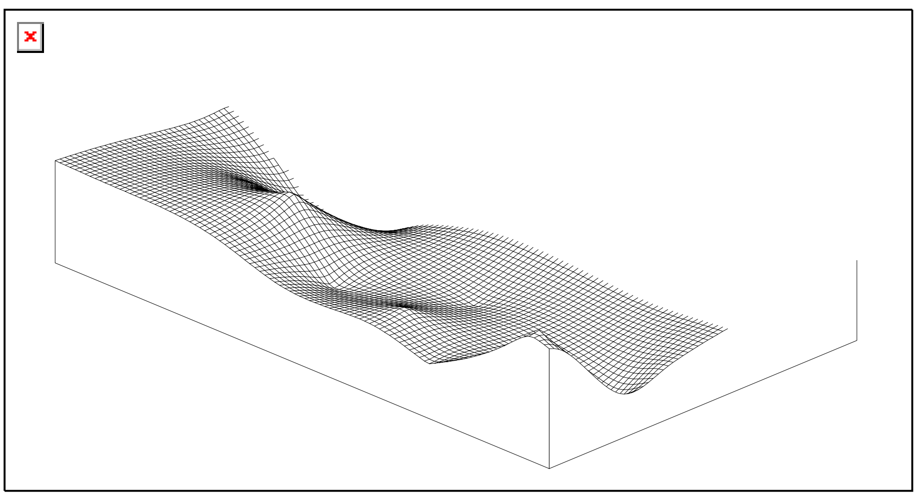


Figure: 4 Three D View of Change in Elevation during Feb 2004 to May 2006

3-D views have been prepared for change in elevation during February 2004 to May 2004 and during February 2004 to May 2006, to observe the area of land subsidence. Figure 3 is showing 3-D view for change in elevation during February 2004 to May 2004. There was no significant change in elevation observed during February 2004 to May 2004. During this period almost all deformation stations have shown upliftment. Hence, it can be said that, subsidence was not observed, before the hydrocarbon production started. It is clearly seen from Figure 4 that change in elevation is more on northern side of the study area during February 2004 to May 2006. More numbers of gas extracting wells are located on the north side of the reservoir. Maximum pressure is depleted at R2 station by 0.804 N/mm^2. Maximum change in elevation was also calculated about 9 cm at R2 station. Hence, it can be concluded that maximum subsidence is experienced where maximum pressure depletion is observed. On the south side of the reservoir boundary, less gas extraction was recorded compared to north side. Only one gas producing well is situated on south side of the reservoir, hence less subsidence is observed on south side compared to north side. Central part of the reservoir is showing less subsidence compared to north and south side of the reservoir boundary. Pressure depletion at R7 well point is lowest 0.396 N/mm^2. Therefore it is established that subsidence is less, where the pressure depletion is less. Total two bowl shaped depressions have been created, one is on north side and another is on south side of the reservoir boundary.

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 literature, that the central area of the reservoir generally shows more subsidence compared to surrounding region. 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**.**

V. Conclusions

GPS has overcome the limitations of conventional levelling, hence is widely used for precise geodetic work. In India GPS is being used for crustal deformation studies; however land subsidence monitoring using GPS has not been reported in literature. Probably, this is the first attempt in India to measure land subsidence with GPS. The accuracy of GPS derived vertical components is 4-5 mm and 1-2 mm for horizontal components. This accuracy is adequate to detect and monitor subsidence rates that are usually measured in the magnitude range of centimetres per year. Accuracy of GPS derived coordinates depends on the GPS network, design of monuments, quality of data, data collection time, processing technique used etc. For this study, data was collected very precisely with dual frequency geodetic GPS receiver. To improve the quality of data, special care has been taken for monument design, data collection time etc. Data processing has been done in post processing mode with scientific software using precise ephemeris files, so results obtained are precise. Hence, it can be concluded that GPS technique is reliable technique for monitoring and measuring land subsidence.

From the consistent monitoring of deformation stations over nine campaigns, it has been observed that, in general land is showing downward movement before monsoon and showing upward movement after monsoon. This can be attributed to seasonal change in water level. No permanent depletion in water level has been observed over the study area. Hence, the observed subsidence can not be attributed to ground water extraction. The results of statistical test show that subsidence values obtained by GPS survey are significant. It is concluded that deformation stations within the reservoir boundary are showing significant vertical deformations compared to the stations outside the reservoir boundary. Average subsidence over the study area is found to be 34 mm during two years. Subsidence is found to be 67 mm within reservoir boundary during two years.

Two subsidence bowls were observed, a big subsidence bowl was observed in the area, where more numbers of gas extracting wells are situated. Significant subsidence is observed, where more gas is extracted and insignificant subsidence estimated in the area, where less amount of gas is extracted. Hence gas extraction is one of the main causes of land subsidence over the study area. To study and monitor subsidence and to find the rate of subsidence, extensive monitoring for longer duration is required. In future, rigorous monitoring will be carried out to find the rate of subsidence and measured subsidence will be co-rrelated with other parameters responsible for subsidence like pressure depletion, water extraction, gas extraction rate etc. In future other geodetic techniques like levelling and Synthetic Aperture Radar Interferometry (InSAR) will be implemented to validate GPS results.

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