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Monitoring land subsidence over a shallow gas reservoir in India using GPS

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Abstract Subsidence is one of the most significant results of reservoir compaction due to extraction of gas/oil. It is difficult to predict the subsidence as it takes place well below the ground surface. Therefore, the prediction of subsidence is a challenging task. Subsidence measuring techniques should be such that they are capable of detecting even 1-mm level change in elevation. With the advancement of space technology, subsidence measurement is being carried out using Global Positioning System (GPS). Subsidence studies have been carried out over the shallow gas reservoir in Gujarat, India. A precise GPS network was established in 2004. Dual-frequency GPS receivers were used to collect the data. A significant amount of subsidence, 86 mm, was observed along with the horizontal displacement. Subsidence is correlated with the parameters responsible for subsidence. The coefficient of compaction is estimated from the subsidence. Subsidence is predicted over this area using empirical methods.

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Key words GPS, land subsidence, prediction

INTRODUCTION

Subsidence monitoring techniques should be capable of measuring small change in elevation within a short period. With the development of space technology, now GPS is used to measure land subsidence. GPS is capable of giving millimetre-level accuracy with a geodetic dual-frequency receiver, longer data collection time and data processing with scientific software in post processing mode. Many scientists worldwide have tried to measure subsidence with GPS. Notable are subsidence studies in Jakarta, Indonesia (Abidin *et al.*, 2006), in Ojiya city, Japan (Sato *et al.*, 2003) and in Iran (Mousavi *et al.*, 2001). In this study, subsidence is measured over the shallow gas reservoir in Gujarat, India, by the author along with the IIT Bombay GPS team. Significant subsidence of 86 mm is observed during the period of three years with GPS. Gas extraction is considered as the main cause of subsidence in this region. Pressure depletion is observed in reservoir area, where greater subsidence is measured. Other factors responsible for subsidence, such as the amount of gas extraction and water extraction have been studied rigorously; the study results indicate that there is a definite correlation between gas extraction and pressure depletion with subsidence. An attempt has been made to establish certain empirical methods to predict the subsidence over the study area using the reservoir parameters. Arguably this is the first attempt in India to measure subsidence with GPS.

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STUDY AREA, GPS DATA COLLECTION AND PROCEDURE

The subsidence study was carried out over the 14 km^2 shallow gas reservoir, on the north side of the Surat, Gujarat, India. The potential gas-producing zone consists of two unconsolidated sandstone layers, located at between 170 and 240 m below the ground surface. This study has been carried out to understand the subsidence pattern, which may have an adverse effect on the safety of the villages and infrastructure lying above the reservoir.

A precise GPS network of 31 stations (4 Reference and 27 Deformation) has been established. Out of 27 deformation stations, 10 are within the presumed reservoir boundary and the rest are outside. In total, 12 GPS campaigns were carried out between February 2004 and March 2007 at intervals of 3 to 4 months. Dual frequency GPS receivers were used to collect the data. The reference stations were running continuously during the entire field campaign. At each deformation station, at least five to six hours of continuous GPS data were collected during each campaign. Figure 1 shows the details of the deformation stations.

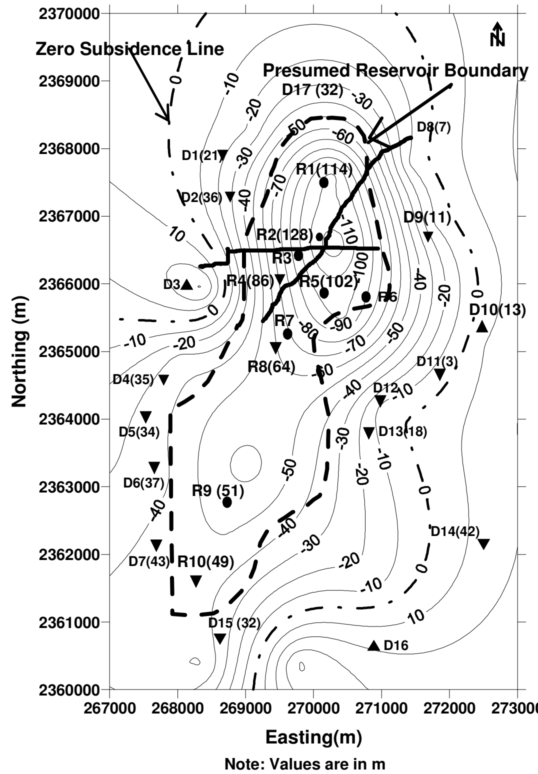

Fig. 1 Contours showing change in elevation (February 2004 to March 2007). (Note: ▼ Subsidence stations, ▲ Uplift stations, ● Stations near gas wells showing subsidence, ——— Contour lines, — — — zero subsidence line. Values in parentheses indicate uplift/subsidence. D1 to D17 are deformation stations outside the reservoir boundary and R1 to R10 are deformation stations within the boundary).

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The GPS data was processed with BERNESE V4.2 in post processing mode. Three IGS (International GNNS Service) stations (LHAS, BAHR and IISC on three different plates) were selected for constraining the solutions in the ITRF 2000 (International Terrestrial Reference Frame 2000). The precise ephemeris files were also used. Data from a permanent GPS station located at IIT Bombay were also used for this study. The factors that affect the vertical accuracy were taken into account while processing data in post-processing mode, such as satellite geometry, tropospheric and ionospheric correction, and ocean loading effects. During processing, first, precise coordinates for three IGS stations were tightly constrained. Then, the averages of the daily solutions per campaign were determined using the ADDNEQ programme in BERNESE V4.2, and the coordinates of the reference stations thus obtained were used for the second stage. In the second stage, to get the coordinates of all 27 deformation stations, two reference stations and the IITB station were tightly constrained.

ANALYSIS OF SUBSIDENCE

GPS-derived ellipsoidal heights have been used (Abidin *et al.*, 2006) to measure the subsidence. The accuracy of GPS-derived coordinates is quite good, being 3–5 mm for horizontal coordinates and 5–8 mm for heights. This accuracy is adequate to detect and monitor subsidence. In the present GPS network, the lengths of all baselines are less than 25 km, hence the precision estimated for latitude and longitude is 1 to 2 mm and for height, 4 to 5 mm.

To eliminate the effect of swelling/shrinking on elevations due to the top 4–5 m deep layer of expansive black cotton soil, the elevations in the season just prior to monsoon (May 2004, May 2005, May 2006 and March 2007) were compared. To calculate the subsidence, the results of these four campaigns are compared. Average changes in elevation with respect to May 2004 are calculated for the May 2005, May 2006 and March 2007 campaigns using equation (1):.

$$(\Delta h)_{i,j} = h_{i,j} - h_{i,1}[i = 1, n;\ j = 1, m] \quad (1)$$

where, $(\Delta h)_{i,j}$ is change in elevation at station i from (1 May 2004) to the jth campaign, n is the number of deformation stations and m is the number of campaigns. Thus, the average subsidence for any campaign j can be written as:

$$\left[(\Delta h)_{i,j}\right]_{av} = \frac{\sum_{i=1}^{n} (\Delta h)_{i,j}}{n} \quad (2)$$

The effective subsidence is the difference between the average subsidence of the deformation stations of the area and the average subsidence of the reference stations and is calculated as:

$$\left[(\Delta h)_{i,j}\right]_{eff} = \frac{\sum_{i=1}^{n} \Delta h_{i,j}}{n} - \frac{\sum_{k=1}^{r} \Delta h_{k,j}}{n} \quad (3)$$

where i = 1, n; j = 2, m; k = 1, r, and r is the number of the reference stations. The results are shown in Fig. 2. It is seen that, cumulative effective subsidence is 86 mm during May 2004 to March 2007 and the corresponding rate of subsidence is 30 mm per year.

Subsidence contours

To evaluate the subsidence, contours of change in elevation during May 2004 to March 2007 are plotted along with the deformation stations and approximate reservoir boundary superimposed on them (see Fig. 1). It is observed from the contour map that change in elevation is greater on the north side of the study area during May 2004 to March 2007. Two subsidence bowls have been produced, one relatively larger, in the north and a smaller one south of the reservoir. This confirms to the fact that five out of seven gas-producing wells (R1, R2, R3, R5 and R6) were on the north side leading to greater pressure depletion. Only one gas producing well (R9) is located on the south side, and the effect of subsidence is not significant. The local horizontal displacements between two successive campaigns are obtained by subtracting the velocity vector (displacement of Indian plate) during the same time interval from the total displacement observed with GPS. The local displacements of most of the stations are towards the centre of the reservoir. This supports the conclusion that subsidence is taking place in the observation area.

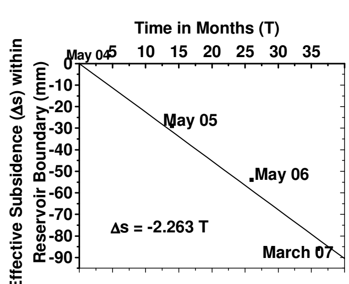

Fig. 2 Cumulative effective subsidence (May 2004 to March 2007).

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Relation of subsidence with parameters responsible for subsidence

The volume of gas extraction, the pressure depletion and water level change are the main parameters responsible for subsidence over the present study area. Hence, an attempt has been made to evaluate and model their effects on subsidence.

The relation between the average reservoir pressure and cumulative gas volume extracted from all wells at different points of time from May 2004 to June 2007 is studied to understand the correlation between them. A linear relationship with a correlation coefficient of 0.99 exists between these quantities. Mayuga & Allen (1969) have reported a close correlation between cumulative subsidence and cumulative extraction of gas and oil for California's largest oil field. In the present study, a linear relation with a high correlation of 0.86 was observed between cumulative land subsidence (Δs in mm) and cumulative gas extracted (G in m^3).

To find the relation between subsidence and pressure depletion, the total pressure depletion (Δp) for each campaign with respect to May 2004 and corresponding subsidence values (Δs) for the same wells are plotted. This shows that subsidence is increasing with increase in pressure depletion and linear relationships are observed. In short, pressure depletion is the major cause of subsidence. To determine the relation between subsidence and water level, the average water levels of six different gas wells for campaigns starting from October 2004 were measured along with the corresponding average ellipsoidal heights for the same gas wells. No permanent depletion in water level was observed over the study area. But, there is a consistent reduction in the average ellipsoidal height. Thus, subsidence is not influenced by water level.

Prediction of subsidence over the study area

Experienced from observed data and predicted subsidence values shows that subsidence prediction based on laboratory tests often does not give realistic values. Hence, an attempt has been made to predict the subsidence over the existing gas reservoir based on the actual field measurements. Here, two different methods are suggested to predict subsidence over the study area. Attempt has been made to find out correlation between land subsidence and gas extraction. Figure 3(a) shows cumulative gas extraction and subsidence with respect to May 2004.

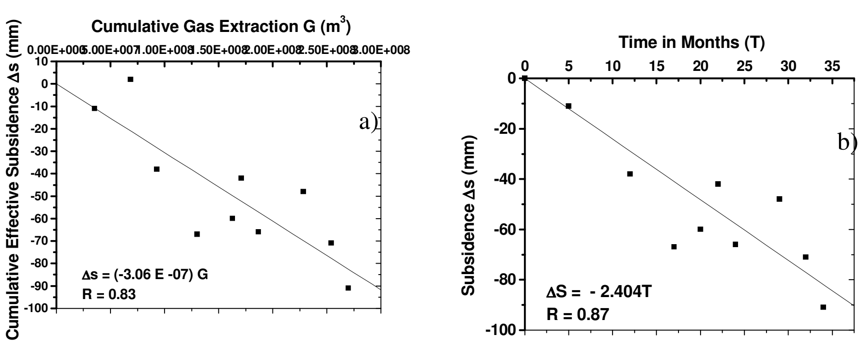

Fig. 3 (a) Relations between cumulative effective. (b) Relation between cumulative subsidence with cumulative gas extraction effective subsidence and time.

Subsidence may be predicted as a function of gas production using equation (4). The correlation coefficient between these parameters was observed to be high (0.83).

$$\Delta s = -(3.06E - 07)G \tag{4}$$

In another method, the available GPS data are extrapolated to derive the future trend. The amount of subsidence is plotted against time expressed in months in Fig. 3(b). Equation (5) can be used to predict subsidence (Δs) with time T (months) in this study.

$$\Delta s = -(2.40)T \quad (5)$$

Estimation of the uniaxial compaction coefficient

Subsidence is a manifestation of reservoir compaction on the surface of the earth. Three main parameters are responsible for reservoir compaction: uniaxial compaction coefficient (C_m), pressure depletion of reservoir (Δp) and the initial thickness of the reservoir (H). Here an attempt has been made to find the value of C_m, assuming that, for a shallow reservoir, the amount of subsidence is equal to reservoir compaction.

To arrive at an average value of C_m for the entire study area, all values of subsidence and the corresponding values of [(Δp) H] for all wells and for all campaigns were plotted as shown in Fig. 4. Regression analysis was carried out and a linear relationship was observed to be suitable to relate these parameters. Equation (6) is obtained after regression analysis.

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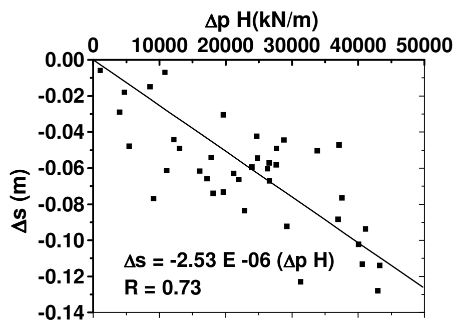

Fig. 4 Average C_m for all wells and all campaigns.

$$\Delta S = -2.53E-06[(\Delta p)H] \quad (6)$$

The value of C_m obtained from this graph is 2.53 E-06 m^2/kN. This value is very near to the values suggested by Geertsma (1973) for loose soil. C_m is calculated as 2.7E-05 m^2/kN using the laboratory measured Poisson's ratio (0.33) and modulus of elasticity (2.50E 04 m^2/kN). It is observed that, the theoretical C_m is almost more than ten times the value obtained with GPS. Hence, it is concluded from the study that laboratory measured C_m is always higher than the field value (Cassiani & Zoccatelli, 2000).

CONCLUSIONS

With accurate planning of the GPS survey, a good level of precision can be achieved (1 to 2 mm) for horizontal coordinates. The vertical accuracy of the GPS-derived results is half of the horizontal accuracy, i.e. 4 to 5 mm. this accuracy is enough to measure the subsidence.

verage effective subsidence during May 2004 to March 2007 was 86 mm for stations within the presumed reservoir boundary and 20 mm for stations outside. Hence, the rate of subsidence within reservoir area is 30 mm per year.

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A subsidence bowl of approximately 4 km diameter was observed in the north where more gas wells are located, and a small one of approximately 2 km diameter on the south side of the reservoir. In general, local displacements of the stations are towards the centre of the reservoir.

Subsidence is directly related to the amount of gas extracted and resulting pressure depletion. A linear relationship is observed between cumulative gas extraction and average reservoir pressure. A linear relationship with a correlation coefficient of 0.83 exists between subsidence and cumulative gas extraction. A linear relationship is observed between pressure depletion and subsidence.

Subsidence can be predicted based on actual field measured data as experience shows that subsidence prediction based on laboratory test often does not give realistic values.

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