USE OF GPS FOR SUBSIDENCE MONITORING IN THE INDIAN CONTEXT—
A CASE STUDY

P.R. Patel
Associate Professor, Department of Civil Engineering, Nirma University, Ahmedabad, India.

E.P. Rao
Associate Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai–400 076, India.

G. Venkatachalam
Emeritus Fellow, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai–400 076, India.

ABSTRACT: Here, a case study of subsidence measurement in the shallow gas reservoir area of Olpad region, Gujarat, using Global Positioning System (GPS), is presented. The areal extent of the study area is about 20 km². A GPS network of a total of 31 subsidence monitoring stations was used to carry out twelve campaigns during February 2004 to March 2007 at an interval of 3 to 4 months. Geodetic GPS receivers were used to collect data and scientific software BerneseV.4.2 was used for processing. The GPS results show a total subsidence of about 83 mm. Uniaxial compaction coefficient (Cm) is the prime parameter controlling the reservoir compaction. This paper highlights the difficulties in getting reasonable values of compaction coefficient from prevailing approaches and recommends that it be calculated from GPS data rather than from laboratory samples. This estimated Cm for the present area can be used to predict the subsidence at different points of time for different values of pressure depletion for this unconsolidated shallow gas reservoir.

1. INTRODUCTION

Subsidence is defined as gradual sinking of ground surface due to natural or man-made causes like sub-surface reservoir exploitation. The basic mechanics of reservoir compaction and subsequent surface subsidence is fairly simple. Initially, the weight of overlying sediments of the reservoir is partly supported by the soil matrix and partly by the oil/gas present in the pores. Due to extraction of gas/oil, pore pressure (p) declines and overburden load is transferred to the soil matrix. If the reservoir soil is compressible, then volume of the reservoir decreases. The actual land settlement depends primarily on depth, thickness and compressibility of the reservoir and adjacent formations. Other major factors affecting the surface subsidence are porosity, permeability, fluid properties, production volume and pressure depletion (Whittaker & Reddish, 1989; Settari, 2002).

However, the most fundamental parameter, which controls the amount of compaction, is the Compaction Coefficient (Cm). For monitoring subsidence, a reliable value of Cm is needed. In practice, it is quite satisfactory to assume one-dimensional compaction. There are evidences in literature that, laboratory measured soil compressibility values are usually overestimated particularly when soil mass is unconsolidated (Geertsma, 1973). Rigorous theoretical evaluation of Cm from observed data is also quite involved owing to the complexity of the phenomenon of subsidence. Literature suggests that, to find the value of Cm, field measurements are more reliable than laboratory methods. Therefore, an alternative method, which gives reasonable estimates using simple computation procedures is required. In the present study, Global Positioning System (GPS) measured subsidence values have been used and an attempt has been made to estimate uniaxial compaction coefficient for the present study area and to compare it with the laboratory measured Cm.

2. GPS DATA COLLECTION & ANALYSIS

Perhaps the first reported incidence of subsidence was by two geologists (Whittakar & Reddish, 1989), Pratt and Johnson, in Goose Creek, S. Jacinto Bay, Texas due to oil, water and gas extraction during 1900–1920. Over the years, subsidence has become one of the important subjects of research. The early conclusion of Pratt and Johnson was confirmed later by innumerable examples of anthropogenic subsidence. The Boliwar coast oil fields, Venezuela experienced subsidence during 1920’s. Also mentioned are Gilluly and Grant’s observed subsidence over the Wilmington oil field, Long Beach, California during 1930’s and Schoonbeck’s reported subsidence in Groningen gas field, Netherlands. Martin & Serdengecti (1984) observed subsidence in Huntington Beach oil field of California. Subsidence was also reported in the oil fields of Ilijn USSR in 1977 (Whittakar & Reddish, 1989). However, reported information on subsidence in these reservoirs is virtually
absent. In any case, GPS measurements do not seem to have been used.

Thus, probably for the first time in India, in the present study, subsidence was measured over the shallow gas reservoir in Olpad region, Gujarat state by IIT Bombay team using Global Positioning System. A precise network of 31 GPS stations was established over the study area in February 2004. A schematic layout of all the stations including the Reference and subsidence measurement stations is presented in Figure 1. In all, twelve GPS campaigns were carried out during the period of three years up to March 2007 at an interval of 3 to 4 months. Each fieldwork period spanned approximately one week. Dual frequency geodetic GPS receivers were used to collect the data. Reference stations were running continuously during the entire field campaigns of GPS data collection. At each deformation station, minimum five hours of continuous GPS data was collected. The data processing was done using scientific software Bernese V4.2 in post processing mode using precise ephemeris data. These data were downloaded from IGS website. SAASTAMOINEN model was used for tropospheric correction and L1 and L2 frequencies were combined for ionospheric error free solution.

**2.1 GPS Results**

The GPS results show a total subsidence of about 83 mm during February 2004 to March 2007 within the presumed reservoir boundary. The rate of subsidence is thus estimated as 27 mm/year within reservoir boundary. Keeping in mind the possible effect of season, GPS data was collected by repeated observations; this included data collection in dry season, usually in May, and after monsoon, in October. Usually water level rises after the monsoon. The water levels remain close to maximum up to December and January and then start to drop. During May usually water level is found to be minimum. The results of only May campaigns show the subsidence of 86 mm with subsidence rate of 30 mm/year.

Other data like reservoir pressure data, reservoir temperature, volume of gas extraction, geology and soil properties of the study area are equally important for the rigorous study of the land subsidence. Petro-physical properties and geology of reservoir were referred from Fekete (2003). Amount of gas extraction, surface pressure data, water levels were collected. Darcy Reservoir Company, Ahmedabad (Darcy, 2006) had supplied Reservoir pressure data. Consistent pressure depletion is also observed in the present gas field.

**3. ESTIMATION OF C_m**

Prediction of subsidence is important for the safety of infrastructure lying above the reservoir. Subsidence occurs mainly due to pressure depletion (Δp), the dimensions of the reservoirs and uniaxial compaction coefficient (C_m) of the reservoir, which is obtained either in the laboratory or in-situ measurement. Laboratory measurements are carried out by oedometer test. Estimation of reliable value of C_m is the most crucial task. The results of laboratory analysis usually overestimate the C_m, when compared to in-situ measured C_m particularly for unconsolidated soil mass. Hence, for the subsidence study, field measurements are important (Cassiani & Zoccatelli, 2000)

### 3.1 Using One-dimensional Compaction Theory

To estimate the reservoir compaction, a simple one-dimensional analytical estimate of reservoir compaction can be derived. Reservoir of thickness H compacts in the vertical direction in an elastic manner and vertical stress remains constant (no arching) and if reservoir experiences the pressure reduction (Δp), then by applying simple linear elastic theory with constant Modulus of Elasticity (E) and Poisson’s ratio (υ), vertical strain can be calculated as,

\[ \Delta \varepsilon = \frac{\Delta H}{H} = - \alpha C_m \Delta p \]  

(1)

where \( \alpha \) is Biot’s constant, considered as unity and \( \Delta H \) is reservoir compaction. Vertical strain is expressed generally through the uniaxial compaction coefficient (C_m), where

\[ C_m = \frac{[1 + \nu] (1 - 2 \nu) / (1 - \nu)}{E} \]  

(2)

For the present study area, Golder Associates Ltd. (Taurus, 2003) had carried out laboratory tests for soil compressibility before the starting of hydrocarbon production. A Poisson’s ratio (υ) of 0.33 was assumed for the material. For calculation of C_m, Modulus of Elasticity was considered as 25000 kN/m², giving an estimated C_m of 2.70E-05 m²/kN. Corresponding subsidence (As) was 953 mm (for \( \Delta p = 905 \) kN/m² and \( H = 39 \) m) by considering subsidence equal to reservoir compaction for a shallow gas reservoir (Martin & Serdenegecti, 1984), while field measured subsidence with GPS technology is only 86 mm during May 2004 to March 2007.

### 3.2 Using GPS Measured Subsidence

To begin with, to find the average value of C_m, average value of subsidence over the entire study area and the corresponding

![Fig. 1: Schematic Layout of Deformation and Reference Stations (Kulkarni & Patel, 2007)](image-url)
average \( \Delta p H \), for all campaigns are calculated and plotted in Figure 2. This gives an average value of \( C_m = 1.84 \times 10^{-6} \text{ m}^2/\text{kN} \) based on GPS measured subsidences.

![Figure 2: Average \( C_m \) for All Wells and All Campaigns](image)

### 3.3 Using Nucleus of Strain Method

The “Nucleus of Strain Method” was developed by Geertsma (1973) to calculate the surface subsidence for a disc shaped reservoir of thickness \( H \) and radius \( R \) at depth \( D \) for a uniform reservoir pressure reduction \( \Delta p \) throughout the reservoir. \( C_m \) and \( v \) values were assumed uniform throughout the reservoir. In this technique, the volumetric strain at a point in reservoir caused by a local reduction in pore pressure is treated as a centre of compression in an elastic half-space that produces a subsidence at the surface. By integrating the contributions of all the compression points over the reservoir, the subsidence developed by reservoir pressure reduction can be calculated. The following Equations were suggested by Geertsma to find out the subsidence over the reservoir area.

\[
\text{Subsidence} = \frac{-2(1-v)A}{\text{Reservoir Compaction}}
\]

\[
\Delta s = - C_m H \Delta p \{2(1-v)A\}
\]

\[
C_m = \frac{-\Delta s}{\Delta p H \{2(1-v)A\}}
\]

where value of \( A \) depends on two dimensionless ratios \( \rho = r/R \) and \( \eta = D/R \), \( r \) is the radial distance from the centre of the reservoir to the point, at which subsidence is observed. The following method is proposed for calculating \( C_m \) using Nucleus of Strain Method.

#### 3.3.1 The Basis of the Method

In this Method, a rigorous evaluation of effect of each well on each deformation station is carried out and added and then an average value of \( C_m \) is calculated. For this purpose, nine stations are selected around the reservoir, five on East side of the reservoir and four on the West. These are divided into two sets – Calibration and Validation sets. The extreme and the middle stations are chosen on either side of the reservoir for Calibration and other stations are used for Validation. At each station, the subsidence value is measured with GPS. This measured value \( (\Delta s)_i \) is compared with the subsidence value \( (\Delta s)_{CUM} \) calculated at station \( i \) using nucleus of strain method. Here, \( (\Delta s)_{CUM} \) is the cumulative subsidence at station \( i \), i.e., the sum of subsidences induced at station \( i \) due to each of the wells \( g \).

\[
(\Delta s)_{CUM} = \sum_{g=1}^{A} (\Delta s)_{i,g}
\]

\[
(\Delta s)_{i,g} = C_m H \Delta p \{2(1-v)A\}
\]

where \( i = 1, n \) and \( n \) is number of stations. \( H \) is the thickness of the reservoir measured at the well and \( \Delta p \) is the pressure depletion measured at the well. The values of ‘\( A \)’ are calculated based on two dimensionless parameters \( \rho = r/R \) and \( \eta = D/R \) (Geertsma, 1973). Using Equation (8), we can compute \( C_m \).

\[
(\Delta s)_{GPS} = (\Delta s)_{CUM}
\]

#### 3.3.2 Calibration

Finally, \( C_m \) is calculated for each Calibration station for radius of reservoir of 2000 m and 2500 m using Equation (5). For reservoir radius of 2000 m, the \( C_m \) obtained for different stations are ranging from 3.89E-08 to 2.63E-06 m²/kN and the average value obtained is 8.73E-07 m²/kN. For reservoir radius 2500 m, the \( C_m \) obtained for different stations are ranging from 2.83 E-08 to 1.27E-06 m²/kN and the average value obtained is 3.16E-07.

#### 3.3.3 Validation

The average values of \( C_m \) obtained from GPS measurements are now used in equations (6) to (8) to calculate \( (\Delta s)_{CUM} \) for the Validation stations. These are compared with the corresponding GPS measured subsidences at these stations. The comparison shows that the predicted results are in good agreement with the GPS measured values for reservoir radius of 2500 m, which corresponds to an area of approximately 20 km² and agrees with the area extent within the presumed reservoir boundary.

These values vary widely, as is inevitable in a real situation such as this. However, value of \( C_m \) obtained by the proposed relatively rigorous Method is recommended for use for this study area for prognosis of subsidence.

#### 3.3.4 Comparison of Three Methods

a. Laboratory measured \( C_m \) is estimated as 2.70E-05 m²/kN.

b. Average \( C_m \) based on GPS measured subsidence for all wells and campaigns is 1.84E-06 m²/kN.

c. From Nucleus of Strain method, assuming subsidence ≠ compaction, by proposed Method, Average \( C_m = 3.16 \) E-07 m²/kN.
d. Hence for subsidence monitoring in this reservoir in the future, this value of $C_m$ is recommended.

3.3.5 The Indian Context

The use of GPS for subsidence measurement is not widely adopted in India. In fact, monitoring of subsidence and its adverse effects have not been addressed seriously yet. Thus, implementation of a scheme such as this is beset with several difficulties.

The lack of infrastructure development in areas where reservoir exploitation is carried out, the poor awareness of its consequences and occasional vandalism make it equally difficult to install and maintain the GPS stations and ensure their safety and security. There are other causes such as presence of electrical posts which interfere with the signals, the seasonal inundation of the area, inaccessibility due to obstacles such as vegetation growth. The movement of the station itself due to the subsidence is another problem. This is unavoidable, since the reservoir boundary is not precisely known and a station might lie within the region of subsidence.

It is, therefore, worth mentioning that, some of the well data could not be used because of problems typical of such field monitoring. For two of the gas wells are not used in Figure 2. GPS data for one well was not reliable due to high RMS error. The GPS station at this location was shifted to another location in January 2006. Gas extraction from the other was started only in May 2005. Hence, GPS data is not available for this station beyond January 2006.

These aspects are taken into account in the present study and only data of reliable stations has been used.

4. CONCLUSIONS

The present study shows:

1. For accurate prediction of land subsidence, reliable value of $C_m$ is required. Radioactive marker method is widely used in the field to estimate $C_m$. But in the absence of radioactive marker method, GPS measured subsidence can be used to estimate the $C_m$ for the present study area.

2. A comparison of the three methods described above shows that the proposed Method is rigorous and fairly accurate for subsidence prediction in the given study area based on GPS measurements. However, reservoir shape is irregular and hence, it is difficult to estimate the exact shape from this equivalent radius of the reservoir. Nevertheless, this $C_m$ can be used to predict the subsidence from time to time for different values of $\Delta p$ using Equation (2), for this study area. It must be noted that, this has to be applied with caution to any area with a different geological setting.

ACKNOWLEDGEMENTS

The authors are grateful to Late Prof. M.N. Kulkarni, under whose guidance and supervision the entire GPS campaign was carried out. Thanks are due to Mr. Shashank Shekar and Mr. D. Borgohain for data collection required for research work. We are also grateful to entire IIT Bombay GPS team for Field work for the twelve campaigns. The valuable help given by Mr. A. Kulkarni of SAMEER and Dr. C.D. Reddy of IIG in processing the data are gratefully acknowledged.

REFERENCES


Taurus. (2003). “Pre-production Assessment of the Potential for Subsidence Due to Shallow Gas Production (Surat block)”, prepared by Taurus Reservoir Solutions Ltd, Canada, for Niko Resources India Limited, Personal Communication.