Integrated Geophysical and Geotechnical Study of a Southern Oil and Gas Field in Western Offshore, India

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Abstract. The field under study is located towards the south of petroleum producing area of western Indian offshore. The field was initially partly developed and redevelopment has been started in recent years. During the initial and redevelopment phases, many geotechnical investigations and geophysical surveys have been performed. A collated data study of old and new Geophysical and Geotechnical data was done with the objective to establish the field wide identification of different soil strata and their engineering parameters. The engineering parameters established from this study will help to verify the reasonability of newly measured in-situ and laboratory parameters. They can also be used to optimize the costly field and laboratory testing programmes. Moreover, this study will help in assessing soil conditions and assigning design parameters for upcoming Geotechnical investigations where either data are inadequate or missing. In this paper, the results and conclusions inferred from the integrated study, shallow geologic and geotechnical conditions of the field are presented.

Keywords: Geophysical; Geotechnical; Integrated; Optimizing; Characterization.

1 Introduction

To augment its hydrocarbon production, ONGC started the redevelopment of one of its field, located towards the south of petroleum producing area of western Indian offshore. The redevelopment involves the installation of a few offshore platforms, pipelines and cables. The pre-engineering surveys of the said field redevelopment had detailed Geophysical surveys and Geotechnical investigations. Geophysical surveys were performed with the aim to identify hazards, which could affect the safety of the infrastructure. The other objectives achieved from Geophysical survey were: collecting the bathymetry data; understanding the seafloor features, shallow geology; and map the existing infrastructure. The Geotechnical investigations were performed with the aim to estimate the design parameters and soil conditions for design and installation of structures.

Reasonably large amount of data from old and new investigations exists and hence, a collated study of old and recent data was done, with the aim to understand the field wide stratigraphy and soil conditions. This paper presents various results and conclusions inferred from this study.

1.1 Origin of Soils in Indian Offshore

The continental shelf on western Indian offshore is wide, around 200 km. In the eastern offshore it is narrow, with 40 km approximate width. The soils in Indian offshore are either terrigenic or pelagic origin. The terrigenic soils originate on land and transported to the sea. The ocean environment by its mechanisms such as cementation at times alters the terrigenic soils. The pelagic soils originate from biological remains of sea organisms either by mineral or chemical precipitation. Sometimes these soils can also get modified from the actions of the ocean environment [1].

2 Data Considered for The Study

Data of 2 Geophysical surveys and 64 Geotechnical investigations for the platform, pipelines (development) and jack-up rig (exploratory) locations are available from the past and present pre-engineering surveys. Of the two geophysical surveys, the recently performed Geophysical survey has more comprehensive information than the survey performed in the initial phase of field development.

The Geotechnical data available has final soil investigation reports done for platforms, pipelines and jack-up rigs in hard copy from the initial phase. The data from redevelopment has data in digital form also e.g. measured CPTU (cone penetration test with pore pressure measurement) data. A few exploratory locations are very far from others; hence the data of these locations are excluded from the study.

3 Review of Geophysical Survey Data

Various tools were used to perform Geophysical survey during the initial and recent field development. The tools used are Multibeam Echosounder, Sidescan Sonar, Sub-bottom profiler, and Magnetometer. The Multibeam Echosounder survey helps to assess the topography/bathymetry; the Sidescan Sonar survey is used to get a photo like image of the seafloor; the Sub-bottom profiler aids to know the stratigraphy; and the Magnetometer identifies metal objects at or just below the seafloor. The study of these survey results shows that major hazards which may hamper infrastructure development are not present in this field. Important observations from the Geophysical survey in comparison with geotechnical data are presented in the following sections.

3.1 Topography of Field

Water depths measured by echo sounders, bathymetry data from the Geophysical survey and bathymetry data from NOAA (National Oceanic and Atmospheric Administration) USA database were studied together to understand the overall topography of the field. All the new and old (exploratory, development) locations, where geotechnical investigations were carried are plotted against contours of the field (see Fig. 1). The 3D surface of the field generated from NOAA data is shown in Fig. 2. By observing the contours and the 3D surface of the field, it can be inferred that the field (where most of the exploratory and development locations are) has a gentle slope towards west and southwest direction.

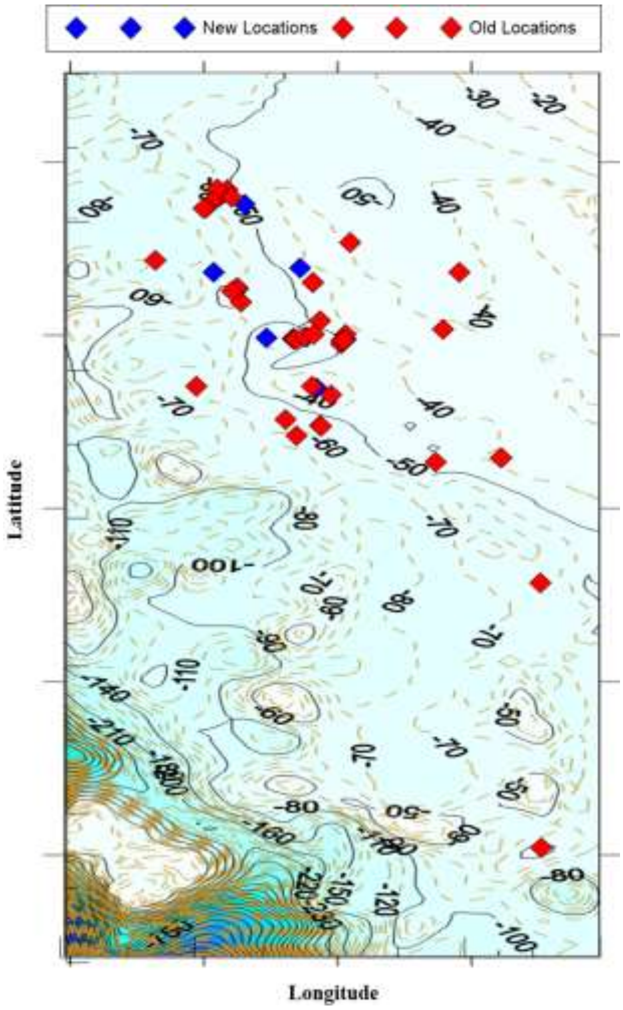

Fig. 1. New and Old Geotechnical Investigation Locations with Respect to Contours

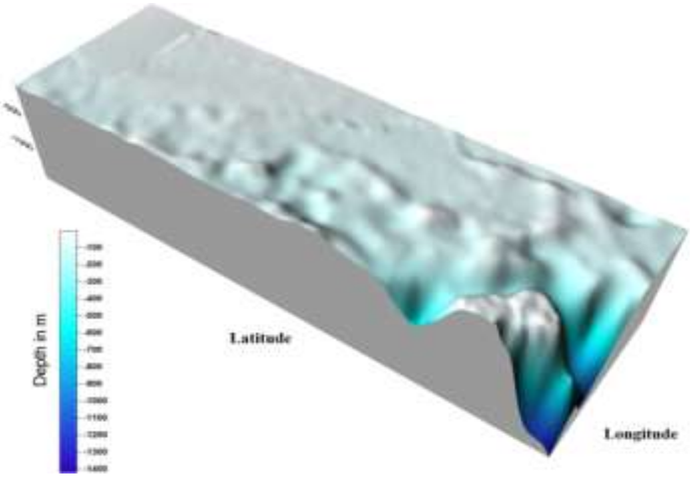

Fig. 2. 3D Surface of Field Generated from NOAA (USA) Data

3.2 Seabed Sediments, Features and Sonar Contacts

The interpretation of acoustic reflectivity of the sidescan sonar data helps to identify the soil present at the seafloor. The sidescan sonar data of the present field were studied; low to medium reflective surficial sediments are interpreted as CLAY and medium reflective sediments can be interpreted as SAND (see Fig. 3). Furthermore, few seabed scars/anchor drag marks, depressions and sonar contacts like debris, wellheads, etc. were also spotted (see Fig. 3).

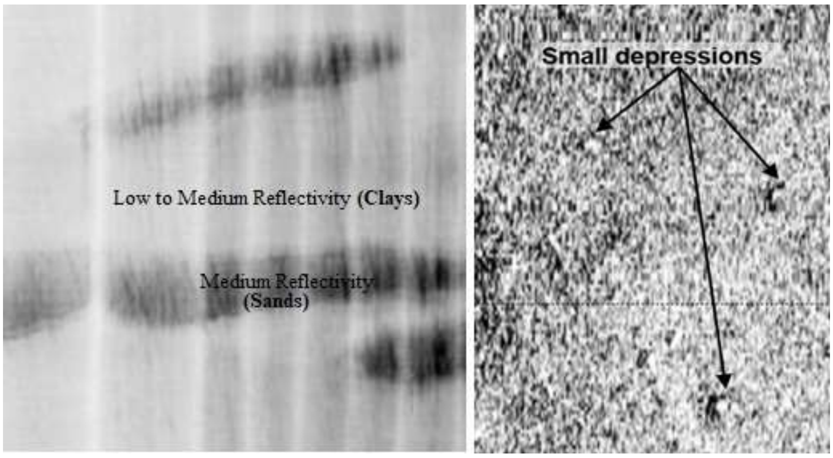

Fig. 3. Sidescan Sonar Image Showing Seafloor Sediments and Depressions

3.3 Subbottom Profiling

Sub-bottom profiling is performed to understand the shallow soil layers below the seafloor. The subbottom profiling for pipeline routes and platform locations were done by Pinger system. The soil layers identified from the subbottom records can be classified into two types. The topmost soil layer (Unit A) is interpreted as 'Sandy Silty CLAY' and the second soil layer (Unit B) identified as a firm to stiff CLAY. The first soil layer thickness varied from 20 m to 40 m and the thickness of the second soil layer could not be estimated due to the limitations of the acoustic signal penetration. It can also be observed that the thickness of first soil layer interpreted from subbottom profiling data shows good agreement with CPTU interpretation (Soil Behaviour Type Index and cone resistance) plots as shown in Fig. 4 & 5.

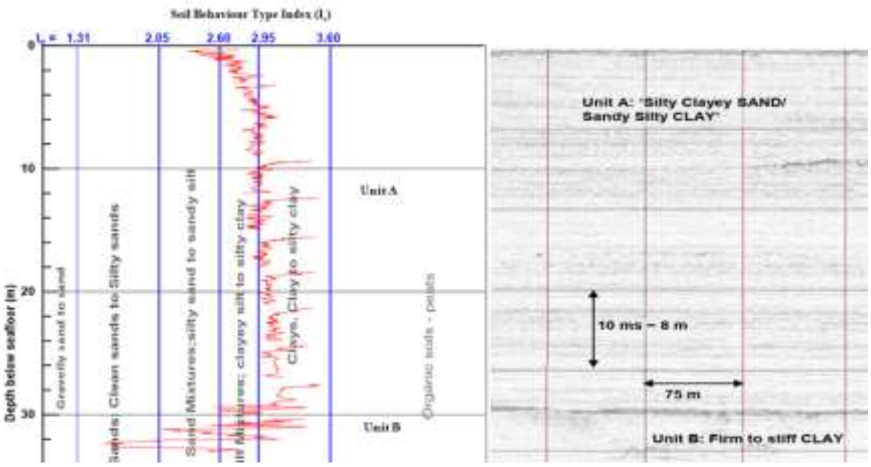

Fig. 4. Comparison of SBT and Subbottom Profiling Records

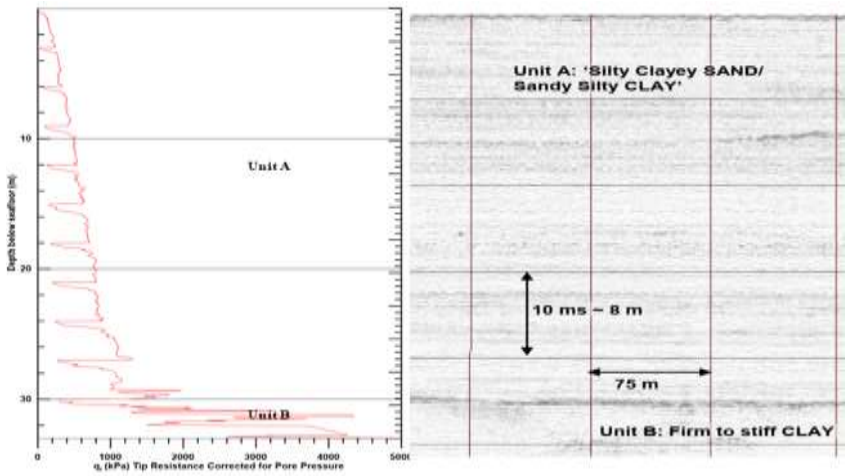

Fig. 5. Comparison of q_t and Subbottom Profiling Records

Finally, acoustic masking (possibly due to shallow gas) as shown in Fig. 6 was identified within the first soil layer (Unit A) occasionally along the proposed pipeline/cable routes.

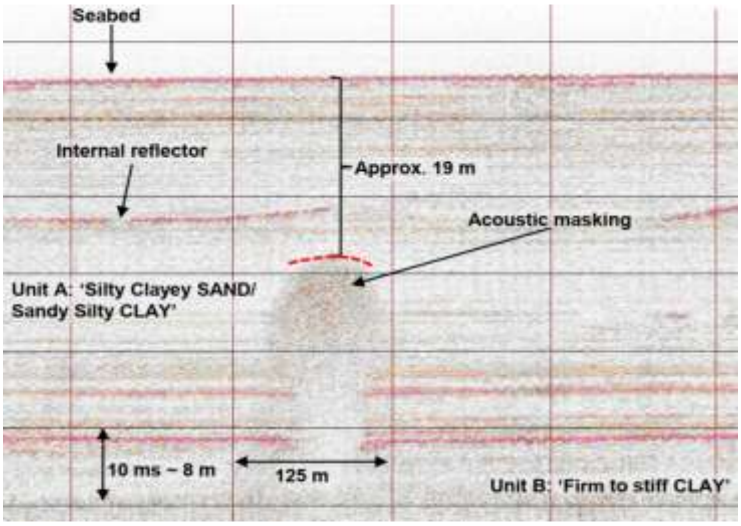

Fig. 6. Shallow Gas in Unit A

3.4 Magnetic Anomalies

Magnetic anomalies found during the magnetic survey were due to the existing pipelines and other sonar contacts.

4 Reviews of Geotechnical Investigations Data

The Geotechnical investigation data considered for the study have been classified into two categories. The recent data with digital CPTU records and final soil investigation reports; and the hard-copy final soil investigation reports of locations investigated during the initial phase of the field development.

The raw CPTU data of the recently investigated locations were processed and parameters: q_t (measured cone resistance corrected for pore pressure effect and seabed reference), f_s (sleeve friction), B_q (pore pressure parameter - $\Delta u/(q_t-\sigma_v)$, $\Delta u = u_2-u_0$, u_2 = pore pressure measured at the shoulder of piezocone, u_0 = in-situ equilibrium pore pressure, σ_v = total vertical stress) [2] and Soil Behavior Type index (I_c) [3] were plotted against the depth from seafloor.

The Soil Behavior Type index (I_c) was developed by Robertson et al., (1998) to identify the type of soil from the CPTU data. The stratigraphy at a location can be easily visualized from the plot of I_c against depth from the seafloor. The recent Geotechnical investigations are located sufficiently far from each other within the field. Hence, a combined plot of all I_c against depth from seafloor identified a few major site-wide (see Fig. 7) and some locally present clay and sand layers. The parameter wise (q_t, f_s, and B_q) combined plots of all locations (not presented here due to paucity of space) also support the above observation.

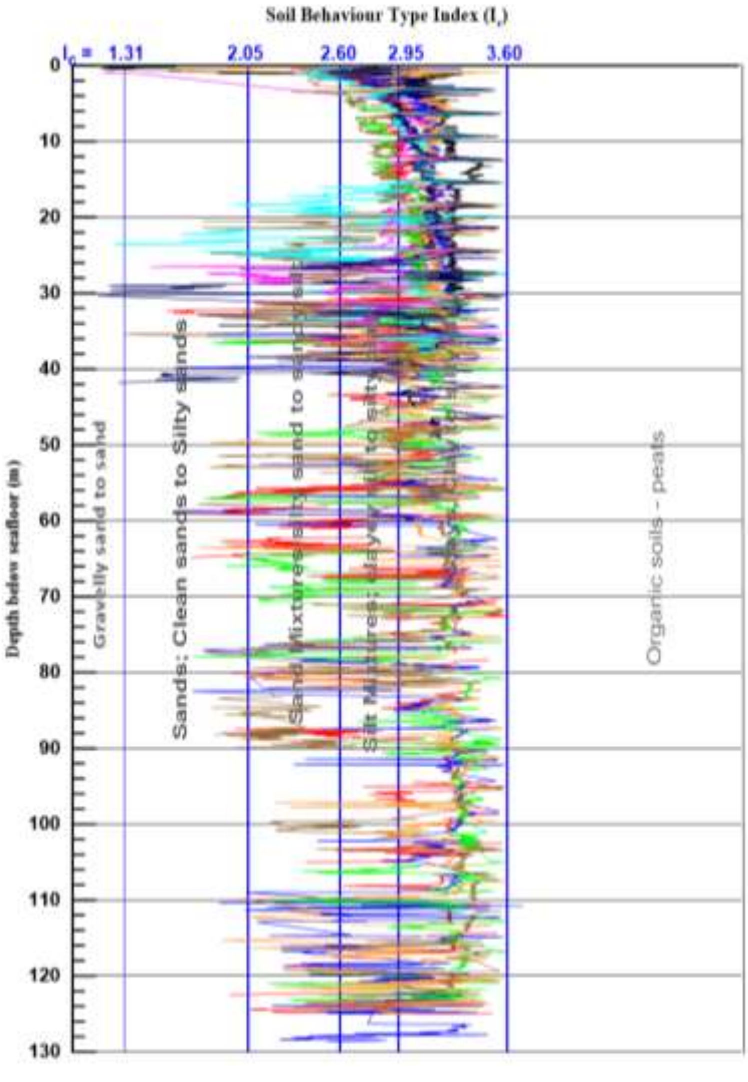

Fig. 7. Combined Plot of All SBT (I_c) With Respect to Depth From Seafloor

Furthermore, the bore logs from the old and new soil investigation reports were studied to understand the field wide soil stratigraphy. From the review of all the Geotechnical information, it can be concluded that the soil stratigraphy in the present field is clay dominated. At any location, more numbers of clay layers and few sand layers are present. Likewise, some soil layers are having field-wide and others having only local presence can be confirmed. Other important observations from the study of Geotechnical data are presented in the following sections.

4.1 Carbonate Content

One of the important characteristic of soils in western Indian offshore is the presence of a high quantity of carbonate. The soils in the present field also have high carbonate content. For clays, the carbonate content affects the plasticity characteristics but has no significant influence on shear strength. For sands, higher carbonate content indicates higher particle crushing and compressibility resulting in lower pile-soil friction. The modified Clark and Walker (1977) classification system was used to classify clays and sands in the present field.

4.2 Relative Density, Friction Angle of Sands in the Field

The sands in the present field have high quantities of carbonate content and varying degree of cementation. Hence, most of the sands were classified into siliceous carbonate sands, calcareous sands, and calcarenites [4]. The relative densities of the coarse-grained soils present in the field were estimated by the correlation proposed by Jamiolkowski et al., (2001). The correlation used was developed for silica sands; hence the API recommended frictions angles were adjusted to accommodate the nature of carbonate bearing sands.

A very thin loose silty sand layer (siliceous carbonate) was observed at the seafloor in some locations. Its thickness varies from 0.5 m to 2 m. The presence of this layer can also be confirmed from sidescan sonar records. Another thin medium dense silty sand layer (siliceous carbonate) of 3 to 4 m approximate thickness is present around 25 to 35 m depth from the seafloor. At some locations, this layer is interbedded with clay.

The other sand layers present in the field didn’t show any specific pattern in their position from the seafloor. Hence, their site-wide presence could not be established.

4.3 Shear Strength and Stress History of Clays in the Field

A number of in-situ and laboratory tests were performed to measure the undrained shear strength of clays. Insitu tests like field vane shear and CPTU were performed. Laboratory tests to measure shear strength like PP (Pocket Penetrometer), TV (Tor Vane), MV (Motor Vane), UU (Unconsolidated-Undrained Triaxial Test) and CU (Consolidated Undrained Triaxial Test) were performed. The final design strength profile was estimated considering in-situ and laboratory strength results.

The soil stratigraphy of the field shows several calcareous and carbonates clay layers [4]. A large clay layer with consistency varying from very soft to firm is present all over the field located at a depth of 0 to 2 m from the seafloor. The presence of this layer can also be seen in subbottom profiling records (see Fig. 5). The thickness of this layer varies from 18 m to 40 m. Effective unit weight of soil in this layer is between 4 to 6 kN/m^3. Also, the moisture content and liquidity index of this layer are more than 70% and 0.75 respectively. The S_{uUU}/σ'_v (S_{uUU} = unconsolidated undrained shear strength of clays, σ'_v = effective vertical stress) on average are 0.2 indicating normally consolidated clays.

Several stiff and very stiff clay layers are present after the first clay layer. In these layers, the consistency of clays increases and liquidity index decreases with depth. The effective unit weights also support the trend in consistency. The moisture content of these stiff and very stiff clay soil layers is around 40% and liquidity indices are in between 0.1 to 0.3. The S_{uUU}/σ'_v values are around 0.5; and the OCR as per CPTU based correlation by Mayne (2007) is around 2 indicating the presence of slightly overconsolidated clays.

Some overconsolidated hard clay layers are present mostly after 125 m depth from the seafloor. But their field wide presence couldn't be established due to the deficiency of data.

5 Three Dimensional (3D) Soil Model of The Field

As a part of the integrated study, a 3D model was developed to get a better understanding of the soil stratigraphy. The creation of 3D soil model helps to visualize the spatial variation in stratigraphy. The isosurface obtained from the 3D model can help to locate a specific type of soil from the seafloor.

5.1 Procedure to Create 3D Model

The XYZ data to create the model were obtained from the bore logs of each Geotechnical investigation. The easting, northing, and depth from the seafloor are chosen as Cartesian coordinates (XYZ) to create 3D scatter plots (see Fig. 8). The consistency of clays and relative density of sands were color-coded (clays in green and sands in brown) and displayed at each coordinate of the scatter plot. The increase in the intensity of green color from light to dark shows the increase in consistency. Similarly, the increase in the intensity of brown color i.e., from light to dark shows the increase in relative density. Finally, the coordinates of the scatter plot along with their respective color, are interpolated to create the 3D model (see Fig. 9) showing stratigraphy.

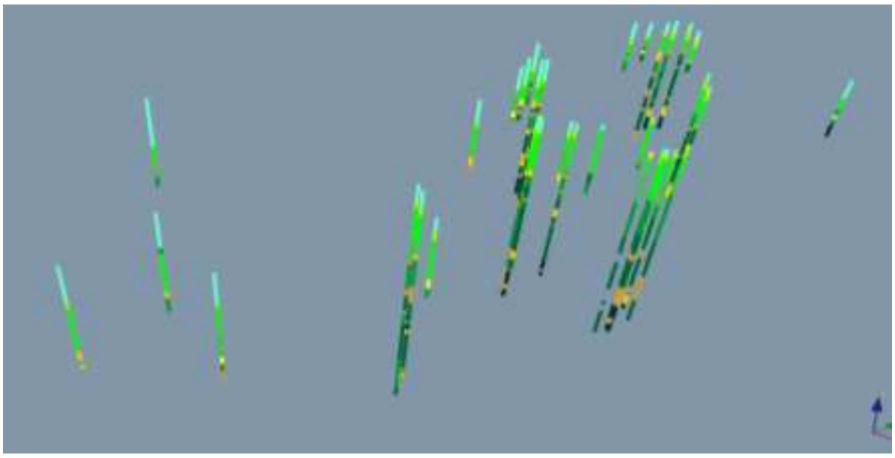

Fig. 8. Scatter Plot of Bore logs

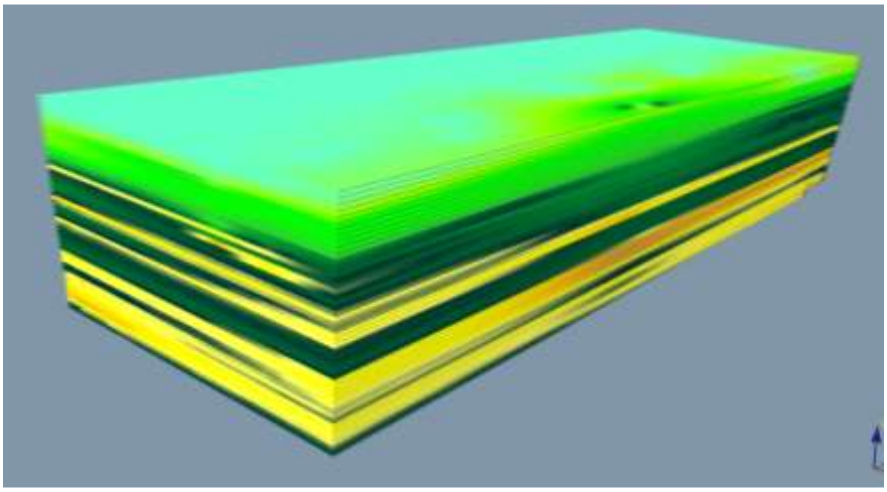

Fig. 9. 3D Model of the Field

5.2 Inferences from the 3D Soil Model

A cross-section at the location of interest, either orthogonal or oblique to the 3D model helps to view soil stratigraphy (see Fig. 10).

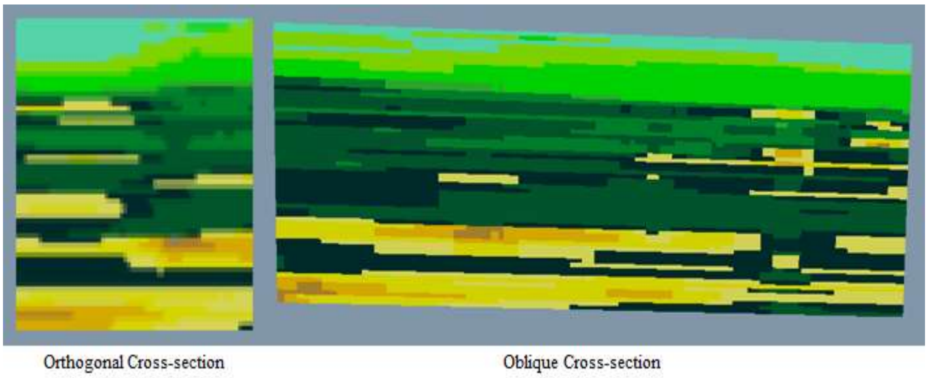

Fig. 10. Cross-sections Showing Soil Stratigraphy

An isosurface from the 3D model shows the location of a particular type of soil present at different depths from the seafloor. (see Fig. 11).

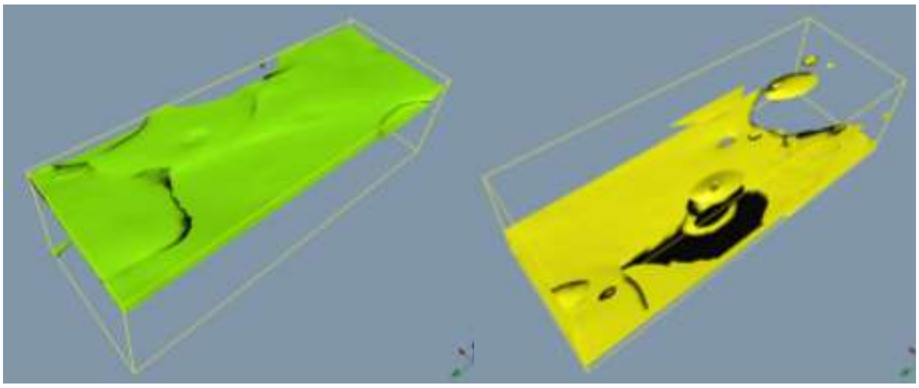

Fig. 11. Isosurface showing Very Soft Clay and Loose Sand Layers

6 Conclusions

- The present study reaffirmed how large quantity of independent data from a given area can be integrated to derive useful inferences in site investigations.
- From the study of Geophysical survey data, it can be concluded that serious hazards which may hamper field development are not present in the study area. Also, most of the field has a gentle sloping terrain.
- The soil stratigraphy is dominated by clayey strata with few sand layers. Few clay and sand layers having field wide presence are identified. A high percentage of carbonate is found in the soils of this field.

- The integrated study allowed the creation of a 3D soil stratigraphic model of the field. The 3D model helps is assessing the stratigraphy at locations where geotechnical information is not available.
- Even though the 3D model has many advantages, the quality of the 3D model depends on the number of data point available and numerical interpolation method used to interpolate that data. The users should be aware of the limitations of the 3D soil model while using it to optimize the project work of soil investigations.
- Since the redevelopment of the field is in progress, the presented model shall be used to forecast the stratigraphy at new locations, to compare the results using actual field investigation data and to refine the model further. It is proposed that the results of such an endeavor shall be presented in a future paper.

Acknowledgment and Disclaimer

The authors are grateful to the management of ONGC for permission to publish the paper. Views expressed in the paper are the authors' own and not necessarily those of ONGC.

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