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Liquefaction Assessment of Gulf of Kutch Offshore Soils using CPTU Data

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Abstract. The Kutch area in the state of Gujrat, India is a zone 5 earthquake region as per IS 1893 (Part 1): (2016). This area has been seismologically active and the Bhuj (2001) earthquake also confirms this. Notably, liquefaction at many locations was observed during this earthquake. In recent times, offshore infrastructure such as wellhead platforms, pipelines are being developed in this region to produce hydrocarbons. The general soil stratigraphy of the offshore region has a mix of clay, silt and sand layers. In the case of seismic activity, the pore pressure increases in the soil with subsequent loss of stiffness and/or strength. It is well established in the literature that the CPTU (Cone Penetration Testing with Pore Pressure Measurement) based methods of liquefaction assessment are more reliable compared to other methods based on laboratory tests because of the difficulties in collecting the undisturbed soil samples, especially for sands. This paper presents the results of liquefaction assessment carried out for the Gulf of Kutch offshore soils using the CPTU data.

Keywords: Liquefaction; Kutch; Offshore; CPTU.

1 Introduction

The Kutch basin (see Fig. 1) in the state of Gujrat, India has known accumulation of hydrocarbons. The offshore of this basin extends from the coast to the areas with water depths up to 200 m [1]. Hydrocarbons from the offshore of this basin are to be produced after developing infrastructure. Hence, detailed pre-engineering surveys such as metocean, geophysical, and geotechnical surveys were conducted. The Himalayan and the Kutch regions of India are in zone 5 seismic region as per IS 1893 (Part 1): 2016. Forensic investigations conducted after earthquakes around the world confirmed damages even to offshore structures due to liquefaction [2]. The damage to the offshore structures can have a serious economic and environmental impact. It was observed that most of the published research available on liquefaction assessment of the Kutch region were for the onshore soils using SPT (Standard Penetration Test) data or from cyclic testing of soil samples (on reconstituted samples in the case of sands) in the laboratory. However, the CPTU (Cone Penetration Testing with Pore Pressure Measurement) based liquefaction assessments done for either onshore or offshore soils of the Kutch are sparse. In the present study, liquefaction assessment for the Kutch offshore soils using CPTU data was performed and the results are presented.

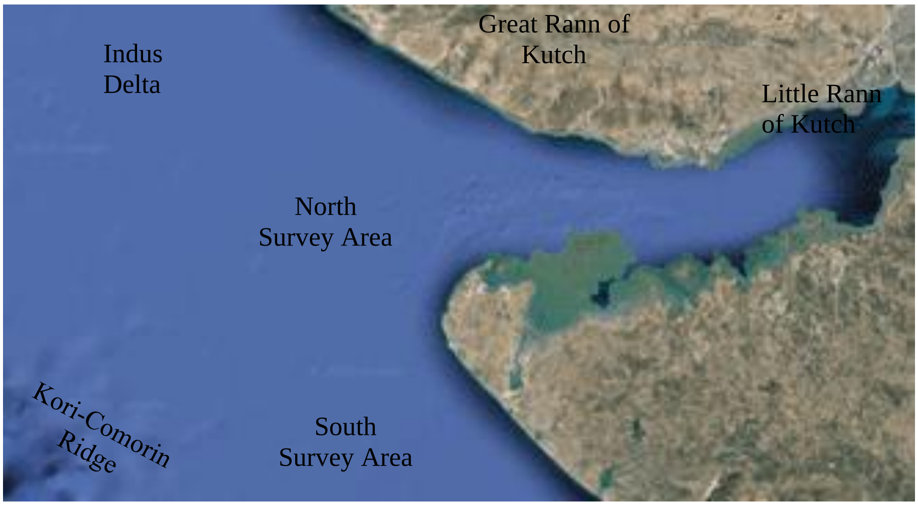

Fig. 1. Kutch Offshore [3]

2 Seismic History of Kutch Offshore Area

The Kutch onshore and offshore regions have several major and minor faults. Remarkably, the origin of the earthquakes that occurred on the onshore of this region can be traced along the faults [4]. A similar trend can also be reasonably assumed for the earthquake occurrences in the offshore region. The data from the National Center of Seismology, Ministry of Earth Sciences, Government of India were studied to know earthquake occurrences in offshore. It was observed that several minor, few light and moderate earthquakes have occurred in this region [5].

3 Soil Behavior under Earthquake Loading

The soil behavior can be divided into two broad categories, namely undrained and drained based on its permeability and rate of loading experienced. When loads are applied on soils, in an undrained condition the pore water cannot leave the soil matrix because of less permeability or the quicker rate of loading, whereas in a drained condition the pore water drains easily. In general, “clays-like” soils show undrained behavior and “sands-like” soils show drained behavior. However, during an earthquake, all types of soils are considered to show undrained behavior. All soils deform during an earthquake. They either experience “liquefaction” or “cyclic failure” explained in the following sections 3.1 and 3.2.

Liquefaction of soils can be divided into two types viz. flow and cyclic liquefaction. Flow liquefaction occurs in strain-softening soils associated with gravitational stress greater than undrained shear strength, and cyclic liquefaction occurs due to cyclic loading in an undrained condition arising during an earthquake. This paper focuses only on cyclic liquefaction. During undrained cyclic loading condition, the pore pressures in soils rise, resulting in a decrease in effective stresses, subsequently in the loss of stiffness and/or strength. Losing stiffness and/or strength can lead to severe consequences such as displacement or floating of pipelines, tilting of structures, bearing capacity failure of foundations, failure of slopes. [6].

3.1 Cyclic liquefaction of "sand-like" soils

Gravels, sands and silts with very low plasticity are soils with sand-like (cohesionless) behavior. During an undrained cyclic loading condition, these soils develop high positive pore pressures often leading to zero effective stress. The condition of zero effective stress is called liquefaction. Loose uncemented sand-like soils are prone to liquefaction while dense sand-like soils lose stiffness and/or strength. There are many factors such as effective confining stress, relative density, fabric, age, cementation, duration and magnitude of a seismic event influencing the liquefaction potential of sand-like soils [7].

3.2 Cyclic failure of "clay-like" soils

Fine grained soils such as clays and silts with plasticity are considered as clay-like (cohesive) soils. During an undrained cyclic loading condition, clay-like soils develop positive pore pressure. Soft highly sensitive normally consolidated clay-like soils respond similarly to loose sands and over consolidated clay-like soils respond similarly to dense sands. Though pore pressures rise in clay-like soils during cyclic loading in undrained condition, the effective stresses don't reach zero. Hence, the clay-like soils are considered failed, i.e., attain cyclic failure when they reach a shear strain of 3% [8].

3.3 Liquefaction in the marine environment

The fundamental mechanism of liquefaction is same in onshore and offshore soils. However, the following features of the offshore environment distinguish the liquefaction of offshore soils. Generally, the stratigraphy in offshore regions is dominated by fine-grained soils and silty sands, but exceptions exist. Also, the deep-water regions of the world are with fine-grained soils in normally consolidated or under consolidated state. Some marine soils (Indian offshore, south China sea, Australia etc.) have significant carbonate content. Although the calcareous/carbonate sands are more resistant to liquefaction, the mechanical properties of these types of sands are not clearly understood. Another important feature of the marine environment is the presence of water. The rise of water waves during an earthquake contributes to an additional rise of pore pressure, consequently taking a long time for the dissipation. Gas-charged (CH_4, H_2S

etc.) sediments and natural gas hydrates are often found in offshore regions. The presence of gases in soils increases their susceptibility to instantaneous liquefaction. The dissociation of gas hydrates during an earthquake causes considerable excess pore pressures. Thus, the factors mentioned above make the offshore soils more susceptible to liquefaction/cyclic failure [2].

3.4 Liquefaction analysis using CPTU data

Liquefaction analysis primarily involves the estimation of resistance of soils to earthquake loading. It can be performed in several ways. An overview of liquefaction analysis is shown in Fig 2. The use of CPTU data for evaluating the resistance has many advantages. CPTU has been the fundamental insitu testing instrument used in offshore soil investigations for a long time. Moreover, the CPTU parameters measured are repeatable and accurate. It also provides near continuous data, unlike SPT which is conducted in intervals. Hence, the liquefaction assessments carried out using CPTU data give better results. Another important factor favoring liquefaction assessment by insitu tests compared to laboratory testing, i.e., either by cyclic simple shear tests (CDSS) or cyclic triaxial tests (CTX) can be attributed to the difficulty in collecting undisturbed soil samples. Though high-quality samples can be easily obtained in clays, sand samples collected often are of poor quality. Normally loose sands get densified and dense sands get loosen during sampling.

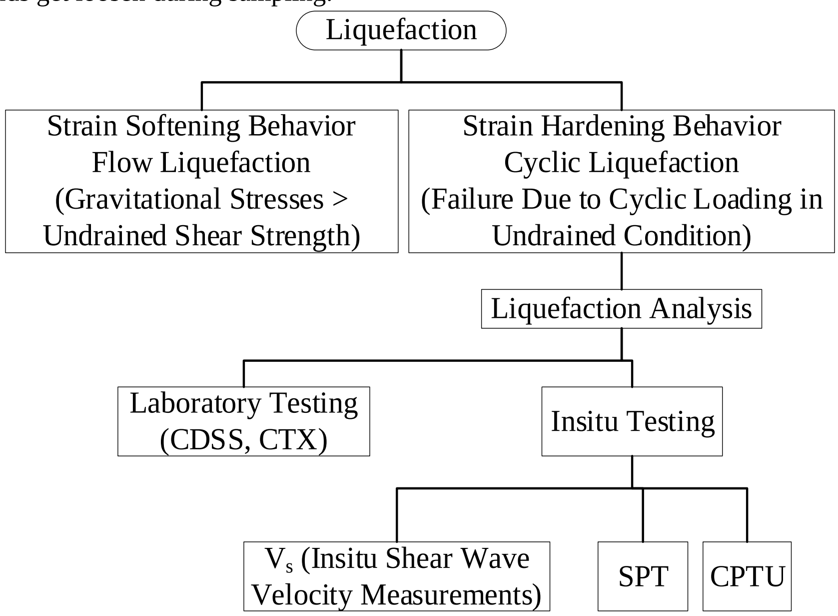

Fig. 2. Liquefaction Analysis Overview

4 Data Considered for the Study

The data of the pre-engineering surveys performed over the past few years were used in the present study. These surveys were done for the development of infrastructures such as wellhead platforms, mooring buoys, pipelines and jack-up rig deployments in the Kutch offshore region. The total survey data was divided into two sets viz. north and south based on the location of infrastructure in the offshore. The geotechnical data of the north were denoted as Location A, Location B etc. and the data from the south as Location 1, Location 2.

4.1 Inferences from the geophysical survey

The geophysical survey was performed using multibeam echosounder, sidescan sonar, sub-bottom profiler, and magnetometer instruments. 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 shallow stratigraphy and geology; and the magnetometer identifies metal objects at or just below the seafloor. Important observations from the geophysical survey in comparison with geotechnical data are presented.

Seafloor soils. The soil at the seafloor was interpreted based on its reflectivity in the sidescan sonar records.
North. The platform locations are with low to medium or medium reflective soil interpreted as very soft silty clay. The soil along most of the proposed pipeline route corridor was found similar to the platform locations. However, medium to coarse silty sand, dense sand, coral outcrops and cemented sand were also found.
South. The platform location is with medium reflective soil interpreted as silty clayey sand. The soil along most of the proposed pipeline route corridor is similar to the platform location. However, very soft sandy clay, coarse sand with shell fragments, coral outcrops and cemented sand were also found.

Sub-Bottom Profiling (SBP). The sub-bottom profiling helps to understand the near-surface stratigraphy and geology.
North. The shallow stratigraphy at the platform locations is dominated with clay-like soils. The maximum acoustic signal penetration observed from the sub-bottom profiling records of the pipeline corridors was between 14 m to 25 m. Higher signal penetration than the southern region was achieved where the stratigraphy was dominated with clay-like soils.
South. The shallow stratigraphy at the platform location is dominated with sand-like soils. The maximum acoustic signal penetration observed from the sub-bottom profiling records in the pipeline corridors was around 14 m. The signal penetration achieved was less because of sand-like soils near the seafloor.

Grain size analysis. A geophysical survey always has an associated limited geotechnical investigation. In the present case, soil samples were collected at the seafloor using either gravity piston corers or drop corers or grab samplers. Subsequently, several Atterberg limits tests, grain size analyses, chemical (sulphate, sulfite, chloride and carbonate) and strength tests (direct shear test, lab vane shear test etc.) were performed.

North. The soil at the platform locations was classified as silty clay of high plasticity (CH). The soil along the pipeline corridor was also mostly with silty clays of high plasticity (CH) however poorly graded sand or gravel (with /without silt) and silty sand or gravel was also found. The apparent cohesion and effective friction angle measured using direct shear tests were 0 kPa and around 30º (relative density in between loose to medium dense) respectively.

South. The soil at the platform location and pipeline corridor were classified into clayey sands (SC), silty sands (SM) and silty clays of high plasticity (CH). Notably, the sands contain a high percentage of fines. The content of fines has a significant influence on liquefaction resistance of sands [9]. The apparent cohesion and effective friction angle measured using direct shear tests are mostly in between 0 kPa to 3 kPa and 25º to 30º (relative density in between loose to medium dense) respectively.

4.2 The Geotechnical investigation

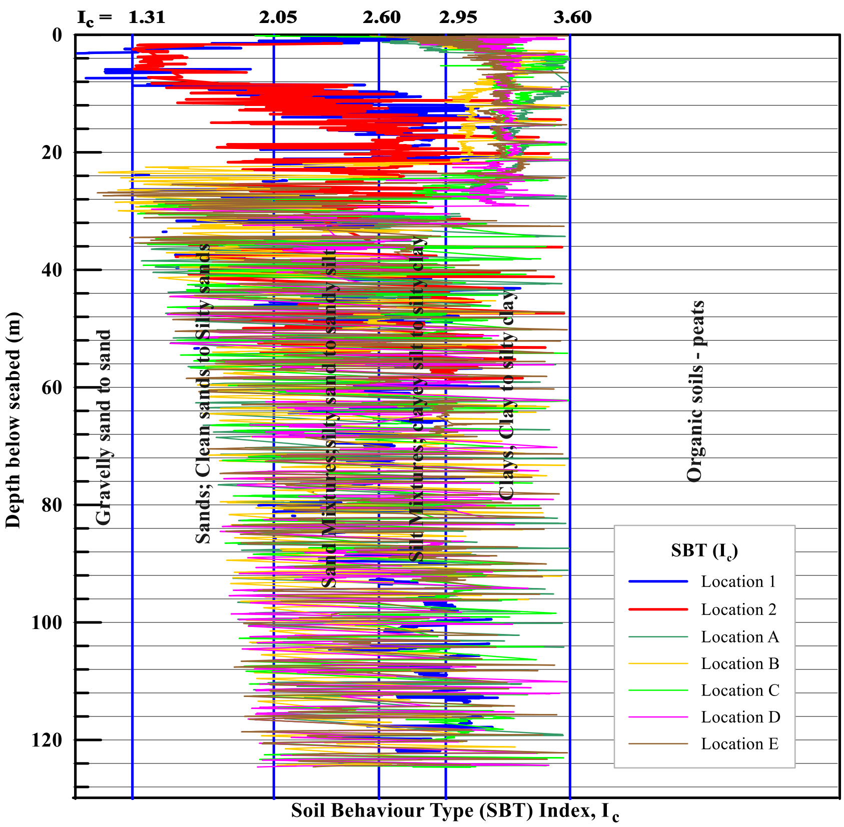

Fig. 3. Soil Behavior Type Index (I_c) of North and South Locations Against Depth from Seafloor

The scope of geotechnical investigations for platform locations comprised two boreholes, the first borehole up to 30.0 m (approximately) depth exclusively for CPTU tests and the second borehole, few meters apart, where alternate sampling and CPTU testing up to 125.0 m (approximately) was done. The scope of geotechnical investigation for mooring buoys and jack-up rigs is similar to the platforms except that the second borehole was terminated around 40 to 60 m depth.

Stratigraphy. To identify the soil layers present sitewide, the raw CPTU data of all the 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 = insitu equilibrium pore pressure, σ_v = total vertical stress) and Soil Behavior Type index (SBT) plots with respect to depth were studied. The SBT (I_c) was developed by Robertson et al. (1998) to identify the type of soil from the CPTU data. The stratigraphy can be easily visualized (see Fig. 3) from the plot of I_c against depth from the seafloor.

5 Liquefaction of Sands and Cyclic Failure of Clays

The cyclic liquefaction of sands or cyclic failure of clays involves the estimation of the factor of safety (FS_{li}) equal to the ratio of cyclic resistance ratio (CRR) and cyclic stress ratio (CSR). The CRR represents the resistance of soils, and CSR represents the cyclic stress developed due to the design earthquake.

$$FS_{li} = \frac{CRR_{M,\sigma'v}}{CSR_{M,\sigma'v}} \tag{1}$$

M is the design earthquake moment magnitude and σ'_v insitu effective overburden stress. Generally, it is common to calculate both CRR and CSR for reference conditions of earthquake 7.5 M_w and effective stress of 100 kPa or 1 atm (represented as CRR7.5, CSR7.5).

FS_{li} of 1 is adopted for low-risk projects. If consequences of soil failure could have a significant economic and environmental effects a higher value may be adopted.

5.1 Cyclic Resistance Ratio ($CRR_{7.5}$)

There are many CPTU based methods to evaluate the $CRR_{7.5}$ of soils. In the present study, Robertson and Wride (1998) method was used for “sand-like” soils and Robertson (2009) method was used for “clay-like” soils. The SBT (I_c) was used to distinguish between “sand-like” and “clay-like” soils. If I_c is less than 2.6 the soil was classified as “sand-like” and similarly if I_c is greater than 2.6 the soil was considered as “clay-like”. A program in Excel VBA was developed to calculate $CRR_{7.5}$. A flowchart is presented in fig.4., which describes the steps followed by the program to calculate $CRR_{7.5}$. A minimum value of $CRR_{7.5}$ equal to 0.05 for “sand-like” and 0.17 for “clay-like” soils was adopted as per Robertson (2009).

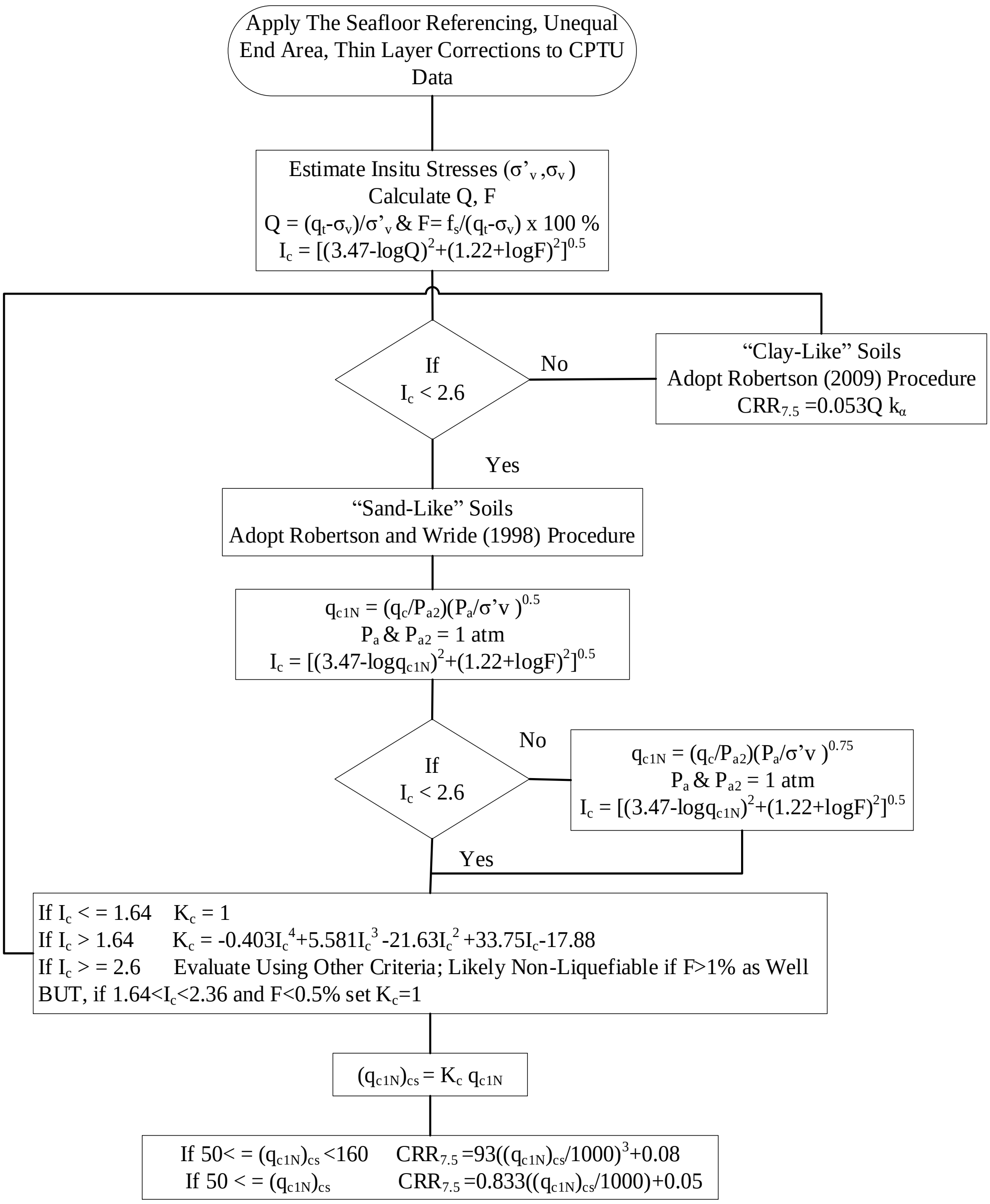

Fig. 4. $CRR_{7.5}$ Calculation Procedure as per Robertson and Wride (1998) and Robertson (2009)

5.2 Cyclic Stress Ratio ($CSR_{7.5}$)

The cyclic stress ratio ($CSR_{7.5}$) is calculated by the following equation [8].

$$CSR_{7.5}=0.65\left[\frac{a_{max}}{g}\right]\left[\frac{\sigma_v}{\sigma_v'}\right]r_d\left[\frac{1}{MSF}\right]\left[\frac{1}{k_\alpha}\right]\left[\frac{1}{k_\sigma}\right] \quad (2)$$

Where a_{max} maximum horizontal acceleration at the ground surface; g is the acceleration due to gravity; σ_v total vertical overburden stress; σ'_v effective overburden stress; r_d stress reduction factor; MSF is the magnitude scaling factor; k_α is the static horizontal shear stress correction factor; k_σ overburden correction factor.

The state of Gujarat has three seismic zones viz. Zone III, IV and V as per IS 1893 (Part 1): 2016. To carry out the computations, Zone V was assumed for the offshore region. Hence, a_{max} of 0.36 g is considered in the present study. Stress reduction factor r_d [10] depends on depth from the seafloor. The equation from Youd et al. (2001) was used to estimate r_d. MSF equals to 1 in the present study as all the calculations are performed for 7.5 M_w earthquake. The results of the geophysical survey within the survey area indicate that the slope of the seafloor is very less, and the soil layers are nearly horizontal. Hence, the factor to account horizontal static shear stress k_α can be assumed as 1. The overburden correction factor K_σ was calculated as per Idriss and Boulanger (2004).

6 Observations and Inferences

The soil stratigraphy at the platform locations in the northern region of the Kutch survey area generally starts with a very soft to firm silty clay zone of around 30 m thickness. This clay zone is also present along most of the pipeline corridor. The presence of this clay zone can also be confirmed from the study of geophysical survey data. This clay zone showed FS_{li} <1 indicating it may fail during an earthquake. Other soil layers, in this part of the survey area, are in general resistant to liquefaction or cyclic failure.

The FS_{li} near the seafloor at platform location in the southern region of Kutch offshore is very less. This is due to the presence of very soft silty clay and loose to medium dense silty sand zones. Soil stratigraphy similar to platform location was observed along most of the pipeline corridor from the study of geophysical data. Notably, FS_{li} < 1 was observed in several sand-like zones within the stratigraphy. However, the "zone of liquefaction" in this part of the survey area was considered up to 50 m due to the following reasons.

1. Considerably high overburden pressures.
2. Offshore piles are steel tubulars, driven to the target depth. The driving process densifies the soil around piles, thus decreasing the chance of liquefaction.
3. The sand zones were mostly dense after 50 m depth.

The soil zones with FS_{li} <1 in the northern and southern parts of the survey area are shown in Fig. 5 and Fig. 6 respectively.

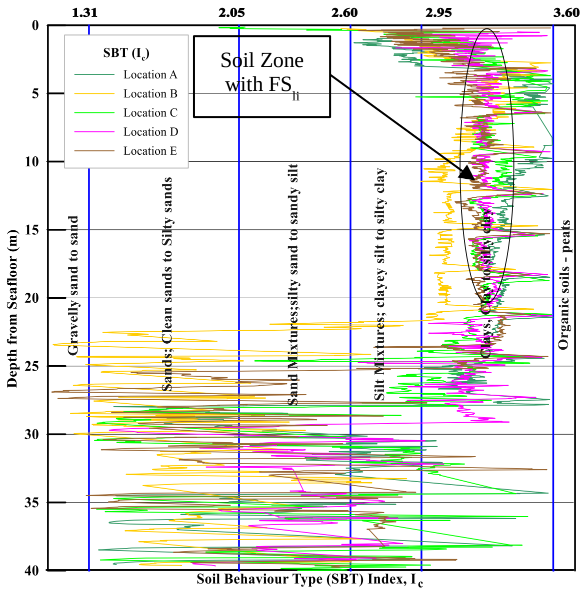

Fig. 5. Soil Zones with $FS_{li} < 1$ in Northern Part of Survey Area

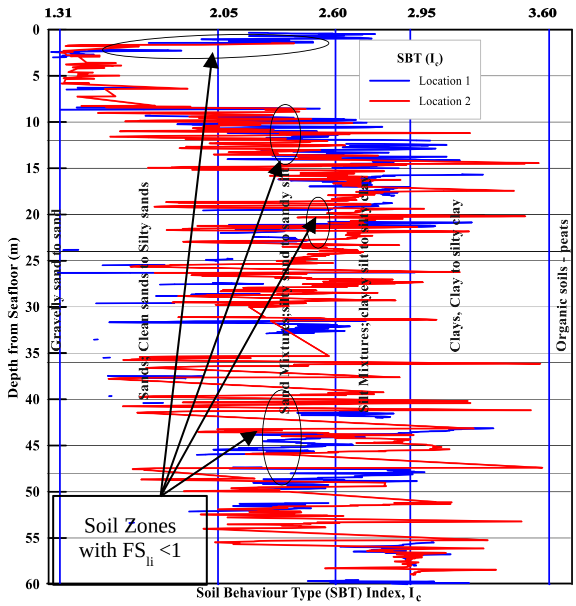

Fig. 6. Soil Zones with $FS_{li} < 1$ in Southern Part of Survey Area

7 Conclusions and Recommendations

The total surveyed area in the offshore of Kutch basin was separated into two parts for convenience. The soil at the seafloor in the northern part is with very soft to firm silty clay zone approximately 30 m thick. Subsequently, the stratigraphy up to the investigated depth is dominated by silty sands. The stratigraphy in the southern part comprises alternate zones of clays, silts and sands starting at the seafloor with very soft silty clay and silty sand layers.

$CRR_{7.5}$ for sand-like and clay-like soils was calculated using Robertson and Wride (1998) and Robertson (2009) methods. $CSR_{7.5}$ was calculated as per Robertson (2009). The conclusions and recommendations of the study are as follows:

1. The 'zone of liquefaction' i.e., where $FS_{li} < 1$ was estimated up to 30 m and 50 m from the seafloor in the northern and southern parts of the survey area.
2. The methods used to estimate $CRR_{7.5}$ in the present study are suitable for low-risk projects, and hydrocarbon projects are classified into medium to high-risk. Hence, the results of this study should be confirmed by a site-specific seismic microzonation study.
3. The seismic microzonation study should include SCPTU (seismic CPTU) tests, high-quality soil sampling especially for sands and advanced laboratory tests such as CDSS, resonant column tests, and CTX, etc. Also the influence of fines and carbonate content on liquefaction resistance of sands should be studied.

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