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LIQUEFACTION SUSCEPTIBILITY ANALYSIS FOR AN OFFSHORE SITE BASED ON INDEX PROPERTIES AND GEOTECHNICAL FIELD TEST DATA

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Abstract

Liquefaction is one of the most devastating effects of earthquakes resulting in a sudden decrease in shear strength due to excess pore water pressure generation. This will result in the differential settlement of structures and causing severe damages. This paper presents a detailed evaluation of liquefaction susceptibility for an offshore site in Western Yemen based on extensive field tests. The offshore site is the key location where major structures such as single point mooring (SPM) system along with the associated pipeline end manifold are located. The presence of loose marine sediments and submerged condition, favours liquefaction during an earthquake event, which can affect the lateral load carrying capacity of pile foundation. This signifies the need for a liquefaction susceptibility analysis of in-situ soils, before the estimation of load carrying capacity of piles in the marine soil strata. In this paper, the liquefaction susceptibility of the marine soil sediments was evaluated based on extensive field and laboratory tests. The liquefaction susceptibility was predicted based on grain size distribution, liquid limit data along with cone penetration test data. Potentially liquefiable soil layers in offshore site are identified based on the results of these test data.

Keywords: liquefaction susceptibility, CPT, offshore site, earthquake, cyclic load.

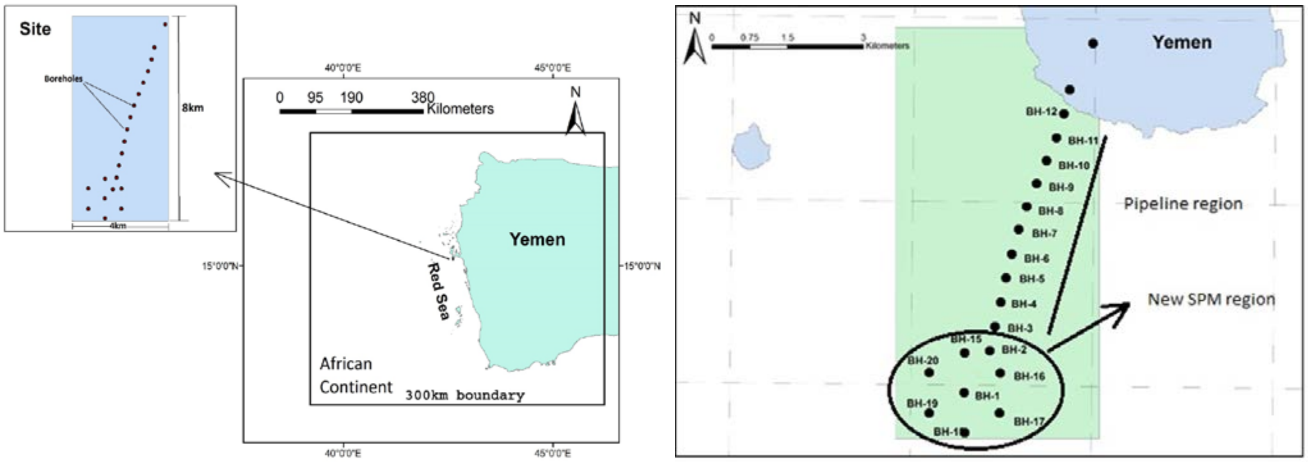
1. Introduction

Liquefaction is defined as the loss of strength of saturated loose sands due to the sudden increase in pore water pressure resulting from dynamic loading. The liquefied sand behaves like a viscous fluid with drastic reduction in the bearing capacity, resulting in landslides, lateral spreading, or large ground settlement. As the devastating effects of liquefaction were observed during several earthquakes (Niigata and Alaska 1964), a significant amount of research work was carried out to identify the liquefaction susceptible areas and to develop different methods for its mitigation. The evaluation procedure for liquefaction potential requires two steps, 1) characterizing earthquake loading and 2) characterizing soil resistance. [1] has proposed a simplified approach for characterizing the earthquake loading which is most popular. In this approach, the earthquake loading is characterized in terms of cyclic shear stress (or cyclic stress ratio). There are several methods available for evaluating the cyclic resistance of the soil against liquefaction. Important ones are laboratory tests and in-situ field tests. Laboratory tests which are available for measuring soil resistance include, cyclic tri-axial tests [2, 3] cyclic simple shear test [4], cyclic torsional test [5]. However the evaluation of cyclic resistance using laboratory tests is restricted to research purpose because of the cost and the difficulties involved in getting undisturbed samples. As there are many difficulties and the associated with laboratory tests, evaluating liquefaction potential using in-situ tests have become more convenient. Major geotechnical field tests used for evaluating the cyclic resistance of soil are, 1) Standard Penetration Test [6, 7, 8], 2) Cone penetration tests [9, 10 and 11] and 3) Based on shear wave velocity [12 and 13]. [14] have suggested proposed a method to evaluate earthquake loading in terms of cyclic shear strain (γ_c) and to characterize the soil resistance against liquefaction in terms of threshold shear strain (γ_t). Hence the possibility of liquefaction will be maximum if $\gamma_c > \gamma_t$.

The first step toward the assessment of liquefaction potential is to check the liquefaction susceptibility of the soil. The liquefaction susceptibility of a soil is defined as the easiness with which it can undergo liquefaction without considering the earthquake loading. The liquefaction susceptibility depends only upon the soil properties alone. If a soil at a particular site is susceptible to liquefaction, then only it is prone to the liquefaction hazards. The existing site is going to house many offshore structures which are generally supported on pile foundations. It has been proved that liquefaction poses a great threat to the stability of piles, especially during when it is under dynamic loading due to earthquake and wave action [15, 16]. Studies have shown that the long and slender pile in a liquefied sands, fails under buckling action due to loss of lateral confinement under liquefaction. Similarly, the pile groups in liquefied sand will undergo very large lateral displacement when compared to that of in non-liquefied soils. Hence, the assessment of liquefaction susceptibility based on field test data and index properties is very important and forms first steps towards the evaluation of liquefaction potential, especially for the offshore infrastructures. This paper presents the liquefaction susceptibility analysis for an offshore site in Yemen using the grain size analysis, the natural moisture content and liquid limit variation, CPT values.

2. Study Area and Geology

The study area is located on the offshore which is on the Western side of Yemen within the Red Sea. The site forms a part of the Arabian Peninsula, which is a segment Arabian-Nubian Shield. Geologically, the site is in the offshore parts of the Tihama Basin. Studies have shown that the seismicity in this region is mainly due to the tectonic movement between the Arabian and the African plates (fig. 2) [17, 18, 19 and 20]. The region has subjected to slow subsidence prior to tectonic rifting about a 100 million years ago [21]. [21] has described in detail about the tectonic evolution of the southeastern part of the Red Sea Rift between Al Hudaydah and Sana’a. The Dhamar earthquake of 1982 (M=6) which caused more than 15,000 causalities is one of the davastating earthquake in the region. A series of earthquakes occurred in 1941 (M=6. 5) have resulted in 12,000 casualties [21]. [22] have reported the continuous occurrence of moderate to large earthquakes over the past 12 centuries. Several researchers have performed the seismic hazard studies for Yemen and its various territories.



(a) Location of the study area (b) Borehole locations within the offshore site

Fig. 1 Geographic location of the study area along with borehole locations [after 22]

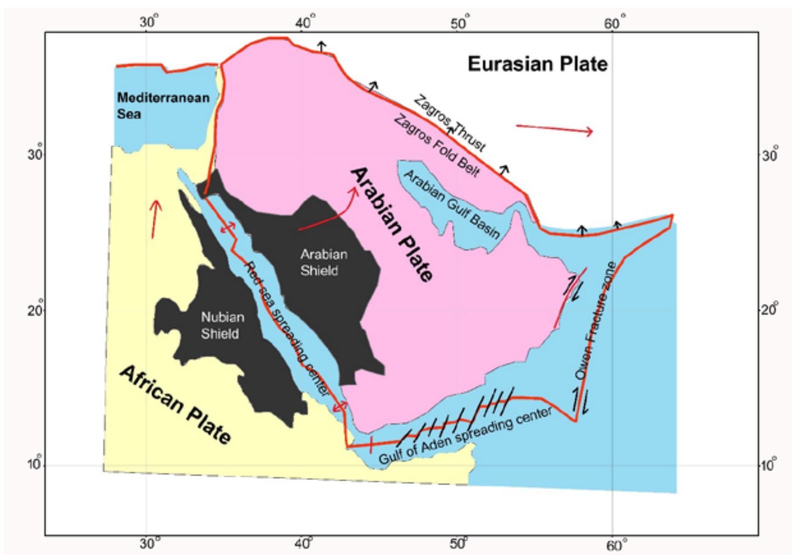


Fig. 2 Tectonics of Middle East region [after 22]

3. Liquefaction Susceptibility Analysis

The important factors that will decide the susceptibility of soil liquefaction at a given site are soil type, particle shape and soil permeability, depth of ground water table, historic environment, and age of soil deposit, relative density and occurrence of strong shaking. Ishihara [25, 26] has observed the liquefaction behaviour in non-plastic silts and emphasized the influence of plasticity characteristics on liquefaction than the grain size. [27, 28] have shown that gravelly soils can also liquefy. However, sensitive clays are found to exhibit strain softening behaviour. [29] has formulated a criteria (Chinese criteria) for fine grained soil to undergo liquefaction. [30] revised the above criteria based on the data from the subsequent earthquakes. For the other cases, the liquefaction susceptibility of soil needs to be tested further. Moreover, the particle shape and gradation also influence the liquefaction susceptibility. Soils with round shaped particles can densify more easily hence are less susceptible to liquefaction than angular shaped particles [31]. Well graded soil have minimum void ratio, hence result in small volume change under drained condition and less excess pore pressure during undrained condition. Thus well graded soils are less susceptible when compared to poorly graded soil.

3.1 Based on Grain Size Analysis

It is generally considered that liquefaction resistance for sandy soils increases as the grain size becomes coarser due to improved drainage. Consequently, clarifying the gradation curve of liquefiable soil is an important approach to liquefaction susceptibility of a ground. [32] already showed the ranges of grain size distribution of liquefiable soil in 1970. These ranges are used in the Technical standards for Port and Harbour Facilities published by the Japan Port and Harbour Association (fig. 3).

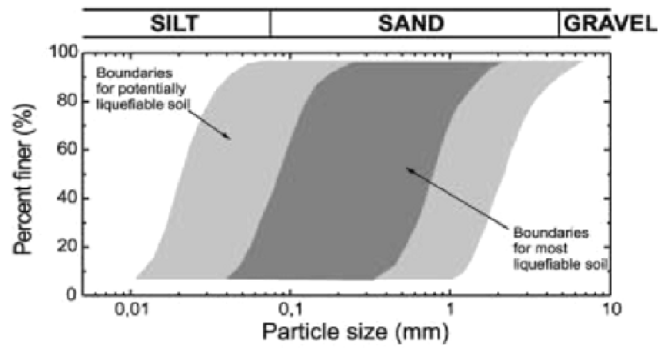
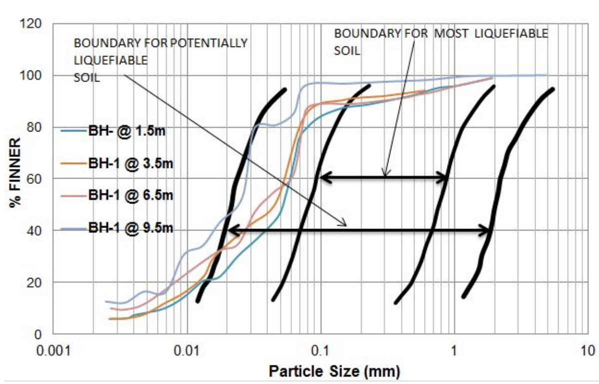
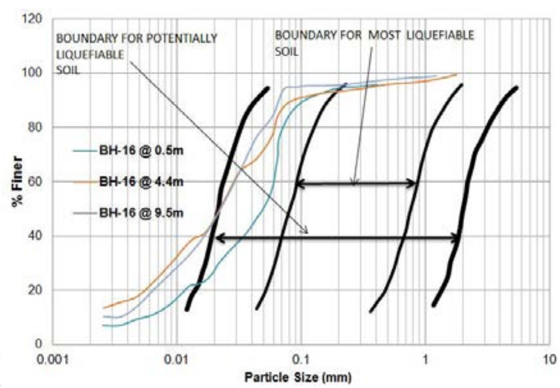


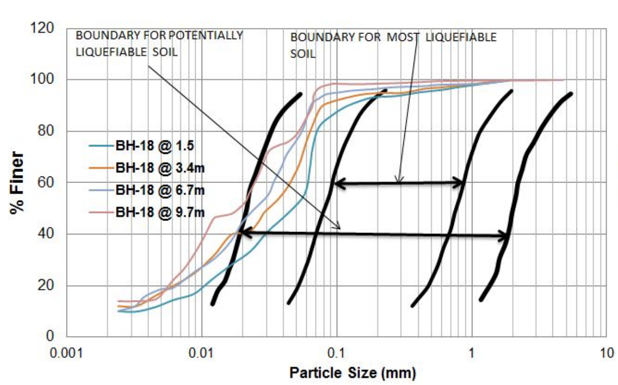
Fig. 3 Grain size boundary for defining most liquefiable and potentially liquefiable soils



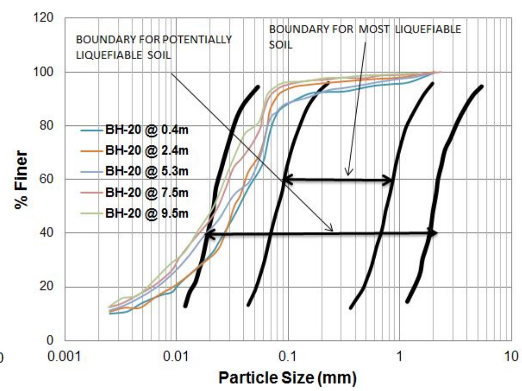
(a) Borehole BH-1



(b) Borehole BH-16



(c) Borehole BH-20

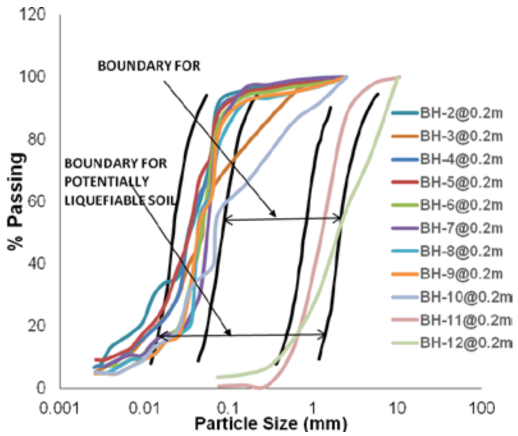


(d) Borehole BH-18

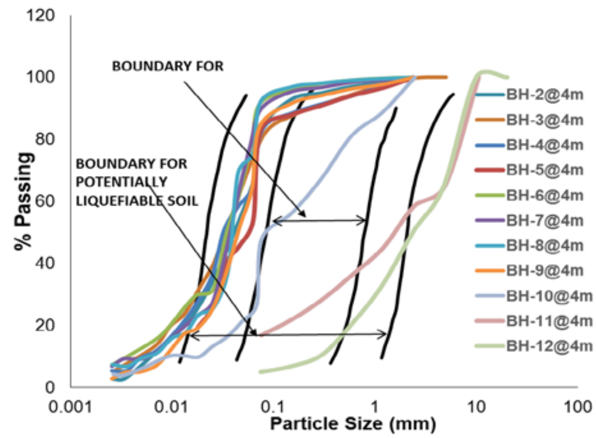
Fig. 4 Grain size distribution of undisturbed samples collected from boreholes along the new SPM region

Figures 4 (a to d) shows the grain size distribution of soils (upto 10m depth) from different boreholes (mainly BH-1, BH-16, BH-18 and BH-20) at the new SPM region which was superposed over graph showing the range of grain size distribution for liquefaction susceptibility soils.

From the above grain size distribution of soil samples (See fig. 4(a) to 4(d)) it is observed that at new SPM region none of soil sample lies completely within most liquefiable region. For the soil samples whose some part is within most liquefiable or potentially liquefiable zone, consist of excessive fines which make them non liquefiable.



(a) at 0.25m depth



(b) at 4m depth

Fig. 5 Grain size distribution of undisturbed samples collected from boreholes along the Pipeline region

Similarly, the grain size distribution curves for BH 2 to 12 in the pipeline region are presented in fig. 5(a) and 5(b). From grain size analysis data (fig. 5) it is evident that the particle gradation curve all soil samples obtained from 0.2m and 4m depth fall within the range of potentially liquefiable soil.

3.2 Based on Liquid Limit and Natural Water Content

[26] suggested that liquefaction susceptibility of fine grained soils like silts and clays is mainly influenced by liquid limit and water content which was presented in fig. 6 as per [33]. The liquid limit versus natural moisture content for major soil layers from BH-1, BH-16, BH-18, BH-20 and BH-7 were plotted in fig. 7. If the soil samples do not fall in the safe zone (as in fig. 6) based its natural moisture content and liquid limit, the liquefaction susceptibility of such soil sample must be verified using undrained cyclic loading tests.

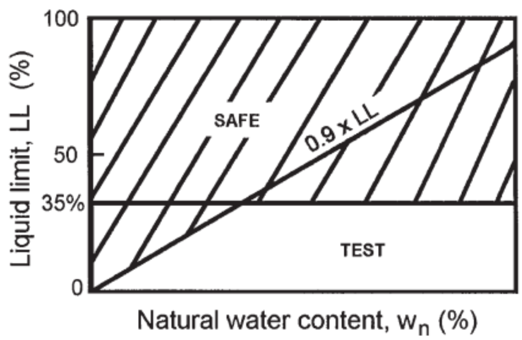


Fig. 6 Graphical representation of liquefaction criteria for silts and clays from studies by [29] in China (after [33])

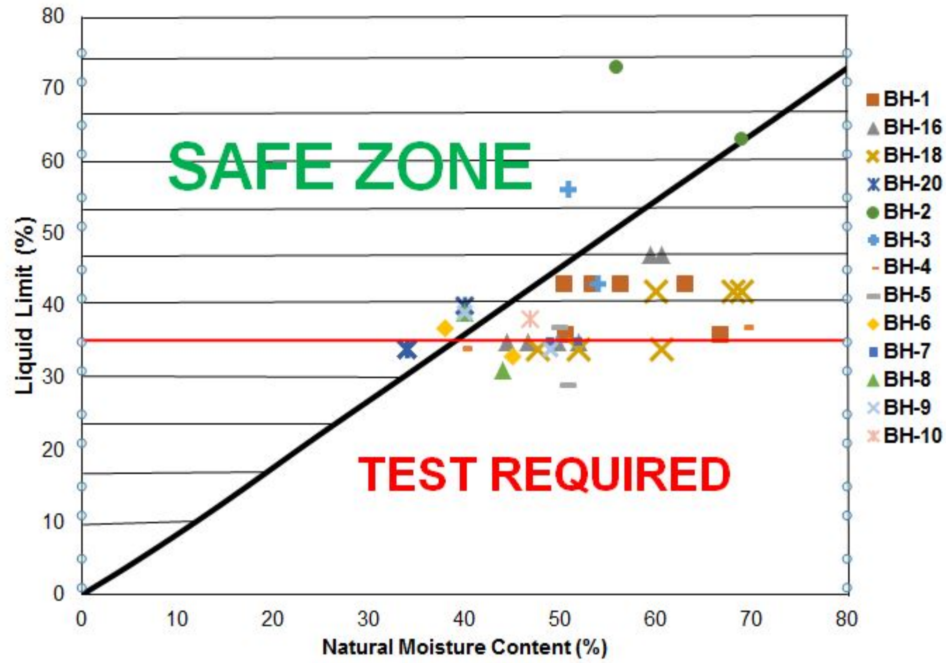


Fig. 7 Liquefaction susceptibility analysis based on liquid limit criteria [33] for soils within 6m depth

Table 1 Properties of soil samples that found to be critical based on liquid limit criteria

Borehole No.	Sample depth (m)	Liquid Limit (%)	Moisture Content	Soil Type
4	0.2	37	69	CI
	4.1	34	50	CL
5	0.2	37	50	ML
	4.1	29	51	CL
6	0.2	33	45	ML
	4.1	37	38	CI
7	0.2	35	52	ML
	4.1	35	49	ML
8	0.2	31	44	ML
	4.1	39	40	ML
9	0.2	34	49	ML
	4.1	39	40	CI
10	0.2	0	56	SM-ML
	4.1	38	47	CI

The top layer soil samples mainly from BH-1, BH-2, BH-20 and BH-16 are found to be in safe zone based on liquid limit and natural water content. However, soil samples within 6m depth from BH-4, BH-5, BH-6, BH-7, BH-8, BH-9, and BH-18 etc. are found to be on the boundary and hence requires other criteria to assess liquefaction susceptibility. Those are not falling into the safe zone, the details for those are given below in the Table 1.

3.3 Based on CPT Data

Evaluation of liquefaction potential based on field tests have gained much popularity due to the difficulties associated with obtaining good soil samples for laboratory testing. Major in-situ tests are the standard penetration test (SPT), cone penetration test (CPT), shear wave velocity test and the Becker penetration test (BPT). SPT being an inevitable part of soil investigation for civil engineering constructions, evaluation of liquefaction potential in terms of SPT value will be very beneficial for geotechnical engineers to make quick evaluation of liquefaction hazard for the sites from known SPT value. However, the main advantage of using CPT data is that the percentage of errors are considerably less than that of SPT method. In the present study the liquefaction susceptibility of soil layers was examined using CPT data. Based on the studies of [34], [35] have presented a soil classification based on CPT for assessing liquefaction susceptibility of fine grained soil as in Fig. 8. The present analysis is also done based on this criteria. The zone A in Fig 8 represents the region where cyclic liquefaction is possible depending on size and duration of cyclic loading. Soil samples whose tip resistance and sleeve friction combination lies in zone B is unlikely to liquefy, check other criteria; zone C, flow liquefaction and (or) cyclic liquefaction possible, depending on soil plasticity and sensitivity as well as size and duration of cyclic loading A plot of normalized CPT penetration resistance Q (dimensionless) versus normalized friction ratio F was generated first, where Q and F are defined as per equation 1 and 2.

$$Q = \frac{q_c - \sigma_{vo}}{\sigma'_{vo}} \tag{1}$$

$$F = \frac{f_s}{q_c - \sigma_{vo}} \tag{2}$$

Where q_c and f_s are the tip resistance and sleeve friction from the cone penetration test. This scattered plot was superimposed over the soil classification chart proposed by [35] as in Fig.9. The CPT data from BH-1, BH-16, BH-18 and BH-20 (in the new SPM region) and BH-2 to BH-12 (from pipeline region) were taken to generate scattered plots on Soil classification chart.

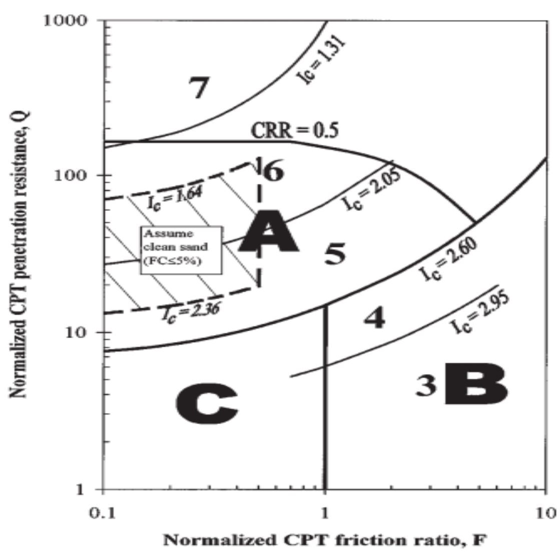


Fig.8 Soil classification chart by [34]

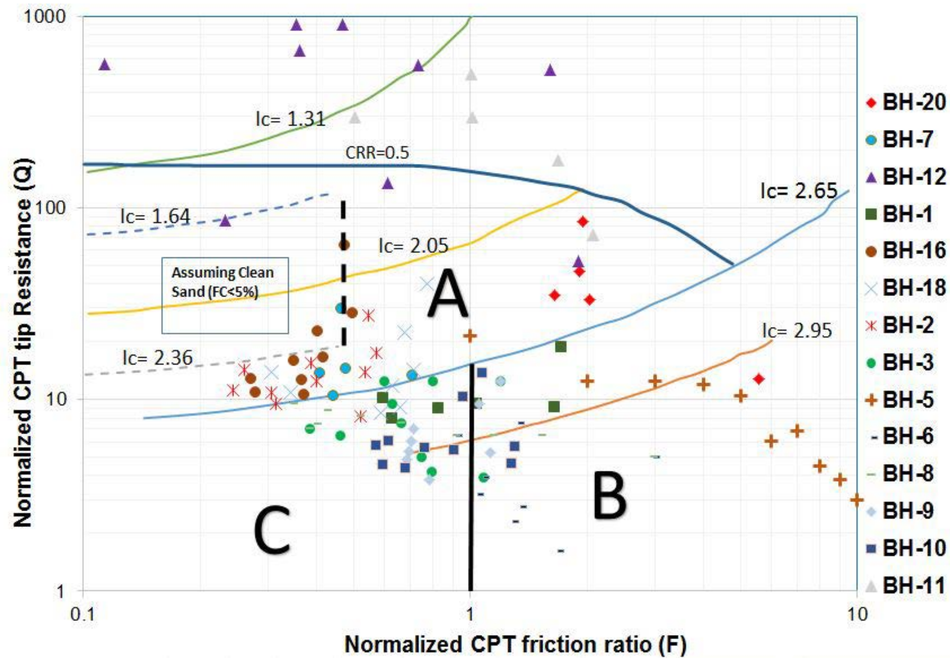


Fig. 9 Scattered plots of CPT data for other boreholes

From fig. 9, it was found that the top layers within 3m depth, especially in BH-2, BH-3, BH-5, BH-7, BH-11, BH-12, BH-16, BH-18 and BH-20 falls in zone A of the soil classification chart where there is a possibility of liquefaction depending on the size and duration of cyclic loading. It is also evident from fig. 9 that the soil beyond 3m depth in BH-1, BH-3, BH-9, BH-10 and BH-18 fall in zone C,which represents soils susceptible to cyclic and (or) flow liquefaction. [34] also suggested that the liquefaction susceptibility of soils in the zone C should be evaluated and verified using other criteria.

3. Conclusions

This paper presents the liquefaction susceptibility analysis of the offshore shore site in Yemen, based on the grain size distribution, index properties, and cone penetration test (CPT) data. The current study is the first and foremost step toward the assessment of the liquefaction potential. The liquefaction susceptibility analysis based on grain size distribution, index properties, and CPT data as it is an inexpensive and effective way to identify liquefiable soil layers whose liquefaction potential can be further assessed using dynamic laboratory tests such as cyclic triaxial tests. The analysis based on the grain size distribution, index properties, and the CPT data shows that that soil samples from the new SPM site is less susceptible to liquefaction than the soil samples from the pipeline region. This is mainly because the top overburden soil in the new SPM site is more plastic in nature than that of in the Pipeline site. Thus, even if having low cone penetration resistance, the soil stratum in the new SPM site will not undergo flow liquefaction due to high plasticity index. The soil stratum in the Pipeline site is more of silty nature with low plasticity index. Based on all the three analysis, it was found that the soil samples in BH-4 @ 4m depth, BH-6 @ 0.2m depth, BH-7 @ 0.5m depth, BH-9 @ 0.2m, BH-10 @ 0.5m depth, BH-11 @ 2m depth, BH-12 @ 2.5m depth BH-16 @1.5m and BH-18 @1.5m depth were found to be critical. The liquid limit and natural water content of these samples are in the boundary of liquefaction susceptible soils. Further, it is also observed that the top 4m to 6m soil in these borehole locations fall under the category of low compressible silts (ML) to poorly grade sand with fines (SP-SM). Hence it is recommended to perform dynamic laboratory testing such as cyclic triaxial/torsional/simple shear tests to determine the liquefaction potential. Further, it is also recommended to assess the strength degradation of these soils under different strain levels of cyclic loading using the dynamic laboratory tests which useful for performing site response studies.

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