CHAPTER 7

CONCLUSIONS AND FUTURE RECOMMENDATIONS

7.1 Conclusions of the Study

The fundamental objective of this dissertation is to study the liquefaction propensity of hydrocarbon contaminated Guwahati sand. The research was conducted in three phases. Each phase involved a separate parametric analysis of various other factors apart from the impact of degree of hydrocarbon contamination. The first phase included an indicative assessment of impact of hydrocarbon on the liquefaction potential through evaluating its effect on the shear wave velocity and shear modulus. The second phase involved the testing at relatively large scale by simulating the earthquake shaking using shake table tests. The effect of contamination depth ratio as well as shaking history were also encompassed. The third phase employed cyclic triaxial test to evaluate the pore pressure dynamics and cyclic degradation in contaminated sand. The purpose of incorporating three different set of experiments was to check the validity and reliability of the obtained results. Finally, an innovative and sustainable EICP remediation technique was designed to counter the deteriorating effects of hydrocarbon contamination on the cyclic response of Guwahati sand.

Each chapter of the thesis ends with some specific conclusions from that chapter. The overall conclusions obtained from this study are as follows:

a) Hydrocarbon contamination adversely impacts the geotechnical properties such as apparent specific gravity, hydraulic conductivity, shear strength characteristics and compaction characteristics.

b) Mineralogical characteristics did not show much deviations upon contamination while a substantial change was observed in morphological characteristics through SEM analysis. The percentage pore volume occupied by the oil defined as volumetric oil content increases almost linearly with increasing crude oil content.

c) In Bender element test, for excitation frequencies greater than or equal to 8 kHz, the peaks of transmitted and received waves were placed at almost similar position implying that there was no substantial change in the shear wave velocity. Since the observation was consistent for saturated specimens also therefore excitation frequency greater than 8kHz was regarded as consistency range.

d) The proposed frequency range in bender element test exceeds the critical value of number of wavelengths occurring between the bender elements and therefore NFE effects were greatly alleviated.

e) A critical/threshold crude oil content exists below which the effect of oil contamination on shear wave velocity is positive. This effect gradually weakens as the oil content reaches the threshold point. Soon after the oil content exceeds the critical oil content, its effect on shear wave velocity is negative. The variation of shear wave velocity profile with crude oil content results into an inverted V-shaped profile. For saturated condition at 200 kPa, $V_{s\text{-}6\%} = 1.32V_{s\text{-}clean}$ and $V_{s\text{-}12\%} = 0.72V_{s\text{-}clean}$.

f) The values of small strain shear modulus were also calculated to assess the impact of hydrocarbon on it. The trend of $G_{max\_cont}/G_{max\_clean}$ was analogous to that of shear wave velocity profiles.

g) The variation in confining pressures brings about substantial alterations in the shear wave velocity of both clean and contaminated sand. The shear wave velocity increased with increasing the confining pressure for all percentages of crude oil for both dry and saturated states. Further, the confinement-induced changes in shear wave velocity of contaminated sand is slightly diminished at higher confining pressures.

h) In case of dry sand, the influence of depth of contamination incorporated in terms of β ratio implies that the change in V_s after β = 0.6 was insignificant meaning thereby that after 60% of the total considered layer thickness is contaminated, no substantial change in V_s will be observed with further increase in the depth of contamination. As a non-destructive test, this observation may prove to be helpful in determining the extent of contamination along the ground depth. The influence of contamination depth ratio in saturated samples showed a nonlinear trend.

i) Coupled effect of crude oil content and contamination depth ratio was also undertaken. A critical oil content was observed irrespective of β at which the peak shear wave velocity was observed. However, with decreasing β, this peak seems to get suppressed.

j) There exist a "zero change point" at which the positive influences of oil contamination get counter-balanced by the negative influences and hence there is no net change in shear wave velocity of oil contaminated sands when compared to clean sand. In case of dry sand, $V_{s\text{-}9.35\%} \approx V_{s\text{-clean}}$.

k) Model testing in shake table revealed the liquefaction behavior in terms of pore pressure dynamics. It was observed that initial contamination moderately increases the liquefaction resistance up to ω = 6% after which it drops dramatically with further increase in crude oil up to ω = 10%. For the first shaking event, $r_{u,\ max\ (\omega=0\%)} = 0.62 r_{u,\ max\ (\omega=6\%)}$ while $r_{u,\ max\ (\omega=0\%)} = 1.12 r_{u,\ max\ (\omega=10\%)}$

l) The history of previous shakings considerably affects the liquefaction resistance of the sand bed. Remarkably higher resistance was observed during second and third shaking events particularly in contaminated sand bed. The effect of oil contamination was reduced after first shaking as oil being lighter gets displaced from the pore spaces by the water.

m) The CPT test indicated a decrease in DPI during shake 2 and shake 3and hence an improved strength as compared to the initial condition for all values of ω. It also indicated that the major portion of the settlement was achieved after the first shaking itself. Further, the increase in the value of DPI was directly proportional to the value of ω i.e., higher the value of ω, higher was the DPI value. Also the DPI recovery was constantly increasing with increasing oil content.

n) Coupled effect of contamination depth ratio and crude oil content also resulted into a zero change point similar to that in bender element test where the value of $r_{u,\ max}$ for contaminated samples were almost unchanged with respect to clean sand. This point in case of shake table testing was slightly lower than the one observed in bender element test. No evidence of such a point was observed during second and third shaking events.

o) Cyclic triaxial tests on clean and contaminated samples evaluated the liquefaction potential from the pore pressure ratio criterion. Liquefaction initiation (r_u =0.9) was achieved for all oil contents except for ω = 4% and ω = 6% at 0.5% cyclic shear strain.

At 1% cyclic shear strain, liquefaction initiation was evident at all oil contents. Yet full liquefaction state was not observed in some of the cases.

p) The effect of constituent chemicals on the calcite precipitation ratio was evaluated and a preferred concentration was identified at which maximum precipitation ratio was observed.

q) The effect of EICP treatment on the generation of excess pore pressure and stiffness degradation at various crude oil contents, curing periods and cyclic shear strains was evaluated. A remarkable recovery in the cyclic strength and stiffness degradation rate of contaminated sand was observed. A two-fold increase in the G_{max} value was observed for 7 days cured specimens. Moreover, the stiffness degradation parameter was reduced upto 80% at γ =0.5%.

r) The observed patterns of the excess pore pressure levels and degradation parameters at two different cyclic strains indicated that the efficiency of the EICP treatment diminishes at both higher strain levels and higher oil contents.

s) The effect of curing on the cyclic strength was also determined. The results showed that the 96% of the calcite precipitation was achieved in first 7 days of curing. Therefore, the gain in cyclic strength was maximum during first 7 days.

t) The inferences obtained from cyclic triaxial tests were validated theoretically using an empirical model developed by Seed et al. (1975b). Number of cycles to liquefaction was calculated for cemented as well as uncemented samples.

7.2 Contributions of the Study

The study deals with the dynamic aspects of hydrocarbon-contaminated soils which has been addressed in detail and can be implemented to formulate a systematic approach for their effective management and utilization in construction practices. It would aid in the reclamation of the abandoned oil fields and other such contaminated land masses. Assessment of elastic shear wave velocity in contaminated sand, being a non-destructive test, would aid in the evaluation of an indicative subsoil responses (subjected to variation and lab and field conditions) for both undeveloped as well as developed sites. It may also be helpful in identifying the severity as well as extent of contamination before implementing suitable remediation techniques. EICP technique to stabilize such soil has been carefully designed which has shown a significant improvement in the dynamic behavior of hydrocarbon contaminated sand. It can be effectively utilized either as an active or passive site remediation technique (depending on the site and soil conditions) to arrest liquefaction manifestations.

7.3 Limitations and Future Scope of Study

The contamination considered in the study is homogeneous. However, on field the contamination may not be homogeneous. Therefore, non-homogeneously or partially contaminated soils can also be considered for further study. The EICP technique has been discussed at small/medium strain levels. The efficiency of this technique can be discussed for the cases involving large strains. Further, the implications of this study can be applied to soil-pile/soil-structure interaction studies in oil contaminated soils.