

CHAPTER 1

INTRODUCTION

1.1 General

Earthquakes are widely considered as one of the most catastrophic natural disasters, inflicting considerable damage such as failure of earth structures, building settlement or tipping, lateral spreading of sloping terrain, and densification causing vertical settlements. The roots of these catastrophes can be traced to either compaction of loose soil deposits or a phenomena known as liquefaction. The liquefaction phenomenon can be attributed to a state of zero effective stress caused by a gradual increase in pore water pressure due to soils' tendency to densify under dynamic loading. The sure sign of any liquefaction phenomenon in a soil is the buildup of excess pore water pressure when subjected to cyclic loading. Although earthquakes are the most common cause of this rapid surge in the pore water pressure, other activities such as blasting can also trigger it. Liquefaction can have severe damaging impacts. The strength and stiffness of the soil deposit is completely lost and its ability to support the superstructure above it is also completely lost which may result to sinking of the structures, irregular settlements causing structural damage and even toppling of the entire building, the classic example of which is the one witnessed during Niigata earthquake in 1964 (Fig. 1.1a). It has also the potential to disrupt the distributed subsurface facilities like water and gas pipelines. Some other associated phenomenon with liquefaction are lateral spreading, sand boils (Fig. 1.1b), flow failures, buoyant rise of buried structures etc.

The necessity of accurate estimations of where liquefaction is likely to occur and what are the effects of liquefaction may be underscored by past damage and destruction caused by liquefaction. Such analyses are required to protect human life and property while also minimizing the economic, environmental, and societal implications of liquefaction.



Fig. 1.1 (a) Toppling of a building during Niigata earthquake in 1964 (b) Sand boil during California, earthquake, 1979 (Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley)

Customarily linked with dynamic loadings, liquefaction can also trigger under static loading scenarios. The breakdown of slopes in hydraulic fill dams, spoil tips, and tailings has been associated to static liquefaction. Looking into the severe threats that liquefaction

manifestations pose to the safety of the civil engineering structures, the need to understand the mechanism responsible for it is inevitable.

1.2 Liquefaction Mechanism

Liquefiable soils are typically frictional materials and their resistance to deformation is dominated by their inter-particle contact force which is termed as effective stress. Soils' behavior is in general governed by effective stresses and so is in the case for liquefaction behavior. Prior to understanding the responsible mechanism for liquefaction, it is first important to understand the type of soils which are prone to liquefaction. In general, contractive soils are susceptible to liquefaction while the dilative soils are not and they may show cyclic mobility. Further in contractive soils, loose saturated sands are most susceptible to liquefaction. Fig. 1.2 shows the common range for particle size of soil to witness liquefaction.

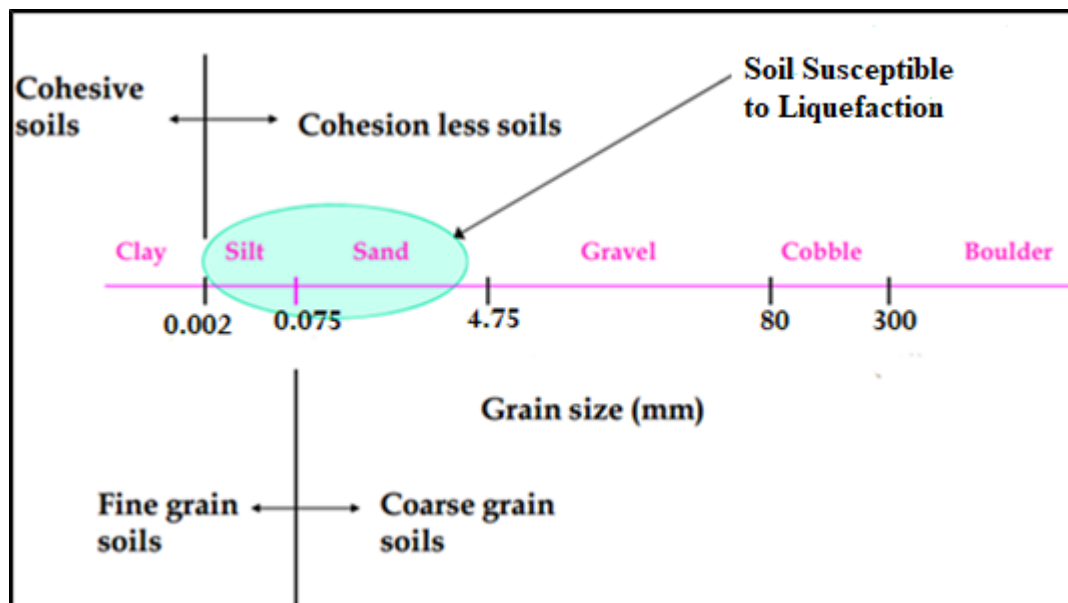


Fig. 1.2 Grain size range of soil susceptible to liquefaction

Whenever any loose saturated sand deposit is subjected to any kind of dynamic loading, there is a rapid generation of excess pore water pressure. However, the water being practically incompressible, restricts the rapid contraction of the soil fabric and thereby increasing the pore pressure with each applied loading cycle. Increase in pore pressure decreases the inter-particle effective stress and the instant at which the excess pore pressure has increased enough to reduce the effective stress to nearly zero, liquefaction has said to occur. Fig. 1.3 shows the concept of liquefaction before and after liquefaction. Based on the above discussion, three necessary conditions that need to be met for liquefaction are:

1. Soil should be contractive
2. Soil should be saturated
3. Soil should be subjected to sufficient number of loading cycles.
4. The time rate of development of pore pressure should be sufficiently greater than its dissipation i.e. the condition should be undrained.

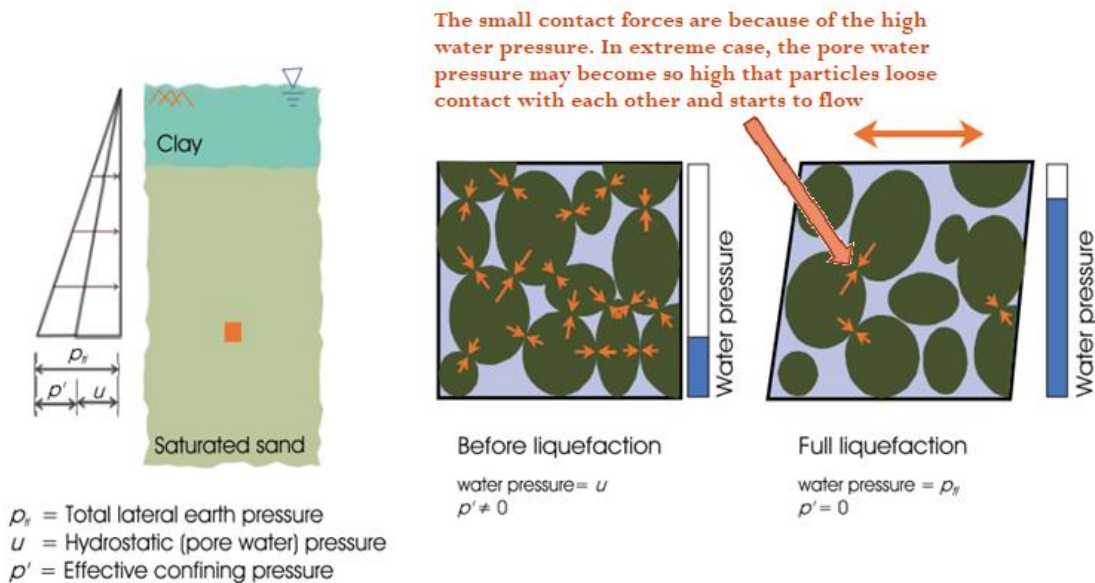


Fig. 1.3 General liquefaction concept (Image source: Dash et al. 2010)

1.3 Factors affecting Liquefaction

All the factors which govern the liquefaction phenomenon have been broadly categorized into two categories:

1. Site specific factors
2. Soil specific factors

Site specific factors includes the intensity and duration of the earthquakes, location of the ground water table (determines the saturation state of the deposit), geological history of the soil deposits and the additional loads on these deposits in the form of buildings and other infrastructures. On the other hand, the soil specific factors include soil type, soil void ratio or relative density, grain size distribution, shape of the soil grains, depositional environment of soil, overburden and confining stresses and age of the soil deposits.

1.4 Hydrocarbon Contamination

Oil and gas are the world's most prominent energy sources, and their importance is ever-increasing because of the rapidly escalating global energy need. However, the biggest disadvantage of this form of energy is the associated environmental damage done by it in the form of oil spills. Every day, over two million tonnes of oil are produced around the world, and around ten percent of that is released into the environment as a result of human activity. Currently, the activities associated with oil industry such as extraction, processing, and transportation of oil have affected a huge portion of landmass by releasing petroleum products into the soil environment. The environmental issues caused by oil spills are not limited to visible emissions, as cumulative effects slowly degrade the soil quality. To add to that, hydrocarbon pollutants can migrate lower into the groundwater zone due to gravity, and

in addition to contaminating soil along the route, they can be carried horizontally by water, reaching soil elsewhere.

Soil contamination is a subject requiring much needed concern given that soil plays critical and fundamental role in our lives, and its efficacy has been continuously enhanced by the ever-increasing pace of life, in which industrialization is an unavoidable need (Yong 2000). Apart from the negative environmental effects of hydrocarbon pollutants, the impact of hydrocarbon compounds on soil engineering properties have piqued researchers' concern, and many have examined them in respect to the fundamental and critical roles of soil in geotechnical applications.

1.4.1 Sources of Hydrocarbon Contamination

Before attempting to resolve contamination issues, it is critical to comprehend the source of the problem. Hydrocarbon contamination can occur at four levels throughout the entire process, from the discovery of oil reserves to their use in everyday life.

1. *Natural seeps of oil:* Natural leaks of crude oil and gas from subsurface reserves through the ocean floor are known as oil seeps. Oil from seeps can be mistaken for oil spills, despite the fact that they are not created by humans.
2. *Extraction Process:* Oil exploration and extraction from the ground or below the ocean surface potentially could release oil into the environment.
3. *Transportation process:* Crude oil is a global commodity, and it may leak from storage tanks, barrels, pipelines, and other bulk transport containers as it transport around the world.
4. *Everyday use of oil:* There is a risk of spilling crude or refined oil whenever it is kept or used, such as for fuel or production.

Fig. 1.4 shows the contribution of various sources through which soil gets contaminated.

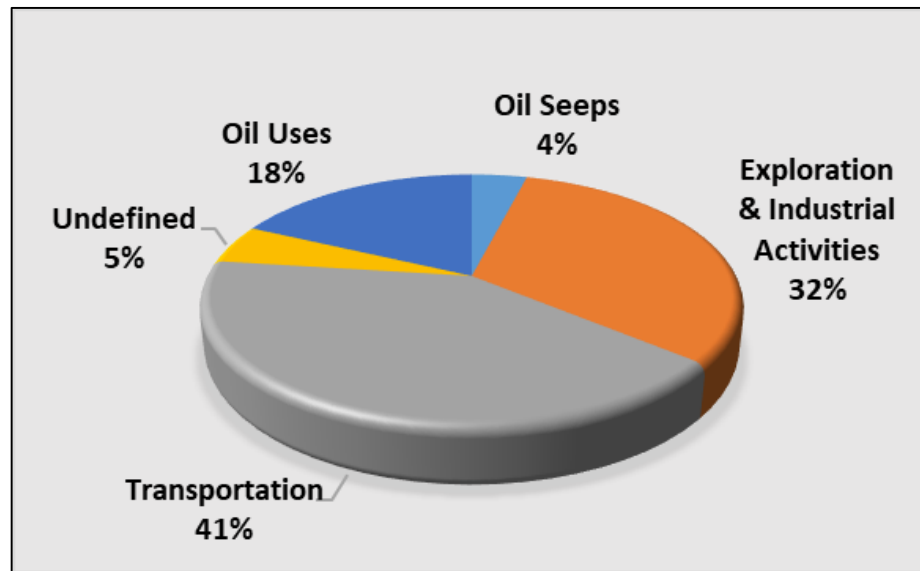


Fig. 1.4 Distribution of potential sources of hydrocarbon contamination (Source: Global Oil Pollution Information Gateway, 2016)

Considering all possible sources, hydrocarbon contamination can be classified as small scale contamination and large scale contamination.

1.4.1.1 Small-scale contamination

Such contamination occurs through leaks and spills through the automobiles. In the high traffic areas, petroleum hydrocarbons leaked through the cars get transported to the nearby soil during the events of rain and ultimately contaminate the soil and groundwater.

1.4.1.2 Large-scale contamination

Spills during transportation (such as train derailments, shipping accidents, or pipeline breaches), extraction (such as the Deepwater Horizon incident), or storage are the most common sources of petroleum hydrocarbon exposure (such as leaking storage tanks). A large portion of landmass in and around the oilfield have been subjected to severe oil spill during the extraction and storage of the crude oil (Fig. 1.5)



Fig. 1.5 A view of contaminated site at Bomu station due to severe spillage (Image source:www.google.com)

1.4.2 Oil Spill Statistics

Hydrocarbon contamination of soil and its consequential after-effects have been recently emphasized by the researchers owing to its escalating frequency of occurrence and also commercial motivations. In order to provide realistic figures about the incidents of hydrocarbon contaminations, some of the largest oil spills in the history, since 1901, have been consolidated and presented in Table 1.1 (Aigner et al. 2010; Etkin 1999; Whitson 1999).

Fig. 1.6 shows the number of spill accidents through various means of transportation along with their respective spill volume over the year 2002-2016. It is evident from the chart that the number of pipeline spills has significantly increased over the years. In the year 2016 itself there has been more than 300 pipeline incidents of volume more than 4 million gallons. Furthermore, Fig. 1.7 presents the volume of different types of hydrocarbon contaminations observed on the west coast of the USA clearly underlining the frequency of their occurrence. Again from the Fig. 1.7 it can be inferred that the crude oil is one among the most significant type of hydrocarbon-based contaminants.

Table 1.1 Major oil spills occurred worldwide (Source: Rajabi and Sharifipour (2019))

Location	Amount (Tones)	Date	Spill Type	Cause(s)
Kern County, California, United States	12,27,600	1909	Oil Spill	Wellhead blowout
Persian Gulf (Kuwait)	10,91,405	1991	Oil Spill	War
Gulf of Mexico	4,70,779	2010	Crude oil	Wellhead blowout
Gulf of Mexico	4,70,000	1979	Oil Spill	Wellhead blowout
Tobago	2,87,000	1979	Oil Spill	Collision
Persian Gulf (Iran)	2,60,000	1983	Crude Oil Spill	Collision and Bombing
700 nautical miles of Angola coast	2,60,000	1991	Iranian Heavy Crude Oil	Fire/Explosion
Saldanha Bay South Africa	2,52,000	1983	Light Crude Oil	Fire
Brittany , France	2,23,000	1978	Oil Spill	Collision
Gulf Of Mexico	1,62,337	2010	Crude Oil	Wellhead Blowout
Mediterranean Sea Near Genoa , Italy	1,44,000	1991	Crude Oil	Explosion
800 Km South-East of Tripoli , Libya	1,42,860	1980	Crude Oil	Wellhead Blowout
700 nautical miles off Nova Scotia Canada	1,32,000	1988	Crude Oil	Heavy Weather/Fire
Isle of Scilly , England	1,19,000	1967	Kuwait Crude Oil	Navigational Error
Gulf of Oman	1,15,000	1972	Crude Oil	Collision
North Sea, Belgium	1,07,140	1971	Oil Spill	Unknown
Shuaiba , Kuwait	1,06,120	1981	Storage Tank	Unknown
Usinsk in Northern Russia(Komi Republic)	1,04,420	1994	Oil Spill	Ruptured pipeline, old equipment
Lo Coruna , Spain	1,00,000	1976	Oil Spill	Collision
Navarino Bay, Greece	1,00,000	1980	Iraqi Crude Oil	Fire/ Explosion

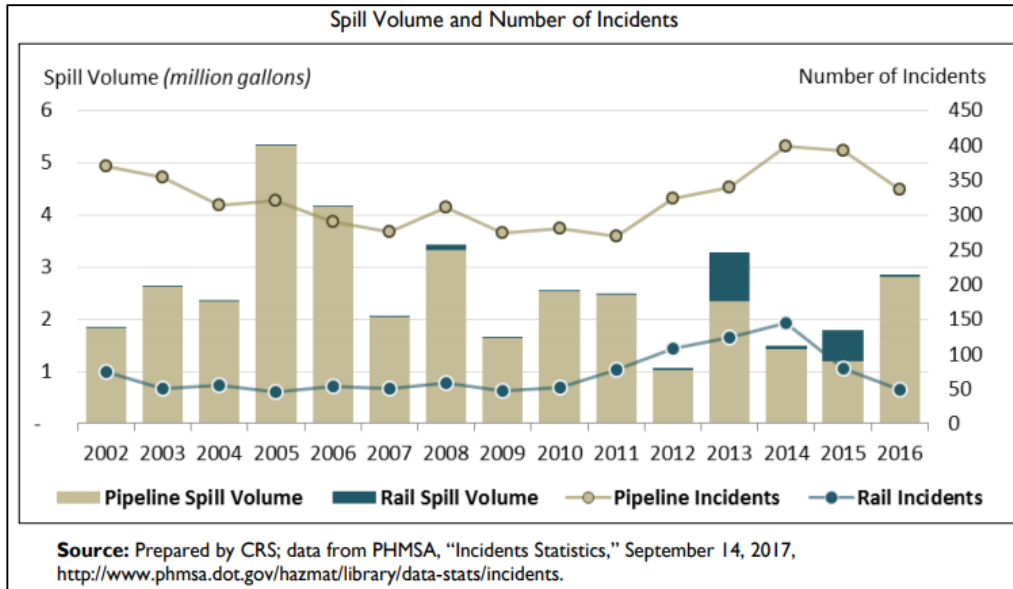


Fig. 1.6 Global statistics of oil spill volume and number of incidents through different sources

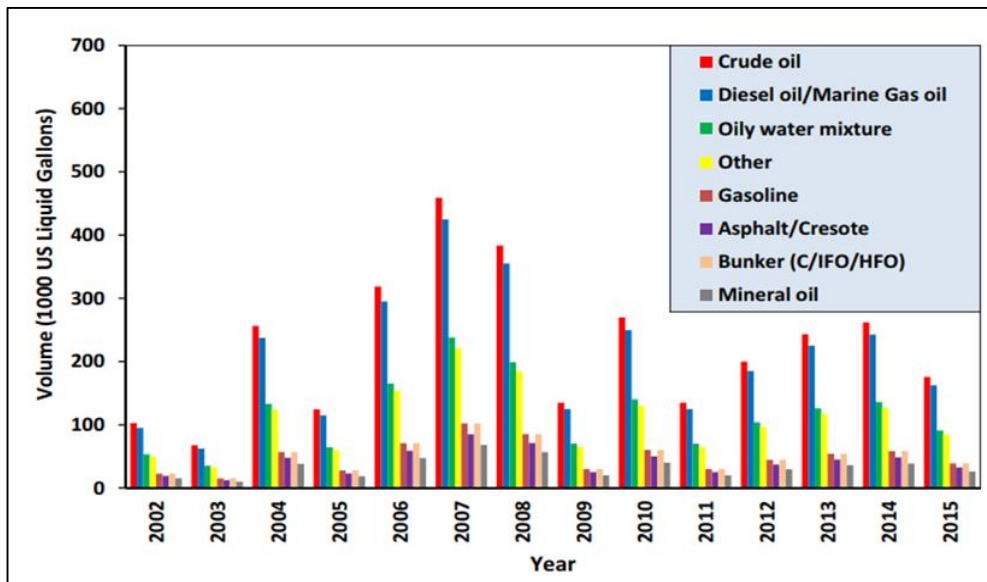


Fig. 1.7 The volumes of different types of hydrocarbon contaminations (2002–2015)

1.4.3 Geotechnical Concerns

Hydrocarbon compounds have the ability to significantly alter the particle-particle interactions, grain size characteristics, morphologies as well as geometrical specifications (in case of fine grained soils). These alterations can severely impact the engineering

properties of the soil. Investigating the impact of hydrocarbon based contaminants on the geotechnical properties of soil has been a mainstream topic of research over a long period of time. Along with many other researchers, Al-Sanad et al. (1995) and Khamehchiyan et al. (2007) were some who conducted a comprehensive experimental tests to evaluate the geotechnical properties of hydrocarbon contamination soils. The studies showed that the geotechnical properties of the soil get compromised upon hydrocarbon contamination. Evgin and Das (1992) studied the stress-strain behavior of loose and dense sands when saturated with water and oil. Influence of hydrocarbon on other geotechnical properties such as Atterberg limits (Rahman et al. 2010a) increase in particle size distribution (Akinwumi et al. 2014; Ijimdiya 2013; Nazir 2011), reduction in hydraulic conductivity (Akinwumi et al. 2014; Rahman et al. 2010b; Khamehchiyan et al. 2007), reduction in optimum moisture content (OMC) (Alhassan and Fagge 2013; JIA et al. 2009; Ochepe and Joseph 2014) were reported in literature. In conclusion, hydrocarbon contamination causes reduction in shear strength, creates collapsible soil skeleton, increases compressibility and settlement, change in physiochemical properties, alters pore pressure and reduces plasticity index. Deterioration of these geotechnical properties of soil will ultimately impact the serviceability and reliability of structures.

1.5 Motivation of Study

Despite the fact that subject of hydrocarbon contamination has received a great deal of attention in the past, there are still a few cases where more information and understanding is required. In comparison to the quite large number of studies conducted on the geotechnical properties of contaminated soils under static loading conditions, there are very few studies related directly or indirectly on the effects of various oil based contaminants on the cyclic

properties of contaminated soils. Therefore, dynamic behavior of the hydrocarbon contaminated soil requires a much needed attention of the researchers.

Crude oil contamination has jeopardized the quality of a huge amount of land area globally many of which lies in the high risk seismic zones which attenuates the complexities in the existing problems. The 1983 Coalinga earthquake in USA, for example, occurred underneath a substantial oil-producing fields, inflicting damage to both surface and sub-surface facilities to varying degrees. Regardless of having huge potential for redevelopment, many of the major oilfields which have been abandoned or expected for so in future cannot be reutilized for new construction practices. For the effective reclamation of the contaminated sites lying in the high risk seismic zone, an effort has been made to conduct a comprehensive study on the dynamic behavior of such a soil and also the impact of hydrocarbon compounds on its liquefaction behavior. Furthermore, a sustainable, environmental-friendly and reliable technique has been developed to counter liquefaction in such a soil system.

1.6 Research Objectives

Preceding section explains the lacunae in the available literature which provides the motivation for taking up the present research. The primary objectives of the present research are as follows:

- Estimate the effect of hydrocarbon contamination on the shear wave velocity using bender element test.
- Study the effect of depth of contaminated layer on shear wave velocity.
- Study the pore pressure evolution and liquefaction propensity in the hydrocarbon contaminated sand performing shake table investigations.

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- Assess the pore pressure dynamics and cyclic degradation in hydrocarbon contaminated sands using cyclic triaxial tests.
 - Design a bio-inspired in-situ remediation techniques (EICP) and estimate its efficiency.

1.7 Organization of the thesis

This thesis outlines the research conducted to accomplish the above stated goals in seven chapters. This chapter starts with an introduction of the current research. Below are brief summaries of the next chapters.

Chapter 2 presents a detailed review of laboratory and field-based liquefaction in conjunction with some observed liquefaction and related phenomenon. The dynamic behavior of hydrocarbon-contaminated soils has also been studied. Following it is an in-depth discussion of liquefaction mitigation techniques and the scope of new emerging techniques using a multidisciplinary approach has been discussed.

Chapter 3 outlines the details of materials and methodologies used in the study. A brief description of all the geotechnical, mineralogical and morphological tests along with their testing procedure as per relevant standards/code of practice has been presented. A detailed discussion of the results of each test has also been included.

Chapter 4 elucidates the effect of crude oil contamination on shear wave velocity of sandy samples by performing a series of bender element tests under various excitation frequencies, confining pressure and contamination depth. A brief description of sample preparation and testing procedures has also been included. The main focus is to investigate the effect of

hydrocarbon contamination on the shear wave velocity of Guwahati sand which can later be used to assess the liquefaction propensity as per the available correlations.

Chapter 5 presents the study conducted on shake table tests to study the effect of degree of contamination in terms of crude oil content (ω), depth of contamination in terms of contamination depth ratio (β), defined as the ratio of contaminated depth to the total considered depth, and shaking history on the pore pressure response. The liquefaction potential was evaluated in terms of normalized pore pressure ratio. A detailed design of shake table model along with the instrumentation, sample preparation and experimental procedure has also been discussed.

Chapter 6 pertains to the application of EICP technique in stabilizing hydrocarbon contaminated sand subjected to cyclic loading using strain-controlled cyclic triaxial tests. The efficiency of the technique was evaluated in terms of cyclic pore pressure and modulus degradation. Prior to that, a supporting analysis to study the effect of crude oil contamination on the cyclic response of sand has also been presented. A detailed process of sample preparation and experimental procedure has been incorporated.

Chapter 7 summarizes the key findings from the experimental investigations. The limitations of present research and its future scope are presented.